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 excursed 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 excurse 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

M etastases to the spine are a common complication of cancer, occurring in up to 40% of cancer patients, and can result in major functional morbidity, including pain, pathological vertebral fractures, myelopathy, and radiculopathy from compression of adjacent neural structures. With the rapid advancement in the precision of imaging and radiation therapy delivery, spine stereotactic body radiation therapy (SBRT) has become an effective noninvasive treatment option for realistic long-term local disease control, maintenance of neurological function, and pain relief in spine metastasis patients.

The spinal cord is the major radiation dose-limiting tissue in spine SBRT, and the risk of irreversible neurological deficits from radiation myelopathy remains a feared complication of this treatment. For the safe practice of spine SBRT, dose constraints have been established for the spinal cord. However, the definition of the spinal cord as a planning organ at risk volume (PRV) has varied considerably with no consensus regarding the use of safety margins...
(PRV expansions) around the cord to account for setup uncertainties, contouring variations, and organ motion. In clinical practice, PRV expansions have ranged from no expansion to 1.5- to 2-mm PRV margins. While the high-precision delineation of the spinal cord and its spatial relationship to the spinal tumor is now generally performed on high-resolution T2-weighted magnetic resonance images, the dose effects from inherent motion of the spinal cord have not been considered in the SBRT plan design and dosimetry process.

Physiological motion of cerebrospinal fluid and spinal cord during the cardiac and respiratory cycle has been well described in normal subjects and patients with nonmalignant spine conditions. However, the inherent motion pattern of the cord in spine tumor patients has been less well understood. A recent study by Tseng et al., using precision MRI-based delineation of the cord, demonstrated, for the first time, significant spinal cord motion in spine SBRT patients. The impact of the cord’s motion on the dose received by the cord, however, remains unknown.

Because the cord is generally located within millimeter distance from the planning target volume (PTV) and thereby subjected to the very sharp dose gradients of ablative SBRT to the tumor, even minimal cord motion may exert a significant effect on the actually received dose to the spinal cord and its vulnerable serial microstructures. There is an unmet need to recognize the potential physiological motion of the “dancing” (ie moving) cord and quantify its dose effect on the cord, particularly for patients with limited cord tolerance due to close proximity of the target to the cord and/or prior spine radiation.

The purpose of this research was to evaluate the pattern of inherent spinal cord motion for SBRT of spine metastases, and assess the effects of cord motion on the dose received by the cord. Our specific aims were to quantitate the cord’s motion by dynamic MRI, and compare the dosimetric parameters between the moving (“dancing”) and static cord defined by the conventional static T2-weighted MRI. Our ultimate goal was to derive recommendations for PRV margins that take into account the effects of spinal cord motion.

METHODS

Study Design and Patient Population

This retrospective study included 21 adult patients with intact spinal metastases (treated October 2017 to March 2019). The study was approved by the Institutional Review Board, including consent waiver. All patients had dosimetry planning and an SBRT-tailored MRI protocol including a dynamic MRI sequence to study spinal cord motion. Patient characteristics are presented in Table 1.

Clinical Imaging and Treatment Planning

All patients underwent standard SBRT planning CT and spine-SBRT-tailored 3 Tesla MRI, including cardiac-gated dynamic balanced fast field echo (BFFE) MRI to assess spinal cord motion. For the BFFE MRI, 15 dynamic images were acquired over 2.5 to 5 min (depending on heart rate) for a total of 315 images in the 21 patients. Details of imaging are presented in Table 2.

For SBRT planning, target and normal tissue contouring had been previously performed based on rigid coregistration of simulation CT and conventional T2-weighted MRI using MIM (v6.7.11, MIM Software, Cleveland, Ohio). Details of imaging and imaging use for target and normal tissue contouring are presented in Table 2. A PRV margin of 2 mm was added to the cord to derive the spinal cord PRV. Routine dosimetry was performed (dose calculation grid size 2 mm). Volumetric-modulated arc therapy was used in 20 patients and fixed-field intensity-modulated radiation therapy in 1 patient. PTV dose and normal tissue constraints were prescribed per routine SBRT dosing standards.
maximal pixel dose to the spinal cord PRV was constrained to 20 Gy in the 3-fraction (11 patients) and to 25 Gy in the 5-fraction regimen (10 patients, Table 1).

Image Evaluation and Spinal Cord\textsubscript{dyn} Contouring
All imaging was coregistered using a research platform within MIM v6.7.11 (Figure 1), and coregistrations were independently reviewed by 2 investigators with extensive SBRT experience (co-authors S.S.L. and N.A.M.). The spinal cord (cord\textsubscript{stat}) was contoured on the each of the 15 T2-weighted images (cord\textsubscript{dyn}) with each reviewer, and uncertainties were resolved in consensus with an additional reviewer. CT simulation image data sets with the treatment plans were coregistered to transfer existing dose data from the previous clinical treatment plan to the BFFE images. On the static images, 1, 1.5, and 2-mm expansions of the cord\textsubscript{stat} contour were created as shown in Figures 1A and 1B.

Dosimetric Analysis
Based on the coregistered BFFE, static T2-weighted MRI, planning CT, and dose data sets, we measured the pixel maximum dose (dose\textsubscript{max}) to the cord, using the BFFE and corresponding static T2-weighted images at the level of the tumor lesion. The dose\textsubscript{max} to the cord\textsubscript{stat} and the cord\textsubscript{dyn} for each of the 15 BFFE images were calculated (Figures 1C and 1D). The average cord\textsubscript{stat} dose, which more closely reflects the real-life situation (Figure 1E) in SBRT delivery, was derived by averaging of cord dose\textsubscript{max} of each of the 15 images. The maximum cord\textsubscript{dyn} dose was defined as the maximum of the 15 cord dose\textsubscript{max} values for each patient.

PTV doses and spinal cord doses were converted to equivalent dose in 2-Gy fraction (EQD\textsubscript{2}) estimates using the linear-quadratic (LQ) model\textsuperscript{12,16} to allow direct comparisons incorporating the number and size of fractions in the different hypofractionated (3- or 5-fraction) regimens. All doses are reported in EQD\textsubscript{2}. The mean PTV dose of the clinical treatment plans was 43.4 ± 9.6 Gy (for α/β = 10 Gy). The mean cord\textsubscript{stat} dose ranged from 23.1 ± 8.5 Gy (for α/β = 3 Gy) to 28.6 ± 11.9 Gy (for α/β = 0.87 Gy),\textsuperscript{2} and 24.9 ± 8.5 Gy for α/β = 2 Gy. Cord doses are reported as EQD\textsubscript{2} (for α/β = 2 Gy). Details of the LQ model and EQD\textsubscript{2} computations are presented in the Supplemental Digital Content.

Quantifying Motion
Dice and Jaccard coefficients were calculated comparing the spinal cord contours in each of the dynamic images (cord\textsubscript{dyn}) with the cord contour in the static T2-weighted image (cord\textsubscript{stat}). Mean and standard deviation of all 15 images were calculated for each patient. Coordinates of the centroids of static and dynamic cord contours were computed. Motion between the 2 images was quantified as the distance between the centroids. Cord\textsubscript{stat} was used as a fixed reference point for motion assessment.

Statistical Analysis
Statistical analysis was performed using SPSS v19.0 (IBM) and R version 3.1.1 (R Foundation for Statistical Computing, Vienna, Austria). Continuous data were summarized using the median and range. The paired t-test was used to compare the magnitude of cord excursions in different directions. Spearman’s rank correlation coefficient was used to examine the relationship between spinal cord motion and changes in dose. For all tests, $P < .05$ was considered statistically significant.
FIGURE 1. BFFE and spinal cord delineation with PRV margins. A, Axial static volumetric T2-weighted (DRIVE) image at the level of the spine metastasis with spinal cord delineation and superimposed isodose lines from the SBRT dosimetry (obtained from coregistration with the radiation therapy planning CT, as done in routine dosimetry planning). The isodose lines demonstrate the steep dose gradients in close proximity to the spinal cord. B, Same T2-weighted image as in A, magnified and without isodose lines: The static cord (cordstat) is contoured in yellow, a 1-mm PRV margin around cordstat in light green, a 1.5-mm margin in blue, and a 2-mm margin in red. C, BFFE image at the same level as A and B. One of corddyn’s motion phases is shown (dark green contour), demonstrating that in this phase, corddyn excurses to 1 mm from the confines of cordstat. The color scheme is the same as in A and B. D, T2-weighted image (same as in B) shows cordstat, 1, 1.5, and 2-mm margins delineated in the same color scheme as in B, and demonstrates the motion phase seen in C where corddyn (dark green contour) excurs to 1 mm from the confines of cordstat. E, Schematic representation of the “dancing” cord moving in and out of the cordstat and cordstat plus PRV margins. Corddyn, cordstat, and the 1, 1.5, and 2-mm margins are shown in same color scheme as in A-D. The schematic illustrates corddyn excursions in multiple directions during the imaging beyond the 1-mm margin up to the 1.5-mm margin of cordstat.
RESULTS

Spinal Cord Dose

The average EQD2 dose received by cord\(_{\text{dync}}\) exceeded that of cord\(_{\text{stact}}\) in 13 of the 21 patients (62%) and was lower than the cord\(_{\text{stact}}\) dose in the remaining 8 patients. The average dose increase of cord\(_{\text{dync}}\) over cord\(_{\text{stact}}\) ranged from 0.6% to 13.8% (median: 4.3%), corresponding to 0.1 to 4.6 Gy (median: 1.0 Gy). The average cord\(_{\text{dync}}\) dose exceeded the cord\(_{\text{stact}}\) dose by >5% in 5 patients (5/21, 24%) and by >10% in 3 patients (3/21, 14%) (Figure 2).

Using the maximal cord\(_{\text{dync}}\) excursion (among the 15 BFFE images), the maximal cord\(_{\text{dync}}\) dose exceeded that of cord\(_{\text{stact}}\) in 76% of the patients (16/21), was lower in 4 patients, and remained unchanged in 1 patient. The maximal dose increase of cord\(_{\text{dync}}\) over cord\(_{\text{stact}}\) ranged from 1.4% to 23.5% (median: 5.7%) or 0.4 to 7.8 Gy (median: 1.4 Gy). Maximal cord\(_{\text{dync}}\) dose exceeded cord\(_{\text{stact}}\) dose by >5% in 10 patients (10/21, 48%) and by >10% in 4 patients (4/21, 19%) (Figure 2).

Spinal Cord Motion

The degree and frequency distribution of cord\(_{\text{dync}}\)’s motion with respect to cord\(_{\text{stact}}\), image by image during BFFE imaging, is presented in Figures 3. The tracing of the cord\(_{\text{dync}}\) motion in each patient is illustrated in Figure 4, and a visual representation of the spinal cord motion is shown in the Video. Across the 315 dynamic
images (15 images x 21 patients), $\text{cord}_{\text{dyn}}$ excursions outside $\text{cord}_{\text{stat}}$ ranged from 0.0 to 1.5 mm (median: 0.6 mm). Dice and Jaccard coefficients of $\text{cord}_{\text{dyn}}$ and $\text{cord}_{\text{stat}}$ ranged from 0.70 to 0.95 (median: 0.87) and 0.54 to 0.90 (median: 0.77), respectively. The $\text{cord}_{\text{dyn}}$ motion in the anteroposterior (AP) direction was significantly greater (median: 0.5 mm, range: 0.1-1.5 mm) than in the lateral direction (median: 0.3 mm, range: 0.0-1.1 mm; $P = .04$). Spinal cord motion of more than 0.5 mm was common and occurred in 86% of the patients (18/21) and 60% of the dynamic images (188/315).

Hypothetical PRV margins of 1, 1.5, and 2 mm surrounding $\text{cord}_{\text{stat}}$, as often used clinically, were evaluated for their ability to encompass the excursions of $\text{cord}_{\text{dyn}}$ (as illustrated in Figure 1B, 1D, and 1E). $\text{cord}_{\text{dyn}}$ spatially extended outside the volume of $\text{cord}_{\text{stat}} + 1$ mm in 43% of the patients (9/21). Of these 9 patients, 7 (78%) had an excess in cord dose. $\text{cord}_{\text{dyn}}$ abutted $\text{cord}_{\text{stat}} + 1.5$ mm in 1 patient (1 image), but did not extend outside $\text{cord}_{\text{stat}} + 1.5$ mm or outside $\text{cord}_{\text{stat}} + 2$ mm PRV margin.

**Spinal Cord Motion and Dose**

The EQD2 dose ratio of $\text{cord}_{\text{dyn}}$ over $\text{cord}_{\text{stat}}$ across the 315 dynamic images ranged from 0.9 to 1.2 for maximal $\text{cord}_{\text{dyn}}$ dose and from 0.9 to 1.1 for average $\text{cord}_{\text{dyn}}$ dose. We did not identify a clear correlation between the spatial degree/extent of $\text{cord}_{\text{dyn}}$’s motion (as illustrated in Figures 1C-1E) and the dose received by $\text{cord}_{\text{dyn}}$ ($r = 0.11, P = .55$).

**DISCUSSION**

While physiological organ motion and its dosimetric consequences have gained much attention in high-precision and stereotactic radiation therapy for many tumor sites,17-21 spinal cord motion and its impact on spinal cord dose have not been...
incorporated into dosimetric planning in spine SBRT. BFFE MRI applied in our patients provided cardiac-gating, exquisite cord-cerebrospinal fluid (CSF) contrast, and excellent spatial and temporal resolution for dynamic imaging to assess real-time cord motion in individual patients (see Video).

**Key Results**

Our results show that physiological spinal cord motion during SBRT results in increases of spinal cord dose in the majority of patients. The proportion of patients with motion-induced dose increase to \(\text{cord}_{\text{dy}}\) over \(\text{cord}_{\text{st}}\) was high, both for the average dose excess (62%) and the maximal dose excess (76%, Figure 2). While it is not well established whether the average dose received over time or short intervals of very high maximal dose are more likely to impart neural injury, our results were largely based on the more conservative measure of the average dose excess to \(\text{cord}_{\text{dy}}\).

The observed wide interindividual heterogeneity of the dose excess received by the moving cord (0.6-13.8%, Figure 2) illustrates the challenges to predict motion-induced cord dose increases for individual patients. Such individual heterogeneity may be influenced by random and variable degrees and direction of the cord’s motion pattern with respect to the tumor target.

A substantial cord dose excess of 10% or more was seen in 14% of our patients, which is beyond the acceptable range of variation in radiation oncology practice. In clinical practice, dose increase to the spinal cord is expected to have greater impact in severely hypofractionated large-fraction SBRT regimens, where small incremental increases in nominal dose can translate into much higher biological effects, particularly in single-fraction regimens.

**Interpretation**

While a range of \(\alpha/\beta\) ratios (0.87-3 Gy, see Supplemental Digital Content) have been reported, we employed an \(\alpha/\beta\) ratio of 2 Gy, as proposed by HyTEC for all spinal levels. The EQD2 based on the LQ cell survival model interpolation of the maximum tolerated spinal cord dose of 12 Gy in 1 fraction (accepted cord dose constraint for myelopathy in single-fraction regimens) corresponds to 36 Gy \((\alpha/\beta = 3\text{ Gy})\) to 53.8 Gy \((\alpha/\beta = 0.87\text{ Gy})\) based on the accepted range of \(\alpha/\beta\) between 0.87 and 3 Gy. For a single-fraction SBRT regimen, a motion-induced cord dose (\(\text{cord}_{\text{dy}}\)) in excess of 10% would correspond to an EQD2 cord dose of 14.9% \((\alpha/\beta = 3\text{ Gy})\) to 16.1% \((\alpha/\beta = 0.87\text{ Gy})\) higher than the accepted SBRT constraint. These considerations suggest that in situations of expected high cord dose (e.g., because of close proximity to the target, and/or diminished cord tolerance from prior irradiation), combined with significant cord motion, caution should be exercised to lessen cord motion-induced dose effects by delivering treatments in multiple (3-5 fractions) rather than a single fraction. The impact of spinal cord motion on spinal cord dose may also explain the observation of radiation-induced myelitis that have been reported in single-fraction SBRT regimens after relatively low doses, as computation of these cord doses was based on static cord assessments.

To our knowledge, our study is the first investigation to assess the dosimetric effects of spinal cord motion using current high-precision MRI-based delineation of the spinal cord. Radiation dose effects from spinal cord motion in cancer patients have been challenging to evaluate with conventional imaging. MRI and CT myelogram can differentiate the spinal cord from CSF and epidural space, but the intrinsic cord motion assessment has been hampered by limited temporal resolution. We employed BFFE, an advanced dynamic MRI sequence which has the advantage of cardiac gating and provides exquisite spatial resolution and tissue contrast. The only other investigation of dosimetric effects from cord motion by Wang et al studied cord dose with respect to respiratory motion using CT imaging. The investigators reported a 1.5% increase in maximal cord/cauda dose in the worst case in a cohort of 33 spinal metastasis patients. However, because CT imaging cannot reliably differentiate the spinal cord from the surrounding CSF, the spinal canal served as surrogate for the spinal cord position and the assessment of intrinsic cord motion was not possible.

The cause for spinal cord motion is thought to be multifactorial and related to CSF pulsation, respiration, arterial pulsation, including the radicular arteries, and biomechanical effects, such as the compliance of the central nervous system. All can contribute to the individual heterogeneity. Existing literature reports oscillatory cord motion to be generally less than 1 mm most of the time in nonmalignant disease and normal individuals; however, the reported values vary, most likely due to different methodologies, patient populations, and small number of cases (Table 3). Our observations on cord motion are overall within the range of previously reported values. Tseng et al reported no excursions beyond 1.5 mm caused by physiological oscillatory motion of the spinal cord. While cord motion beyond 1 mm occurred in 43% (9/21) of our patients, no
### Table 3. Studies Investigating Spinal Cord Motion

| Author                  | Method               | No. of cases | Motion (mm)                          | Comments                                      |
|-------------------------|----------------------|--------------|--------------------------------------|-----------------------------------------------|
| **Oncology patients**   |                      |              |                                      |                                               |
| Oztek et al, 2020       | Cine MRI             | 21 lesions in 21 patients | 0.1-1.5 mm, median 0.6 mm (AP) 0-1.1 mm, median 0.5 mm (LR) 0-1.5 mm, median 0.3 mm (total) | Spine metastasis patients                     |
| Wang et al, 2016        | CT                   | 33 lesions in 30 patients | 4 cases ≤ 0.2 (AP) 2 cases ≤ 0.2 (LR) 8 cases ≤ 0.6 (CC) | Lung cancer patients                          |
| Tseng et al, 2015       | Cine MRI             | 74           | 0.12-0.39 (AP) 0.13-0.41 (LR) 0.29-0.77 (CC) | Spine metastasis patients                     |
| Cai et al, 2007         | Cine MRI             | 7            | Total motion typically <0.5 | Lung cancer patients with normal spine (4); healthy volunteers (3) T spine. Mean total motion |
| **Nononcology pathologies** |                      |              |                                      |                                               |
| Vavasour et al, 2014    | Phase-contrast MRI   | 13 + 15d     | 0.02-2.64 mm (spondylotic myelopathy) | Chronic spondylosis patients (13); controls (15) 0.03-0.54 (controls)d (CC) |
| **Healthy volunteers**  |                      |              |                                      |                                               |
| Winkthofer et al, 2014  | Cine MRI             | 16           | 0.06-1.7 | Healthy volunteers |                                               |
| Figley et al, 2008      | Cine MRI             | 8            | 0.36 ± 0.13 (AP) 0.15 ± 0.07 (LR) | Healthy volunteers | Lower T, L, sacral spine |
| Figley et al, 2007      | Cine MRI             | 10           | 0.72 ± 0.33/0.46 ± 0.32 (AP)d 0.17 ± 0.09 (LR) | Healthy volunteers |                                               |
| Mikulis et al, 1994     | Phase-contrast MRI   | 11           | 0.4-0.5 (CC) | Healthy volunteers |                                               |
| Enzmann et al, 1992     | Phase-contrast MRI   | 10           | 0.22 ± 0.06 (CC) | Healthy volunteers | Upper C-spine |
| **Animal studies**      |                      |              |                                      |                                               |
| Matsuzaki et al, 1996   | M-mode ultrasound    | 5f           | 0.080 ± 0.1132 (AP)f | Canines |                                               |

AP = anteroposterior; CC = craniocaudal; LR = left right.

a In this study, 23 lesions did not demonstrate any motion.
b In this study, 6 cases had CC motion ≤ 0.2 mm and only 2 cases had 0.2 to 0.6 mm motion.
c Motion calculated from velocity data.
d This study presents data separately for patients with chronic spondylotic myelopathy and the control group.
e AP motion data were provided separately for patients with straight spine and curved spine, because a significant difference between the 2 groups was demonstrated.
f This study was conducted on 10 dogs, where cord motion was observed in only 5. The data provided are based on the 5 dogs with observed cord motion before any interventions on the cord were performed. Data in micrometers were converted to mm for this table.

Excursion beyond 1.5 mm was seen, confirming the results from Tseng et al.13

### Generalizability and Implications for Practice

Our results are generalizable to the treatment of patients with metastatic spinal lesions with respect to the PRV margin for the spinal cord in SBRT planning. Based upon the overall consistency of our cord motion findings with the literature,13,15,35,37-43 the unlikely excursion of the cord beyond 1.5 to 2 mm from its static position, and our observed dosimetric effects of spinal cord motion, we recommend to employ a 1.5 to 2 mm margin for the spinal cord PRV in SBRT dosimetry planning to mitigate motion-related dose effects from the “dancing” cord. Our data also suggest that a 1-mm PRV margin is inadequate based on our observation that the cord moves beyond 1 mm of its static position in nearly half (43%) of the patients and that 78% of these showed a motion-induced excess in cord dose.

In challenging cases, where the spinal cord is anticipated to closely approach the cord constraint, a dynamic motion study of the cord can be easily obtained with an added approximately 2.5- to 5-min dynamic MRI sequence to provide additional guidance.

### Limitations

Our patient and lesion numbers were limited, which did not allow meaningful subgroup analyses, such as associations of cord motion and dose with lesion size, spinal level, extent of...
vertebral involvement, Bilsky grade, or patient-related variables, such as coexisting spine pathologies. Assessment of these factors may enable a more patient-tailored approach. Our study is a physics/dosimetry and imaging assessment of motion-induced changes in spinal cord dose, and our cohort is too small to corroborate the observed dosimetric findings with clinical myelopathy. Further, while our 2.5- to 5-min imaging time readily assesses physiological motion, it may not capture all bulk motion that may occur during a typical SBRT fraction delivery.

Additionally, the BFFE images were obtained only in the axial plane, which did not allow assessment of craniocaudal cord motion that has been reported as larger than AP and lateral motion. However, the target and cord are usually assessed and contoured in the axial plane. Thus, we believe that the effects of craniocaudal cord motion on the critical cord–target distance have likely been incorporated, at least in part, in the dose calculations derived from the axial dynamic BFFE images.

**CONCLUSION**

Our preliminary study and dosimetry findings show that spinal cord motion contributes measurable, variable, and potentially detrimental dose effects to the cord in patients treated with SBRT for spine metastasis. We recommend a 1.5- to 2-mm cord PRV margin based on the observed motion properties of the spinal cord and the dose effects from the cord motion. If available, a short dynamic cardiac-gated MRI may also be considered to quantify spinal cord motion. Future studies are required to confirm our results.

**Disclosures**

The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

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**Supplemental Digital Content.** EQD2 computations and linear-quadratic (LQ) model. Details of EQD2 computations and LQ model.