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Non-Coplanar Arc Radioablation for Refractory Ventricular Tachycardia: Validation and Clinic Workflow

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ABSTRACT

Purpose: Noninvasive stereotactic radioablation for refractory ventricular tachycardia (rVT) using a single 25 Gy fraction is an emerging treatment option for patients with advanced heart failure. This complex procedure requires highly non-coplanar beam geometry, stringent dose constraints, and a well-defined clinical workflow. This study establishes institutional physics guidelines and workflow for cardiac rVT radioablation, with emphasis on treatment planning, image guidance, and quality assurance (QA).

Materials/Methods: Two radioablation plans (6MV-FFF, 10MV-FFF) were developed for in-house validation and end-to-end testing using a micro-MLC EDGE linac. Highly non-coplanar VMAT plans employed left-sided partial arcs with optimized collimator and couch angles. For a 48.4 cc rVT target, Acuros-based inverse planning was used to achieve conformal target coverage, steep dose gradients, and minimal dose to organ-at-risk (OARs), including heart-minu- PTV. Target coverage, conformity index (CI), gradient index (GI), and maximum doses to OARs were evaluated. Daily Winston–Lutz (WL) and patient-specific QA results were recorded.

Results: Both plans achieved excellent conformity (CI = 0.96) with steep dose gradients (GI = 2.52 for 6MV-FFF and 2.69 for 10MV-FFF). All OAR constraints were met, with maximum doses <4 Gy to spinal cord, <1.4 Gy to bronchus and stomach, and <5.7 Gy to esophagus. Mean dose to heart-minus-PTV was 3.5 Gy (6MV-FFF) and 3.7 Gy (10MV-FFF). The 10MV-FFF plan reduced beam-on time by 2.5 minutes due to lower modulation (MU: 9,282 vs 10,318). Daily WL results were <1 mm, and patient-specific QA pass rates exceeded 95% using 2%/2 mm criteria.

Conclusion: Highly non-coplanar VMAT radioablation for cardiac rVT achieved exceptional target conformality and reduced mean healthy heart dose (<3.7 Gy), substantially lower than reported values. The 10MV-FFF beam provided equivalent plan quality with shorter treatment time, potentially reducing intrafraction motion. Comprehensive end-to-end testing confirmed robust clinical deliverability. Independent dose verification using the IROC SBRT motion phantom is ongoing.

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INTRODUCTION

Noninvasive stereotactic radioablation using a single 25 Gy fraction has emerged as a promising treatment option for patients with refractory ventricular tachycardia (rVT) and advanced heart failure. This complex therapy requires highly non-coplanar beam arrangements, strict organ-at-risk dose constraints, and a carefully structured clinical workflow to ensure both efficacy and safety. The present work describes our institutional physics guidelines and workflow for cardiac rVT radioablation, with particular emphasis on treatment planning, image guidance, and quality assurance.

METHODS AND MATERIALS

Cardiac rVT substrate radioablation was delivered using highly non-coplanar partial-arc VMAT geometry designed to avoid patient collisions while achieving stereotactic dose conformity. Treatment plans were generated on an EDGE linear accelerator using micro-MLCs and 6 MV FFF (1400 MU/min) and 10 MV FFF (2400 MU/min) beams. Highly non-coplanar partial-arc VMAT geometry was employed. Five partial VMAT arcs, each with an arc span of 160°, were used, with couch angles of 0°, 20°, 45°, and 345° to optimize target coverage and organ-at-risk sparing.

The prescription was a single 25 Gy fraction, with the planning target volume (PTV) receiving at least 95% of the prescribed dose (PTV D95 ≥ 95%), normalized to the 80% isodose line, and allowing up to 120% hotspot confined within the rVT target. The internal target volume for VT (VT-ITV) was defined from 4D-CT simulation, and the PTV was constructed as VT-ITV plus a uniform 5 mm margin.

Treatment delivery incorporated six-degree-of-freedom couch corrections using a PerfectPitch couch and was designed to be completed in less than 20 minutes, including patient setup, pre-treatment cone-beam CT acquisition and setup correction, a dry-run, and beam-on time. Continuous intrafraction motion monitoring was performed using surface-guided radiotherapy (SGRT) system. Organ-at-risk constraints were based on the single-fraction scheme from RTOG-0915, aiming to spare adjacent critical structures while minimizing dose to the non-target heart.

Independent dose validation of this treatment procedure is performed using SBRT motion phantom irradiation from the IROC MD Anderson QA Center (Houston, TX).

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RESULTS

The in-house validation, end-to-end testing, and dosimetric guideline development demonstrated that our cardiac rVT planning and implementation approach is reproducible and practical for clinical use. The highly non-coplanar VMAT geometry yielded compact, conformal dose distributions to the rVT target with steep dose gradients, while maintaining minimal exposure to adjacent critical structures, including the non-target heart. For comparable target coverage, conformity, and dose-gradient characteristics, the beam-on time with 10 MV FFF beams was approximately 2.5 minutes shorter than with 6 MV FFF beams. This reduction in delivery time is expected to improve patient comfort and compliance, reduce overall time on the treatment table, and potentially limit intrafraction motion.

Clinically, pre-treatment CBCT-based image guidance with six-degree-of-freedom couch corrections and intrafraction motion monitoring via SGRT were successfully integrated into the workflow. Target definition involved electrocardiologist contouring, with subsequent verification by the radiation oncologist and medical physicist, supported by a pretreatment safety checklist and device management steps, including pacemaker interrogation before and after radioablation when applicable. The planning and delivery geometry produced highly conformal radioablation of cardiac rVT without clearance issues, and organ-at-risk doses were maintained within recommended constraints.

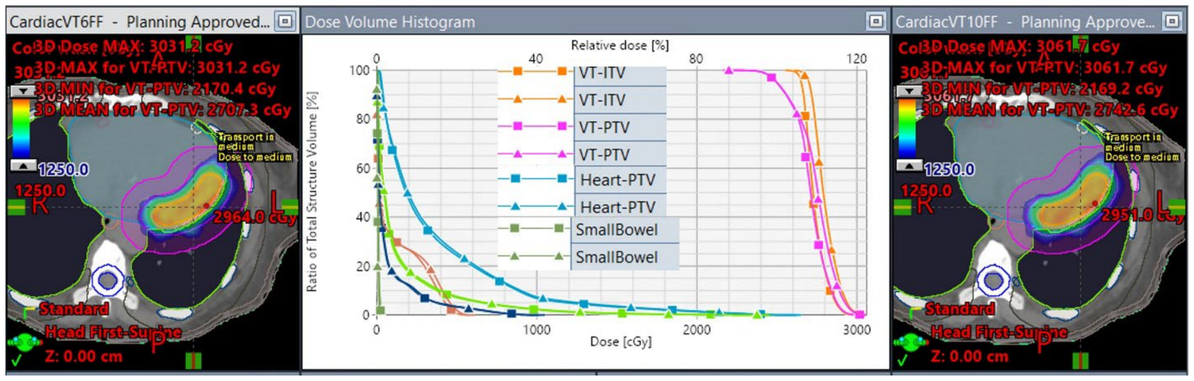

Figure 1. Example of our highly compact radiosurgical dose distributions to refractory cardiac rVT using a highly non-coplanar partial-arc VMAT geometry without patient clearance concerns. The left and right panels show 6 MV-FFF and 10 MV-FFF plans, respectively, with the corresponding DVH in the center. Squares represent 6 MV-FFF and triangles represent 10 MV-FFF data. Validation and testing plans were generated for an inferior-lateral LV wall target (segments 4 and 5; PTV 48.4 cc). For a single 25 Gy fraction, the plan was prescribed to the 80% isodose line (50%–120% isodose lines shown), with the hotspot confined to the rVT target volume while meeting dose constraints for adjacent critical organs, including the esophagus, ribs, stomach, and bowel. The mean dose to Heart–PTV was maintained below 3.7 Gy, thereby potentially reducing dose to the healthy heart.

Location	Measurement vs. Inst.	Criteria	Acceptable
PTV_TLD_sup	0.97	0.92 – 1.05	Yes
PTV_TLD_inf	0.96	0.92 – 1.05	Yes

Film Plane	Gamma Index*	Criteria	Acceptable
Axial	99%	≥ 80%	Yes
Coronal	91%	≥ 80%	Yes
Sagittal	95%	≥ 80%	Yes
Average over 3 planes	95%	≥ 85%	Yes

*Percentage of points meeting gamma-index criteria of 7% and 5 mm

The phantom irradiation results listed in the table above **do meet** the criteria established by IROC in collaboration with the Network Groups. Therefore, your institution **has satisfied** the phantom irradiation component of the credentialing process to enter patients onto clinical trials.

Figure 2. IROC report of an anthropomorphic lung phantom incorporating a cylindrical dosimetry insert that simulated the left lung was placed in the supine position in a CT scanner and imaged. The insert contained an ovoid target. TLD capsules located near the center of the target provided point-dose information, and three sheets of GAFChromic dosimetry media provided dose distributions in the axial, coronal, and sagittal planes. The phantom also included heart, spinal cord, and right lung structures, each containing one TLD capsule.

DISCUSSION

The use of 10 MV FFF beams in this setting offers a meaningful reduction in beam-on time compared with 6 MV FFF, potentially improving patient comfort and limiting intrafraction motion. However, because high-energy, high-dose-rate beams carry increased risk for cardiac implantable electronic devices, 10 MV FFF should be reserved for patients who are not pacemaker-dependent, following careful multidisciplinary review of device status and proximity to the treatment field. In pacemaker-dependent patients, lower-energy beams and more conservative delivery parameters should be prioritized, even at the cost of longer treatments, to appropriately balance the benefits of shorter beam-on time against device-related risks.

CONCLUSIONS

This institutional workflow and physics guideline set for cardiac rVT radioablation demonstrates that highly non-coplanar VMAT delivery of a single 25 Gy fraction can achieve conformal target coverage with low doses to critical cardiac and thoracic structures. The use of 10 MV FFF beams offers a meaningful reduction in beam-on time compared with 6 MV FFF, supporting improved patient comfort and potentially reduced intrafraction motion. The outlined processes—including multidisciplinary target definition, image-guided setup, motion management, safety checklists, and device interrogation—provide a practical framework that can be adopted by other centers, including community practices with similar technology, to develop safe and effective cardiac rVT radioablation programs.

REFERENCES

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