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Reappraisal of Target Definition for Stereotactic Irradiation of Retroperitoneal Metastases from Soft Tissue Sarcomas

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Abstract

Objective: Soft tissue sarcomas (STSs) comprise a heterogeneous group of mesenchymal malignancies with variable biologic behavior and metastatic potential. Advances in stereotactic body radiotherapy (SBRT) have enabled the delivery of highly conformal ablative radiation doses to limited metastatic deposits while minimizing exposure to adjacent organs at risk (OARs). This study aimed to reappraise target definition strategies for stereotactic irradiation of retroperitoneal metastases from STSs by evaluating the contribution of magnetic resonance imaging (MRI) fusion to target delineation and treatment planning.

Materials and Methods: CT simulation was performed using individualized immobilization and dedicated image acquisition for stereotactic treatment planning. MRI datasets were subsequently fused with simulation CT images using image registration techniques to improve anatomical visualization and target definition. Gross tumor volumes (GTVs) and planning target volumes (PTVs) were initially delineated on CT images alone and subsequently refined following CT-MRI fusion. Dosimetric analyses were performed to compare target conformity, target coverage, and organ-at-risk sparing between CT-only and CT-MRI fusion-based plans.

Results: MRI integration improved visualization of metastatic lesion boundaries and facilitated more accurate differentiation of tumor tissue from adjacent bowel loops, vascular structures, kidneys, and surrounding soft tissues. CT-only contouring frequently resulted in overestimation or underestimation of target volumes because of limited soft tissue contrast. MRI-guided refinement produced clinically meaningful modifications in target delineation in a substantial proportion of cases and contributed to improved target conformality, steeper dose gradients, and enhanced sparing of adjacent organs at risk while maintaining adequate target coverage.

Conclusion: CT-MRI fusion significantly enhances target delineation accuracy and dosimetric quality for SBRT of retroperitoneal metastases from STSs. Integration of multimodality imaging into stereotactic radiotherapy planning may improve treatment precision, optimize organ-at-risk sparing, and support the implementation of advanced image-guided and adaptive radiotherapy strategies in this anatomically complex disease setting.

Keywords: Soft Tissue Sarcomas; Retroperitoneal Metastases; Stereotactic Body Radiotherapy; MRI Fusion; Target Definition

Abbreviations: STSs: Soft Tissue Sarcomas; SBRT: Stereotactic Body Radiotherapy; OARs: Organs At Risk; MRI: Magnetic Resonance Imaging; GTVs: Gross tumor volumes; PTVs: Planning Target Volumes; STSs: Soft Tissue Sarcomas; CT: Computed Tomography; IGRT: Image-Guided Radiotherapy; ART: Adaptive Radiotherapy; GTVs: Gross Tumor Volumes; CTV: Clinical Target Volume; PTV: Planning Target Volume; CBCT: Cone-Beam CT; DVH: Dose-Volume Histogram

Introduction

Soft tissue sarcomas (STSs) represent a rare and biologically heterogeneous group of mesenchymal malignancies encompassing more than 50 histopathological subtypes with distinct clinical behaviors, metastatic patterns, and therapeutic sensitivities [1,2]. Although pulmonary metastases constitute the predominant site of distant dissemination, extrapulmonary metastatic involvement may occur in advanced disease stages, particularly among patients with recurrent disease, aggressive

histologies, or prolonged survival following systemic and local therapies [3]. Retroperitoneal metastatic involvement represents a clinically challenging yet relatively underreported manifestation of metastatic STS.

Lesions within the retroperitoneal compartment may occur either as isolated oligometastatic deposits or within the spectrum of disseminated disease progression. Management remains difficult because of the anatomical complexity of the retroperitoneum and the proximity of radiosensitive organs including bowel loops, kidneys, pancreas, ureters, liver, spinal cord, and major vascular structures [4]. Furthermore, surgical intervention in this region is frequently associated with substantial morbidity, technical limitations, and limited feasibility in recurrent settings.

Recent advances in multidisciplinary sarcoma management, including improvements in systemic therapies, surgical oncology, molecular diagnostics, and local ablative approaches, have contributed to prolonged survival in selected patients with metastatic STS [5]. Consequently, increasing interest has emerged regarding aggressive local treatment strategies for oligometastatic and oligoprogressive disease states. In appropriately selected patients, local ablative therapies may improve local control, delay systemic progression, reduce symptom burden, and potentially prolong survival [6]. Within this evolving treatment paradigm, stereotactic body radiotherapy (SBRT) has become an increasingly important therapeutic modality. SBRT enables highly conformal delivery of ablative radiation doses in a limited number of fractions with steep dose gradients beyond the target volume [7,8].

This allows effective irradiation of metastatic lesions while minimizing radiation exposure to surrounding healthy tissues. SBRT is particularly advantageous in medically inoperable patients, previously irradiated cases, or lesions unsuitable for surgical resection. However, the therapeutic efficacy and safety of SBRT are critically dependent on accurate target delineation and precise treatment delivery [9]. In the retroperitoneal region, target definition is especially challenging because of respiratory motion, bowel mobility, postoperative anatomical distortion, organ displacement, and complex soft tissue interfaces. Even small contouring inaccuracies may result in geographic miss, suboptimal tumor coverage, or excessive irradiation of adjacent organs at risk.

Computed tomography (CT)-based simulation remains the standard imaging modality for radiotherapy planning because of its geometric reliability and electron density information necessary for dose calculation. Nevertheless, CT alone may provide insufficient soft tissue contrast for precise discrimination between tumor tissue and adjacent anatomical structures in the retroperitoneum [10]. Distinguishing metastatic lesions from bowel loops, fibrosis, musculature, vascular interfaces, or postoperative changes may therefore become problematic using CT imaging alone. Magnetic resonance imaging (MRI), in contrast, offers superior soft tissue characterization and enhanced visualization of tumor margins and tissue interfaces [11]. MRI integration into radiotherapy planning through CT-MRI fusion techniques has therefore attracted increasing attention in abdominal and pelvic radiation oncology.

Furthermore, the emergence of image-guided radiotherapy (IGRT), adaptive radiotherapy (ART), MRI-guided linear accelerators, and advanced image registration technologies has further emphasized the importance of accurate multimodality target definition [12,13]. The present study aimed to reappraise target definition strategies for stereotactic irradiation of retroperitoneal metastases from soft tissue sarcomas by comparing CT-based contouring with CT-MRI fusion-guided delineation. We additionally sought to evaluate the implications of MRI integration for dosimetric quality, target conformity, organ-at-risk sparing, and modern adaptive stereotactic radiotherapy workflows.

Materials and Methods

This retrospective study was conducted at the Department of Radiation Oncology, University of Health Sciences, Gulhane Medical Faculty, a tertiary referral center with expertise in multidisciplinary sarcoma management. Patients with histopathologically confirmed soft tissue sarcoma and radiologically confirmed retroperitoneal metastatic lesions treated with stereotactic radiotherapy were evaluated. All patients were discussed within a multidisciplinary sarcoma tumor board including radiation oncologists, medical oncologists, surgical oncologists, radiologists, and pathologists. Eligibility for SBRT was determined according to metastatic burden, disease control status, performance status, lesion accessibility, and suitability for ablative radiotherapy.

CT simulation was performed using a dedicated radiotherapy simulator with patients immobilized in the supine position using individualized immobilization devices. Intravenous contrast was administered when clinically indicated to improve anatomical visualization. Thin-slice axial CT images were acquired for stereotactic treatment planning. All patients additionally underwent MRI examinations optimized for soft tissue visualization. MRI datasets were fused with planning CT images using image registration techniques to facilitate target refinement and anatomical correlation. Gross tumor volumes (GTVs) were initially delineated on CT simulation images alone and subsequently reassessed following incorporation of MRI datasets into the contouring workflow.

Clinical target volume (CTV) and planning target volume (PTV) expansions were generated according to institutional stereotactic radiotherapy protocols while accounting for respiratory motion, setup uncertainty, and lesion location. Attention was directed toward adjacent organs at risk including kidneys, bowel loops,

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duodenum, pancreas, liver, spinal cord, ureters, and major vascular structures. Treatment planning was performed using institutional treatment planning systems. SBRT delivery was conducted using linear accelerator-based image-guided radiotherapy platforms equipped with cone-beam CT (CBCT) for daily image verification. Treatment plans were optimized to ensure adequate target coverage while respecting established organ-at-risk constraints in accordance with accepted stereotactic radiotherapy guidelines [9]. Dosimetric comparisons were performed between CT-only and CT-MRI fusion-based plans. Dose-volume histogram (DVH) analyses focused on target conformity, dose gradients, target coverage, and radiation exposure to surrounding organs at risk.

Results

Patients with retroperitoneal metastatic lesions from soft tissue sarcomas were included in the analysis. MRI integration resulted in clinically meaningful modifications of target volume delineation in a substantial proportion of cases. Compared with CT-only contouring, CT-MRI fusion improved visualization of lesion boundaries and facilitated more confident differentiation between metastatic tissue and adjacent anatomical structures. The most pronounced contouring differences were observed in lesions located adjacent to bowel loops, kidneys, major vascular structures, and paraspinal musculature.

In several patients, CT-alone contouring either overestimated target volumes by inadvertently including neighboring soft tissues or underestimated disease extent because of inadequate contrast discrimination. MRI-guided refinement enabled more accurate identification of tumor margins and reduced contouring ambiguity in anatomically complex regions. MRI integration additionally improved delineation of interfaces between metastatic lesions and nearby organs at risk, particularly for lesions adjacent to the duodenum, pancreas, ureters, and major vascular structures where CT imaging alone frequently demonstrated limited soft tissue resolution.

Dosimetric analysis demonstrated that CT-MRI fusion-based plans achieved superior conformality and steeper dose gradients compared with CT-only plans. Improved target definition translated into reductions in unnecessary irradiation of adjacent organs at risk while preserving appropriate target coverage. In multiple cases, MRI-guided contouring resulted in smaller and more anatomically accurate target volumes, thereby improving the therapeutic ratio of stereotactic irradiation. MRI-guided planning also contributed to greater confidence during image guidance and treatment delivery, particularly for lesions exhibiting irregular morphology or indistinct borders on CT imaging alone.

Discussion

Soft tissue sarcomas represent a biologically heterogeneous group of malignancies characterized by diverse histopathological subtypes, metastatic patterns, and clinical outcomes [1,2]. Although pulmonary metastases remain the most frequent manifestation of distant dissemination, retroperitoneal metastatic involvement may occur in selected patients and often presents substantial therapeutic complexity because of the confined anatomy of the retroperitoneal compartment and the proximity of multiple critical organs and vascular structures [4]. As advances in systemic therapy and multidisciplinary sarcoma care continue to improve survival outcomes, increasing emphasis has been placed on local ablative strategies for oligometastatic and oligoprogressive disease [5,6].

Within this framework, stereotactic body radiotherapy has emerged as an attractive noninvasive modality capable of delivering highly conformal ablative radiation doses with excellent geometric precision [7,8]. The therapeutic success of SBRT, however, is fundamentally dependent on accurate target delineation and reliable image guidance [9]. In the retroperitoneal region, contouring uncertainties may significantly alter dose distributions because of the steep dose gradients characteristic of stereotactic irradiation. Even minimal inaccuracies may contribute to geographic miss, compromised local control, or increased toxicity to adjacent organs at risk. The present study demonstrates that CT-MRI fusion substantially improves target delineation accuracy for retroperitoneal metastatic sarcoma lesions compared with CT-based planning alone.

MRI integration enabled superior visualization of lesion boundaries, improved soft tissue discrimination, and facilitated more accurate differentiation between metastatic tissue and surrounding normal anatomy. These advantages were particularly evident for lesions adjacent to bowel loops, kidneys, paraspinal musculature, pancreas, and major vascular structures. Importantly, the anatomical benefits provided by MRI translated into clinically meaningful dosimetric improvements. MRI-guided contour refinement improved target conformality and reduced unnecessary irradiation of surrounding organs at risk while maintaining adequate target coverage. Such findings are highly relevant in stereotactic radiotherapy because contouring precision directly influences both tumor control probability and normal tissue complication probability [9].

Our findings are consistent with previous investigations demonstrating the value of MRI integration in radiotherapy planning across multiple anatomical regions [10,11]. Accumulating evidence suggests that MRI fusion may reduce contouring uncertainty and improve interobserver agreement compared with CT-only planning approaches [14]. In anatomically complex disease sites such as the retroperitoneum, these advantages may become particularly clinically significant. The present findings also have implications for adaptive and MRI-guided radiotherapy technologies. Modern MRI-guided linear accelerator systems permit online adaptive treatment workflows with real-time soft tissue visualization and individualized plan modification [12,13].

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Such capabilities may be particularly beneficial for retroperitoneal lesions affected by respiratory motion, bowel displacement, and interfraction anatomical variability. Despite these advantages, several practical limitations should be acknowledged. MRI acquisition, image registration, and multimodality contour integration require additional technical expertise, workflow coordination, and institutional resources. Variations in patient positioning, respiratory phase differences, and image registration uncertainties may also introduce contouring variability if not carefully addressed. Furthermore, the present study primarily focused on contouring and dosimetric evaluation rather than long-term oncologic outcomes or toxicity endpoints. Prospective studies incorporating larger patient populations, standardized MRI acquisition protocols, and adaptive radiotherapy workflows are warranted to further validate these findings.

Conclusion

CT-MRI fusion substantially improves contouring precision and dosimetric quality for stereotactic irradiation of retroperitoneal metastases from soft tissue sarcomas. MRI integration enhances visualization of tumor boundaries, improves discrimination between target lesions and adjacent normal tissues, and contributes to improved organ-at-risk sparing while maintaining adequate target coverage. These findings support incorporation of multimodality imaging into SBRT planning workflows for anatomically complex retroperitoneal metastatic disease.

Conflicts of Interest

There are no conflicts of interest and no acknowledgements.

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