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Dosimetric quality, accuracy, and deliverability of modulated radiotherapy treatments for spinal metastases

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ABSTRACT

Cancer often metastasizes to the vertebra, and such metastases can be treated successfully using simple, static posterior or opposed-pair radiation fields. However, in some cases, including when re-irradiation is required, spinal cord avoidance becomes necessary and more complex treatment plans must be used. This study evaluated 16 sample intensity-modulated radiation therapy (IMRT) and volumetric-modulated arc therapy (VMAT) treatment plans designed to treat 6 typical vertebral and paraspinal volumes using a standard prescription, with the aim of investigating the advantages and limitations of these treatment techniques and providing recommendations for their optimal use in vertebral treatments. Treatment plan quality and beam complexity metrics were evaluated using the Treatment And Dose Assessor (TADA) code. A portal-imaging–based quality assurance (QA) system was used to evaluate treatment delivery accuracy, and radiochromic film measurements were used to provide high-resolution verification of treatment plan dose accuracy, especially in the steep dose gradient regions between each vertebral target and spinal cord. All treatment modalities delivered approximately the same doses and the same levels of dose heterogeneity to each planning target volume (PTV), although the minimum PTV doses in the vertebral plans were substantially lower than the prescription, because of the requirement that the plans meet a strict constraint on the dose to the spinal cord and cord planning risk volume (PRV). All plans met required dose constraints on all organs at risk, and all measured PTV-cord dose gradients were steeper than planned. Beam complexity analysis suggested that the IMRT treatment plans were more deliverable (less complex, leading to greater QA success) than the VMAT treatment plans, although the IMRT plans also took more time to deliver. The accuracy and deliverability of VMAT treatment plans were found to be substantially increased by limiting the number of monitor units (MU) per beam at the optimization stage, and thereby limiting beam modulation complexity. The VMAT arcs that were optimized with MU limitation had higher QA pass rates as well as higher modulation complexity scores (less complexity), lower modulation indices (less modulation), lower MU per beam, larger beam segments, and fewer small apertures than the VMAT arcs that were optimized without MU limitation. It is recommended that VMAT treatments for vertebral volumes, where the PTV abuts or surrounds the spinal cord, should be optimized with MU limitation. IMRT treatments may be preferable to the VMAT treatments, for dosimetry and deliverability reasons, but may be inappropriate for some patients because of their increased treatment delivery time.

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Introduction

Metastasizing to the vertebra is a common route of tumor progression, reportedly affecting 40% of patients with metastatic cancer,[1] but early treatment before the development of significant neurologic deficits improves the chance for patients to remain ambulatory.[2] Radiotherapy has been shown to be a "safe and effective, noninvasive treatment modality for pain,"[3] which "can provide significant palliation of painful bone metastases in 50% to 80% of patients."[4]

Because the spinal cord is not highly radiosensitive,[5] it is possible to deliver a tumoricidal dose to the treatment volume

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Table 1
Dose constraints and optimization objectives used for all treatments planned in this study

Structure	Proportion of volume (%)	Plan constraint (Gy)	Optimization objective (Gy)	Priority
PTV	98	>30		
PTV	50	>31.6		
PTV	2	<33.8		
Spinal cord	0	<21.5		
Brachial plexus	0	<21.5		
Lungs	20	<20		
Heart	10	<20		
Esophagus	50	<34		
Liver	65	<25		
Kidney	65	<18		
PTV+	100		>30.5	1.00
PTV+	0		<33	1.00
Spinal canal	0		<18	0.86
Kidney	20		<10	0.57
Body	0		<33	0.71
Avoidance	0		<27	0.71

without specifically avoiding the spinal cord, while keeping the spinal cord dose within tolerance. Such a treatment may involve the use of a simple posterior portal or 2 opposed beams.[6] In cases of local recurrence, tumor progression, or increased pain, however, where a re-treatment with a similar dose of radiation needs to be delivered to the same or a neighboring vertebra, adequate spinal cord sparing becomes more challenging.[7-9]

In cases where the radiation dose to the spinal cord needs to be limited, the use of modulated radiotherapy techniques is clearly preferable.[6,10-12] Modulated radiotherapy techniques permit tight conformation to concave and hollow targets[13] and can be used to produce complex dose distributions that avoid the spinal cord while delivering tumoricidal doses to the surrounding and abutting vertebral structures,[2,6,10,11,14,15] which cannot be produced using conventional 3D conformal radiotherapy techniques.[6,10] For example, linac- and TomoTherapy-based modulated treatment plans have been able to achieve dose gradients of 10%/mm[8,11,16] between the spinal planning target volume (PTV) and the spinal cord planning risk volume (PRV), whereas the conventional opposed-pair spinal treatment produces no substantial PTV-PRV gradient.[6]

Therefore, in cases where re-irradiation is planned, specific types of chemotherapy are used, dose escalation or hypofractionation is required, or any other cases where the spinal cord tolerance would otherwise be exceeded, the use of modulated radiotherapy is preferable to the use of conventional posterior or opposed-pair treatment beams. However, the advantages of adopting an intensity-modulated radiation therapy (IMRT) or volumetric-modulated arc therapy (VMAT) method for treating spinal lesions are lost (and substantial risks are introduced) if the modulated treatment cannot be delivered accurately.

This study, therefore, used a small number of clinical case studies to evaluate the dosimetric quality, planned dose accuracy, treatment complexity, and treatment deliverability of typical IMRT and VMAT treatments for vertebral metastases to assess the advantages and limitations of these treatment techniques and provide recommendations for their optimal use.

Methods and Materials

Treatment planning

Computed tomographic (CT) datasets of 2 patients were selected for use in this study, one from a treatment of a thoracic vertebra and the other from a treatment of a lumbar vertebra. For each patient, 3 different PTVs were contoured: a vertebral body PTV, a whole vertebra PTV, and a paraspinal PTV. These PTVs were produced by first contouring a clinically realistic target volume, then adding a 5-mm expansion margin and subtracting any regions of overlap with the spinal canal from the result. The practice of defining the spinal canal as the PRV for the spinal cord was adopted from several recent stereotactic spinal treatment studies.[9,12,15-20]

For inverse-plan optimization purposes, additional planning structures (called 'PTV+') were then produced by subtracting further 2 mm from each PTV in any regions abutting the spinal canal, and adding 1 mm to each PTV in all other directions. Avoidance structures were also contoured as 17 mm thick rings lying 3 mm outside each PTV+ for the purpose of maximizing dose conformity to the PTV.

The prescription dose, for all 6 volumes, was defined as 30 Gy in 10 fractions to correspond with the most commonly used nonstereotactic prescription for the treatment of vertebral metastases.[18] Following the recommendation of ICRU report 83,[21] a coverage dose of 30 Gy was taken to equate to a reference point dose of 31.6 Gy, limiting the "maximum" PTV dose to 33.8 Gy to 2% of the PTV.

A spinal cord PRV dose limit of 21.6 Gy in 10 fractions was selected for use in this study so that treatment plans that allow for re-treatment could be produced. By using an alpha-beta ratio for spinal cord late effects equal to 2, as recommended by Schultheiss *et al.*,[5] a cord dose of 21.6 Gy in 10 fractions was identified as providing a 2 Gy/fraction biologically equivalent dose (referred to by Sahgal *et al.*[9] as nBED) of approximately 120 Gy when combined with a previous or subsequent treatment involving a cord dose of up to 30 Gy in 10 fractions. This limit falls conservatively less than the 140 Gy spinal cord nBED limit recommended in Sahgal *et al.*'s[9] study of spinal cord tolerance.

The other organ-at-risk (OAR) constraints applied to the treatment plans were adapted from the QUANTEC normal tissue tolerance reports.[22,23]

The same dose constraints and inverse-planning optimization objectives were used for all plans generated in this study, and these are provided in Table 1.

A total of 16 treatment plans were devised for the 6 different PTVs used in this study. For each vertebral PTV, 1 IMRT plan and 2 VMAT plans were created. Of each

Table 2
List of treatment plans investigated in the study. Note that plans with "limited" MU used a limit of 500 MU per arc as an optimization objective, while plans with "unlimited" MU did not use any MU limit as an optimization objective

ID	Region	PTV	Modality	Beam arrangement	MU
1	Thoracic	Vertebral body	IMRT	9 Beams, mostly posterior-oblique	Unlimited
2	Thoracic	Vertebral body	VMAT	2 Coplanar 360° arcs	Unlimited
3	Thoracic	Vertebral body	VMAT	2 Coplanar 360° arcs	Limited
4	Thoracic	Whole vertebra	IMRT	9 Beams, mostly posterior-oblique	Unlimited
5	Thoracic	Whole vertebra	VMAT	2 Coplanar 360° arcs	Unlimited
6	Thoracic	Whole vertebra	VMAT	2 Coplanar 360° arcs	Limited
7	Thoracic	Paraspinal	IMRT	7 Beams, custom arrangement	Unlimited
8	Thoracic	Paraspinal	VMAT	2 Coplanar 360° arcs	Unlimited
9	Lumbar	Vertebral body	IMRT	9 Beams, mostly posterior-oblique	Unlimited
10	Lumbar	Vertebral body	VMAT	2 Coplanar 360° arcs	Unlimited
11	Lumbar	Vertebral body	VMAT	2 Coplanar 360° arcs	Limited
12	Lumbar	Whole vertebra	IMRT	9 Beams, mostly posterior-oblique	Unlimited
13	Lumbar	Whole vertebra	VMAT	2 Coplanar 360° arcs	Unlimited
14	Lumbar	Whole vertebra	VMAT	2 Coplanar 360° arcs	Limited
15	Lumbar	Paraspinal	IMRT	7 Beams, custom arrangement	Unlimited
16	Lumbar	Paraspinal	VMAT	2 Coplanar 360° arcs	Unlimited

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