From Scar to STAR with inHEART-guided targeting: A comprehensive evaluation of stereotactic ablation for ventricular tachycardia in a single-center experience.

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Original Report Complete Title:

FROM SCAR TO STAR WITH INHEART-GUIDED TARGETING: A COMPREHENSIVE EVALUATION OF STEREOTACTIC ABLATION FOR VENTRICULAR TACHYCARDIA IN A SINGLE-CENTER EXPERIENCE.

Short Running title:

inHEART-guided STAR Workflow and Dosimetry

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Conflic of interest

Two authors (MJ and HC) are affiliated with inHEART (Pessac, France), the company that developed the software used for image segmentation and target definition in this study. The remaining authors declare no conflicts of interest. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The study was conducted independently, and inHEART had no role in the study design, data collection, analysis, interpretation, or manuscript preparation.

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ABSTRACT

Purpose:

To present the clinical workflow developed for stereotactic arrhythmia radioablation (STAR), with a particular focus on the inHEART multimodality platform used for cardiac imaging integration and 3D substrate segmentation. We also report the clinical outcomes and dosimetric results of the initial 18 patients treated.

Methods and materials:

All patients underwent contrast-enhanced cardiac computed tomography (CT), including late enhancement imaging and optional cardiac magnetic resonance imaging (MRI). Imaging data were processed using the inHeart multimodality platform for specific imaging in cardiology (MUSIC), which enabled automatic 3D segmentation of cardiac anatomy, identification of the scar substrate, and integration of electrophysiological data to define the clinical target volume (CTV). The stereotactic body radiation therapy (SBRT) inHEART module exported target structures in digital imaging and communications in medicine-radiotherapy (DICOM-RT) format to the Eclipse treatment planning system. 4D-CT simulation scans were acquired to account for cardiorespiratory motion, and an internal target volume/planning target volume (ITV/PTV) was derived accordingly on expiratory phases. Treatment was delivered with volumetric modulated arc therapy (VMAT) in a single fraction of 25 Gy to the PTV using a TrueBeam^{TM} STx linac. Clinical effectiveness was assessed through ventricular tachycardia (VT) burden and implantable cardioverter-defibrillators (ICD) shock reduction.

Results:

Median CTV, ITV, and PTV volume were 14.50 cc (range, 4.32-32.6), 22.13 cc (range, 5.15-49.15), and 58.42 cc (range, 20.87-109.76), respectively. Excellent dose coverage was achieved, median PTV D99% was 25.25 Gy (range, 21.94-27.51), with a mean Paddick conformity index of 0.89 ± 0.08. All organs at risk (OARs) met the dose constraints. At 12 months, 78% of patients showed > 75% VT reduction, and 94% of surviving patients experiencing a limited number of shocks (<2).

Conclusions:

Integrating the inHEART SBRT module within a standardized multimodal imaging workflow enables accurate STAR planning and delivery. This approach proved feasible, robust, and safe for managing refractory VT.

Keywords:

Stereotactic arrhythmia radioablation, ventricular tachycardia, inHEART, 4D CT, Motion management, dosimetry

MANUSCRIPT

1. Introduction

The conventional management of ventricular tachycardia (VT) combines antiarrhythmic drugs, implantable cardioverter-defibrillators (ICD), and catheter ablation [1]. Despite these approaches, a significant subset of patients with advanced structural heart disease remains refractory, with poor prognosis and high mortality rates [2].

Re-entrant circuits responsible for VT are typically associated with myocardial scar tissue, which disrupts normal conduction. Radiofrequency ablation (RFA), the standard treatment, often fails when the arrhythmogenic substrate is deep or multifocal [2]. The limited reach of thermal lesions has therefore led to the development of non-invasive alternatives capable of targeting intramyocardial regions.

Stereotactic arrhythmia radioablation (STAR), also referred to as stereotactic body radiotherapy for VT (SBRT-VT), delivers a single high-dose fraction of ionizing radiation (≈25 Gy) to the arrhythmogenic myocardial substrate [3–5]. Preclinical studies in animal models and mechanistic work in irradiated hearts recently demonstrated that 25–40 Gy can alter myocardial conduction — not only via fibrosis but also through radiation-induced reprogramming of electrical conduction — effectively suppressing VT inducibility and raising the possibility of non-fibrotic antiarrhythmic mechanisms [6–9].

Since the first human case in 2015 [3], several clinical studies have confirmed the feasibility and safety of STAR, showing substantial arrhythmia reduction with limited toxicity [10–12]. Recent advances in multimodal cardiac imaging, motion management, and electrophysiological (EP) integration have further improved targeting accuracy [13,14].

STAR thus represents a promising non-invasive therapy for patients with drug-refractory VT and limited options. However, several challenges remain, particularly in treatment targeting, dose optimization, management of late toxicity, and accurate patient selection [4,10,15].

This article presents the clinical workflow implemented in our institut, emphasizing the use of the inHEART platform for multimodal cardiac image integration and 3D substrate segmentation. We report the dosimetric outcomes and workflow optimization based on the first 18 treated patients [16–18].

2. Materials et Methods

2.1. Indication and patient selection

Patient eligibility for STAR was established through collaboration between radiation oncologists and cardiac electrophysiologists, following published criteria [10]. Standard indications included patients with structural heart disease and sustained monomorphic VT refractory to at least one antiarrhythmic drug, usually a beta-blocker and amiodarone, in whom catheter ablation was unsuccessful or contraindicated (e.g., inaccessible epicardial substrate or intracardiac thrombus).

Borderline cases were discussed in multidisciplinary meetings and could include polymorphic VT or ventricular fibrillation with a clearly identified arrhythmogenic substrate. Patients with end-stage heart failure under continuous inotropic support or with a left ventricular assist device were also considered. Previous thoracic irradiation required individualized assessment. Exclusion criteria included absence of structural heart disease or a target volume < 1 cm.

This study reports the dosimetric outcomes of the first 18 STAR-treated patients, focusing on cardiac irradiated volume, target coverage, and changes in VT burden.

2.2. *Clinical Workflow for STAR*

The STAR clinical workflow implemented is illustrated in Figure 1.

Step 1 - SCAR mapping and target definition

Typically, an anatomical modality, such as coronary CT angiography, provides detailed cardiac structural mapping, while a functional imaging modality, such as cardiac magnetic resonance imaging (MRI), with intracavitary sequences, visualizes myocardial contractile or electrical activity [19–21]. In addition, electrophysiological (EP) imaging, combining both anatomical and functional data through three-dimensional electro-anatomical mapping (3D EAM), enables precise identification of low-voltage areas (arrhythmogenic substrate), slow conduction zones involved in re-entry circuits, and the entrance/exit sites of VT circuits [22–24].

In our workflow, all patients underwent multimodality imaging including:

- High-resolution coronary CT, performed using a *GE Apex Elite scanner* (GE Healthcare, Waukesha, WI, USA), with 0.625 mm contiguous slices, minimum axial coverage of 16 cm, performed in two acquisitions (both were ECG-synchronized to minimize cardiac motion):
    - Arterial phase CT (first contrast pass), using prospective diastolic triggering, and performed during a breath-hold at end-inspiration to minimize respiratory artifacts.
    - Late-enhancement CT, (6–8 minutes post-contrast), also under ECG-gating and breath-hold conditions, to assess myocardial fibrosis or scarring.
- 3D EAM; using one of three systems: *RHYTHMIA HDx*™ (Boston Scientific, Marlborough, USA), *CARTO™3* (Biosense Webster, Johnson & Johnson, CA, USA), and *EnSite NavX*™ (Abbott, Chicago, USA).
- Optional cardiac MRI (1.5 Tesla GE scanner, GE Healthcare, Waukesha, WI, USA), with standard T1 gadolinium late enhancement sequences, performed in some patients who did not have an ICD lead prior to the STAR protocol.

All imaging was imported into the inHEART platform (MUSIC, V4.0, Pessac, France), an investigational software not yet approved for clinical use, which enables automated 3D segmentation of cardiac structures from multimodal datasets [18,25]. This integration, illustrated in Figure 1 – Step 1, combined anatomical (arterial and late CT) and electrophysiological data, allowing precise characterization of arrhythmogenic substrates in patients with refractory VT [26].

A multidisciplinary team involving cardiologists, radiation oncologists, and medical physicists systematically reviewed each case to define the arrhythmogenic target volume using the dedicated inHEART SBRT module. In accordance with the EHRA clinical consensus [27], the arrhythmogenic myocardial substrate corresponds to the Cardiac Target Volume (CardTV), which in our radiotherapy workflow was defined as the Clinical Target Volume (CTV) and corresponded to the fibrotic myocardial regions involved in re-entry circuits [28]. An example of target delineation is shown in Figure S1 in the Data Supplement. The list of segmented structures available in inHEART and Eclipse is provided in Table 1.

A dedicated export tool was developed in collaboration with inHEART to convert imaging data into DICOM-RT format compatible with radiotherapy treatment planning systems (TPS) [16,17]. This export included RT Images (arterial CT) and RT Structures (segmented anatomy), ensuring seamless integration into the Eclipse TPS (Varian Medical Systems, versions 15.6 and 18, Palo Alto, CA, USA), used for treatment plan optimization.

Step 2 - Treatment planning design

Eligible patients underwent a four-dimensional 4D simulation CT scan (4D CT, Siemens SOMATOM go.Open Pro, Siemens Healthineers, Forchheim, Germany) with 1 mm slice thickness and resolution [4,26], positioned supine using an ORFIT AIO 3.0 immobilization system (ORFIT industries, Wijnegem, Belgium) with a 6-point thoracic mask, arms raised, and additional mattress and knee supports for comfort and reproducibility.

Two acquisitions were performed (Figure 1 – step 2):

- A non-contrast 4D CT simulation with Varian's Real-time Position Management (RPM) system (Varian Medical Systems, Palo Alto, CA, USA), and 6 respiratory phases (0%, 16%, 33%, 50%, 66%, 83%), to evaluate target motion [14].
- A contrast-enhanced arterial phase free breathing CT (FB CT) to better visualize vascular structure [29].

The arterial CT with inHEART-segmented structures was rigidly registered to the 4D CT simulation in Eclipse. All registrations were reviewed and validated by an expert radiation oncologist, and any residual uncertainty was incorporated into the ITV–PTV margin expansion. The CTV was propagated and manually adjusted on a 3-phases Maximal Intensity Projection CT (MIP3 CT, 33%, 50%, 66%) with cine review to generate the internal target volume (ITV), accounting for combined cardiorespiratory motion [3,30,31]. An averaged CT dataset based on the 3 expiratory phases (AVE3 CT) was subsequently generated for dose calculation. The planning target volume (PTV) was then obtained by adding a 5-mm isotropic margin to the ITV, in accordance with recommendations described in the literature and taking into account our ITV which includes cardiorespiratory movement [26,28,32–34]. This point will be developed in the Discussion section. Organs at risk (OARs, Table 1), were contoured on the AVE3 CT using an artificial intelligence–based auto-contouring software (Limbus AI, version 1.8.0, RADformation, NY, USA) and validated by the radiation oncologist [35]. Similarly, cardiac structures exported from inHEART were adjusted to align with the AVE3 CT dataset used for treatment planning.

To complete, treatment planning was performed using Volumetric Modulated Arc Therapy (VMAT) on a Varian TrueBeam™ STx linear accelerator equipped with a 120-leaf high-definition multileaf collimator (HD120 MLC; Varian Medical Systems, Palo Alto, CA, USA), using 6 MV photons in Flattening Filter Free (X6FFF) mode at 1400 cGy/min, with 4 left hemi-arcs (179°–0°) and jaw-tracking. The prescribed dose was 25 Gy in a single fraction to the PTV, normalized to 30 Gy at the ITV median. Plans were calculated using the Photon Optimizer and Acuros algorithm (PO, AxB dose-to-medium, version 18, resolution 1.25 mm, Varian Medical Systems, Palo Alto, CA, USA). [10,32,35–38]. Dosimetric optimization aimed to achieve PTV coverage with at least 25 Gy (PTV D99% > 25 Gy) while strictly meeting all OAR dose constraints (Table 2). OAR dose constraints were defined according to the AAPM TG-101 report, complemented by published STAR consensus recommendations and dose limits reported in major clinical series [10,32,35–

38]. This combined approach ensured the use of constraints specifically suited to high-dose single-fraction cardiac SBRT, while maintaining consistency with current standards for extracranial stereotactic treatments.

Step 3 –Treatment delivery

The third step involves treatment plan verification, essential for accuracy and safety in stereotactic radiotherapy. Patient-specific quality assurance (QA) were performed to confirm dosimetric accuracy and feasibility [32,37]. Full explanations of patient specific QA is detailed in Data Supplement.

For treatment, patients were positioned supine on the same customized immobilization system used for 4D CT simulation (Figure 1). The ICD device was temporarily deactivated by the cardiologist to avoid interference, and continuous cardiac monitoring was maintained using a bedside monitor (Philips IntelliVue MX450, Amsterdam, Netherlands) connected to thoracic electrodes, enabling rapid detection and immediate management of arrhythmic events.

A 4D cone-beam CT (CBCT) was acquired for the 3 expiratory phases (33%, 50%, 66%) to verify positioning at isocenter. Initial rigid registration on bony landmarks was refined on cardiac structures, with a maximum 5-mm tolerance relative to the AVE3 CT. Fluoroscopy was subsequently performed during the expiratory phases corresponding to the treatment delivery window. This allowed verification that the ICD lead, used as an internal reference marker, remained within the predefined 5-mm PRV throughout all treatment phases. Consistent with recent studies [39,40], the ICD lead was not used as a surrogate for target motion or myocardial deformation, but rather as an ancillary setup verification tool complementing the ITV defined from the expiratory phases of the 4DCT. This approach enabled qualitative monitoring of positional stability within the respiratory-gated treatment window.

Finally, after verification by the radiation oncologist and cardiologist, treatment was delivered on a Varian TrueBeam™ STx using respiratory gating through the three expiratory phases. 2D kV images were acquired during each respiratory cycle to ensure correct ICD probe positioning within the PRV before beam delivery.

Figure 2 shows the STAR treatment decision-making flowchart.

2.3. Outcomes Measures and Statistical analysis

Therapeutic response was assessed by comparing VT episodes and ICD shocks before and after STAR, across defined follow-up periods: pre-treatment, blanking (0–6 weeks), post-blanking (6 weeks–6 months), 6–12 months, and beyond 12 months. The efficacy endpoint was the proportion of patients showing any reduction in VT episodes or ICD shocks, comparing the six months before and after treatment.

Continuous data were summarized by mean or median with range (min-max) or interquartile range (IQR), according to their distribution. The Wilcoxon signed-rang test was used to compare VT events and ICD shocks between baseline and 12 months post treatment.

All statistical tests were two-sided, with $p < 0.05$ considered significant. Analyses were performed using Matlab (version R2024a, MathWorks, Natick, MA, USA).

2.4 Ethical approvement

This study was approved by our Institutional Review Board and our local ethics committee. Patients/participant's guardian received a letter detailing the aim of the study and the use of data collection and could refuse inclusion at any time, but informed consent was not necessary because of the retrospective nature of the study

3. Results

3.1. Patients and targeting details

Patient demographics and targeting parameters are summarized in Table 3. Between May 2021 and March 2025, 18 patients underwent STAR at our institution. All were male (100 %), with a median age of 66 years (range, 45–90).

Most had ischemic cardiomyopathy (n = 15; 83.3%), while 3 patients (16.7%) presented with non-ischemic disease. The median left-ventricular ejection fraction (LVEF) was 35 % (range, 10–64), indicating globally impaired cardiac function.

This cohort represented a heavily pre-treated population, with a median of two prior catheter ablations (range, 1–4). Seventeen patients (94.4%) carried an ICD and one patient (5.6%) had a pacemaker. Almost all were under antiarrhythmic therapy at the time of STAR; only one was not receiving any medication.

Regarding target definition, volumetric analysis showed a progressive increase from CTV to PTV, consistent with the isotropic margin expansion applied during planning. The median CTV volume was 14.5 cc (range, 4.3–32.6), increasing to 22.1 cc (range, 5.2–49.2) for the ITV, and 58.4 cc (range, 20.9–109.8) for the PTV. The median total cardiac volume was 1459.1 cc (range, 883.1–1726.7).

3.2. Dosimetric evaluation of target volumes, organs at risk and specific QA

The dosimetric analysis of CTV, ITV, and PTV for all 18 patients is illustrated in Figure 3A (box plots) and S2 (histogram on supplement data), with the Paddick Conformity Index (PCI) shown in Figure 3B.

Overall, the assessment demonstrated consistent and homogeneous target coverage, in accordance with the prescription goal of 25 Gy to the PTV with a normalization method of 30 Gy to the ITV median. The median dose to 99% of the PTV (D99%) was 25.25 Gy (range, 21.94–27.51), confirming effective coverage. Median D95% values were 27.60 Gy (range, 24.61-28.93), 27.76 Gy (range, 24.73-28.69) and 26.26 Gy (range, 24.01-28.32) for CTV, ITV and PTV respectively.

Median doses (D50%) reached 29.13 Gy for the PTV and 30 Gy for both the CTV and ITV, confirming the achievement of prescription goals. Maximum doses (D2%) indicated good homogeneity, with medians of 30.65 Gy (range, 25.24-31.81), 30.62 Gy (range, 25.28-31.75) and 30.58 Gy (range, 25.49-31.32) for the CTV, ITV and PTV, respectively, all within tolerance. The PCI averaged calculated for the PTV 0.89 ± 0.08 (median, 0.90; range, 0.62–0.96), confirming high conformity.

As shown in Figure 3A, all patients achieved > 99% coverage of the target volumes, except patients 6 and 16, where a homogeneous prescription of 25 Gy to the PTV median was applied, accounting for the minor deviations observed. These specific cases will be addressed in the Discussion.

Detailed dosimetric data, including dose–volume parameters for all OARs, are presented in Figure 4. Across the cohort, all evaluated OAR dose metrics remained within the predefined tolerance limits. For the chest wall, the median Dmax was 15.25 Gy (range, 9.16–29.29) and median D1cc 13.64 Gy (range, 7.92-23.18). Great vessels received a median Dmax of 12.76 Gy (range, 0.97–19.23). The coronary arteries showed a median Dmax of 12.76 Gy (range, 0.97–19.23). Dose to the heart outside the PTV remained limited, with a median D50% of 2.32 Gy (range, 0.77–3.79). Pulmonary exposure was low, with median V1500cGy and V1000cGy values of 0.42% (range, 0.05–1.49%) and 0.91% (range, 0.07–2.31%), respectively. Spinal cord doses were also low, with median Dmax 2.32 Gy (range 0.77–3.79), D0.35 cc 2.08 Gy (range 0.72–3.27), and D1.2 cc 1.91 Gy (range 0.69–2.96). Dose to implantable cardioverter-defibrillator (ICD) leads was minimal, with a median Dmax of 0.10 Gy (range, 0.03–4.18). For the remaining OARs displayed, esophagus (D5 cc, Dmax), stomach (D10 cc, Dmax), and PBT/trachea (D4 cc, Dmax)—all reported metrics were kept within the predefined constraints in our protocol.

Patient-specific QA results, confirming the dosimetric deliverability and calculation-to-measurement agreement of the VMAT plans in stereotactic conditions, are summarized in Figure S3 of the same Data

Supplement and are provided for guidance purposes only. As treatment QA is not the primary focus of the present work, these results are not further discussed in the Discussion section.

3.3. Treatment efficacy

The clinical efficacy of STAR was evaluated for all patients, with a median follow-up of 21 months (range, 1–47) (Figure 5A and 5B).

Among the 18 patients included in our study, the efficacy endpoint, defined as a reduction of VT episodes or ICD shocks, was achieved in 16 of the 18 patients who survived at 6 months (89%).

In the 18 evaluable patients with ICD-treated VT, a total of 1172 VT episodes were documented during the 6 months preceding treatment. During the 6-week blanking period, 83 episodes were observed (median, 0 episode; range, 0–60), with six patients experiencing early recurrences, including one patient with 60 episodes who died within one month. Over the 6 months following treatment, 188 VT episodes occurred in 6 patients (representing an overall reduction of 84%), 2 of whom had a high VT burden (>50 episodes). The median number of VT episodes decreased from 22 (range, 0–666) in the 6 months prior to ablation to 1 (range, 0–130) in the 6 months following ablation ($p < 0.03$). Notably, 2 patients experienced an increase in VT episodes between 6 and 12 months (425 and 556 episodes, respectively), which stabilized after 12 months, yielding a median of 1 VT episode (range, 0–180) and a 77% reduction in episodes at 12 months ($p < 0.03$) in 83% of patients.

A similar pattern was observed for ICD shocks. Among the 16 patients who survived to 6 months, the median number of ICD shocks decreased significantly, from 2 (range, 0–25) before ablation to 0 (range, 0–2) at 6 months post-ablation ($p < 0.01$). Between 6 and 12 months, 3 patients experienced recurrent shocks, all associated with VT recurrence. At 12 months, the total number of shocks was reduced by 84% (median, 0; range, 0–8; $p < 0.02$), with 94% of surviving patients experiencing a limited number of shocks (<2).

Regarding clinical events, 1 patient underwent heart transplantation at 14 months, and 6 died during follow-up (2 before 6 months, related to underlying disease progression, and 4 after 12 months), events not attributable to treatment toxicity. No electrical storm was observed beyond the blanking period among survivors.

4. Discussion

This study demonstrates the feasibility, technical accuracy, and robustness of the STAR protocol implemented on 18 patients with refractory VT. Dosimetric results confirm the reliability of the workflow in a complex clinical setting, consistent with published data [10,11,41].

A major challenge in STAR lies in precise and reproducible target definition [10,13,26], given the heterogeneity and intramural nature of arrhythmogenic substrates [4,13,41]. The integration of the inHEART platform was central to addressing this issue. By combining high-resolution arterial and late-enhancement CT data with automated 3D segmentation, the inHEART SBRT module allowed accurate identification of arrhythmogenic myocardial fibrosis while sparing adjacent critical structures such as coronary arteries. Its standardized DICOM-RT export ensured seamless transfer to the Eclipse planning system, enabling a consistent image-to-plan workflow. This multimodal integration exemplifies the benefit of combining advanced imaging and multidisciplinary expertise for safe and precise STAR treatments [18,42]. These features facilitate a streamlined and reproducible workflow from imaging to treatment planning, while supporting multidisciplinary decision making.

In our workflow, we deliberately used a cardiorespiratory Internal Target Volume (ITV) derived from a standard free-breathing 4DCT. This approach is consistent with the majority of published STAR/SABR-VT workflows. In non-ECG-gated 4DCT acquisitions, cardiac contraction is not temporally resolved and is intrinsically blurred across the respiratory bins. Consequently, the observed target displacement reflects a combined cardiorespiratory motion envelope rather than isolated respiratory motion alone. As described in the literature, including dedicated motion analyses in STAR, free-breathing 4DCT therefore provides a pragmatic assessment of overall target motion and has been widely used to define a combined ITV [14,39,43]. Although ECG-gated or cardiac-resolved imaging techniques have been proposed to better characterize pure cardiac motion, these approaches remain heterogeneous, investigational, and are not yet standardized or validated for routine clinical implementation in non-invasive cardiac radioablation. Our ITV strategy is thus aligned with current clinical practice and published experience in STAR/SABR-VT, ensuring adequate target coverage while maintaining a clinically feasible and reproducible workflow.

Median target volumes (CTV: 14.5 cc; ITV: 22.1 cc; PTV: 58.4 cc) represented approximately 4% of total cardiac volume, confirming a high degree of treatment focus. These values were smaller than those reported in literature [10,41,44], suggesting improved accuracy of target delineation using inHEART. Dosimetrically, all treatment plans achieved their objectives, with PTV D99% > 25 Gy, D50% ≈ 30 Gy, and mean PCI of 0.89. For patients 6 and 16, a homogeneous prescription of 25 Gy to the PTV median was required because the PTV was adjacent to critical structures, particularly the coronary arteries and, in one case, the phrenic nerve. Under this normalization approach, plan evaluation relied on the requirement that 95% of the PTV received at least 95% of the prescribed dose, which was achieved in both cases (PTV D95% of 96.04% and 97.76%). The lower V25 Gy values observed in Figure 4 therefore reflect the homogeneous normalization rather than insufficient coverage. In patient 16, the higher coverage of the ITV compared with the CTV was explained by geometric differences: the ITV generated from expiratory phases differed substantially from the diagnostic CTV, and the homogeneous prescription weighted the optimization more strongly toward the ITV. Overall, these results reflect a strong balance between conformity and safety, while demonstrating the flexibility of the protocol to accommodate patient-specific anatomical constraints—an

essential requirement in non-invasive ventricular tachycardia ablation [3] and consistent with modern VMAT-based STAR workflows [32,36,45–47].

Overall, OAR protection was satisfactory. Doses to critical structures, including the coronary arteries (mean Dmax 12.15 Gy) and chest wall (mean Dmax 18.16 Gy), generally remained within accepted tolerance ranges [10,11]. In a limited number of cases, minor and clinically justified deviations from recommended constraints were accepted after multidisciplinary evaluation, prioritizing target coverage in patients with life-threatening arrhythmias. ICD exposure remained minimal (mean Dmax 0.76 Gy), well below the reported malfunction threshold of 5 Gy [48,49].

Clinically, early outcomes were encouraging. Among patients alive at 6 months, 89% achieved the primary endpoint of arrhythmic burden reduction, and 83% experienced a >75% decrease in VT episodes, consistent with previous reports [10,11]. ICD shocks were markedly reduced or completely suppressed in 83% of patients by 12 months. Late VT recurrences were observed in six patients; most were moderate, except for one case with a substantial recurrence (556 VT episodes). Interpretation of these recurrences was often limited, as many events were documented only through ICD logs without accompanying ECG tracings, preventing precise assessment of VT morphology, substrate location, or its relationship to STAR versus prior circuits. In cases where repeat ablation was performed, the mechanisms varied: some patients exhibited remote new circuits, others showed involvement of previously treated areas, and a few may have developed new arrhythmogenic substrates potentially related to radiation effects. Two deaths occurred within 6 months, both due to progression of advanced cardiomyopathy rather than STAR, underscoring the need for individualized risk assessment and long-term follow-up. No post-blanking electrical storms were reported, further supporting the safety profile of STAR. Regarding medication, 17 patients continued their antiarrhythmic drugs, and 3 changed medications during the post-STAR follow-up (patient 7 switched from beta-blocker to amiodarone, patient 13 from amiodarone + beta blocker to beta blocker and patient 17 from beta blocker to amiodarone + beta blocker).

Several limitations must, however, be acknowledged despite these promising results. First, the cohort size remains limited (18 patients), which precludes robust statistical extrapolation. Nonetheless, the consistency of dosimetric and QA results, and their agreement with previously published multicenter series [10,11], provide important indicative value to this first single-center experience. Second, while the median follow-up of 21 months allows a meaningful intermediate evaluation, it remains insufficient to fully capture the late effects of myocardial irradiation, particularly the risks of cardiac remodelling, extended post-radiation fibrosis, or long-term coronary complications. Third, no systematic post-treatment anatomical evaluation with MRI or EP mapping was performed in this cohort, limiting the possibility of directly correlating the irradiated volume, post-treatment fibrosis distribution, and clinical response. Ongoing studies investigating post-radiation fibrosis modeling and conduction dynamics may help address this gap [6,8,50]. Fourth, although planning relied on 4D-CT with expiratory phase evaluation and standardized ITV-to-PTV

margins, intrinsic cardiac motion (myocardial contraction) was not explicitly modelized. This choice was motivated by the low mobility of fibrotic target regions but may introduce residual uncertainties. Future integration of cardiac gating or multimodal non-rigid registration could further enhance targeting accuracy [13,14,34]. Fifth, while the SBRT module of the inHEART platform played a central role in our workflow and proved effective, its availability is currently restricted to specialized centers with appropriate training. multicenter validation and comparisons with alternative cardiac imaging–integrated platforms, such as ADAS 3D (Adas3D Medical SL, Barcelona, Spain) or CARTO-MRI integration within the CartoTM3 System (Biosense Webster, J&J MedTech, Canada), would be valuable [51–55]. Finally, a selection bias must be acknowledged: all included patients had clear treatment indications and high-quality imaging with a well-individualized arrhythmogenic substrate. This favourable context for target definition may not apply to more complex scenarios such as polymorphic VT or ventricular fibrillation, where invasive EP mapping often remains indispensable.

Conclusion

This single-center experience demonstrates the feasibility, safety, and dosimetric accuracy of an optimized STAR protocol for refractory ventricular tachycardia, with structured target identification facilitated by the inHEART platform. The proposed workflow achieved consistent target coverage, compliance with OARs constraints, robust QA, and encouraging early clinical outcomes, in line with published series. These findings support the broader adoption of STAR in specialized centers, while larger multicenter studies with long-term follow-up will be required to confirm its durability and prognostic value. A national radioablation French registry (FrenchStar) and the STOPSTORM.eu registry [12,28,48,49,56] are ongoing to collect comprehensive multicenter data and enable the evaluation of STAR in larger cohorts.

References

[1] Shivkumar K. Catheter Ablation of Ventricular Arrhythmias. N Engl J Med 2019;380:1555–64. https://doi.org/10.1056/nejmra1615244.

[2] Tokuda M, Kojodjojo P, Tung S, Tedrow UB, Nof E, Inada K, et al. Acute failure of catheter ablation for ventricular tachycardia due to structural heart disease: Causes and significance. J Am Heart Assoc 2013;2:1–10. https://doi.org/10.1161/JAHA.113.000072.

[3] Loo BW, Soltys SG, Wang L, Lo A, Fahimian BP, Iagaru A, et al. Stereotactic Ablative Radiotherapy for the Treatment of Refractory Cardiac Ventricular Arrhythmia. Circ Arrhythmia Electrophysiol

2015;8:748–50. https://doi.org/10.1161/CIRCEP.115.002765.

[4] Cuculich PS, Schill MR, Kashani R, Mutic S, Lang A, Cooper D, et al. Noninvasive Cardiac Radiation for Ablation of Ventricular Tachycardia. N Engl J Med 2017;377:2325–36. https://doi.org/10.1056/nejmoa1613773.

[5] Sacher F, Gandjbakhch E, Maury P, Jenny C, Khalifa J, Boveda S, et al. Focus on stereotactic radiotherapy: A new way to treat severe ventricular arrhythmias? Arch Cardiovasc Dis 2021;114:140–9. https://doi.org/10.1016/j.acvd.2020.11.003.

[6] Lehmann HI, Graeff C, Simoniello P, Constantinescu A, Takami M, Lugenbiel P, et al. Feasibility Study on Cardiac Arrhythmia Ablation Using High-Energy Heavy Ion Beams. Sci Rep 2016;6:1–13. https://doi.org/10.1038/srep38895.

[7] Refaat MM, Ballout JA, Zakka P, Hotait M, Al Feghali KA, Gheida IA, et al. Swine atrioventricular node ablation using stereotactic radiosurgery: Methods and in vivo feasibility investigation for catheter-free ablation of cardiac arrhythmias. J Am Heart Assoc 2017;6:1–7. https://doi.org/10.1161/JAHA.117.007193.

[8] Hohmann S, Deisher AJ, Suzuki A, Konishi H, Rettmann ME, Merrell KW, et al. Left ventricular function after noninvasive cardiac ablation using proton beam therapy in a porcine model. Hear Rhythm 2019;16:1710–9. https://doi.org/10.1016/j.hrthm.2019.04.030.

[9] Zhang DM, Navara R, Yin T, Szymanski J, Goldsztejn U, Kenkel C, et al. Cardiac radiotherapy induces electrical conduction reprogramming in the absence of transmural fibrosis. Nat Commun 2021. https://doi.org/10.1038/s41467-021-25730-0.

[10] Robinson CG, Samson PP, Moore KMS, Hugo GD, Knutson N, Mutic S, et al. Phase I/II Trial of Electrophysiology-Guided Noninvasive Cardiac Radioablation for Ventricular Tachycardia. Circulation 2019;139:313–21. https://doi.org/10.1161/CIRCULATIONAHA.118.038261.

[11] Ninni S, Gallot-Lavallée T, Klein C, Longère B, Brigadeau F, Potelle C, et al. Stereotactic Radioablation for Ventricular Tachycardia in the Setting of Electrical Storm. Circ Arrhythmia Electrophysiol 2022;15:E010955. https://doi.org/10.1161/CIRCEP.122.010955.

[12] Miszczyk M, Hoeksema WF, Kuna K, Blamek S, Cuculich PS, Grehn M, et al. Stereotactic arrhythmia radioablation (STAR)—A systematic review and meta-analysis of prospective trials on behalf of the STOPSTORM.eu consortium. Hear Rhythm 2025;22:80–9. https://doi.org/10.1016/j.hrthm.2024.07.029.

[13] Reis CQM, Cross A, Borsavage JM, Berryhill G, Karnas S, Robar JL, et al. Feasibility of volumetric-

modulated arc therapy gating for cardiac radioablation using real-time ECG signal acquisition and a dynamic phantom. Med Phys 2025;52:1758–68. https://doi.org/10.1002/mp.17582.

[14] Bellec J, Simon A, Jaksic N, Caille P, Léderlin M, Lafond C, et al. Radiothérapie ablative des tachycardies ventriculaires : impact des mouvements cardiaques et respiratoires sur la définition du volume cible. Cancer/Radiothérapie 2020;24:770. https://doi.org/10.1016/j.canrad.2020.08.005.

[15] Lloyd MS, Wight J, Schneider F, Hoskins M, Attia T, Escott C, et al. Clinical experience of stereotactic body radiation for refractory ventricular tachycardia in advanced heart failure patients. Hear Rhythm 2020;17:415–22. https://doi.org/10.1016/j.hrthm.2019.09.028.

[16] Cochet H, Tedrow UB, Maury P, Whitaker J, Woods C, Gandjbakhch E, et al. Ca-533-01 Multimodality Planning of Stereotactic Radio-Ablation for Ventricular Tachycardia: Results From the International Music Consortium. Hear Rhythm 2022;19:S57–8. https://doi.org/https://doi.org/10.1093/europace/euac053.370.

[17] Mehdi Juhoor, Jean-Marc Peyrat, Loïc Cadour, Bruno Sore, Florian Donis, BenjaMehdi Juhoor, Jean-Marc Peyrat, Loïc Cadour, Bruno Sore, Florian Donis, Benjamin Grange, Linda Ouzerout, Hakim Fadil, Frederic Sacher, Maxime Sermesant, Pierre Jais and Hubert PJ and HC. A NOVEL SOFTWARE PLATFORM FOR PLANNING STEREOTACTIC RADIOABLATION OF VENTRICULAR TACHYCARDIA Mehdi. Hear Rhythm 2023;20. https://doi.org/10.1016/j.hrthm.2023.03.1004.

[18] Merle M, Collot F, Castelneau J, Migerditichan P, Juhoor M, Ly B, et al. MUSIC: Cardiac Imaging, Modelling and Visualisation Software for Diagnosis and Therapy. Appl Sci 2022;12. https://doi.org/10.3390/app12126145.

[19] Saagar Mahida, MD P, Frédéric Sacher, MD P, Rémi Dubois P, Maxime Sermesant P, Frank Bogun M, Michel Haïssaguerre M, et al. Cardiac Imaging in Patients With Ventricular Tachycardia. Circulation 2017:2491–507. https://doi.org/10.1161/CIRCULATIONAHA.117.029349.

[20] Burger JC, Hopman LHGA, Kemme MJB, Hoeksema W, Takx RAP, Ventura RMFI, et al. Optimizing ventricular tachycardia ablation through imaging-based assessment of arrhythmic substrate : A comprehensive review and roadmap for the future. Hear Rhythm 2024. https://doi.org/10.1016/j.hroo.2024.07.001.

[21] David Soto-Iglesias P, * Diego Penela, MD P, * Beatriz Jáuregui, MD, Juan Acosta, MD P, Juan Fernández-Armenta, MD, PHD, e Markus Linhart, MD, Giulio Zucchelli, MD, PHD, Vladimir Syrovnev M, Fatima Zaraket, MD, Cheryl Terés, MD, Rosario J. Perea, MD, PHD, Susana Prat-González, MD P, Ada Doltra, MD, PHD, José T. Ortiz-Pérez, MD, PHD, Xavier Bosch, MD, PHD, Oscar Camara, PHD G, et al. Cardiac Magnetic Resonance-Guided Ventricular Tachycardia Substrate

Ablation. JACC Clin Electrophysiol 2020;6. https://doi.org/10.1016/j.jacep.2019.11.004.

[22] Maury P, Rollin A, Domain G, Mondoly P, Mandel F, Beneyto M, et al. New techniques of navigation and mapping in electrophysiology: Usefulness and limitations. Arch Des Mal Du Coeur Des Vaiss - Prat 2023;2023:8–11. https://doi.org/10.1016/j.amcp.2023.01.001.

[23] Mantziari L, Butcher C, Kontogeorgis A, Panikker S, Roy K, Markides V, et al. Utility of a Novel Rapid High-Resolution Mapping System in the Catheter Ablation of Arrhythmias An Initial Human Experience of Mapping the Atria and the Left Ventricle. JACC Clin Electrophysiol 2015;1:411–20. https://doi.org/10.1016/j.jacep.2015.06.002.

[24] Maury P, Monteil B, Marty L, Duparc A, Mondoly P, Rollin A. Three-dimensional mapping in the electrophysiological laboratory. Arch Cardiovasc Dis 2018;111:456–64. https://doi.org/10.1016/j.acvd.2018.03.013.

[25] Sacristan B, Cochet H, Bouyer B, Tixier R, Duchateau J, Derval N, et al. Imaging-Aided VT Ablation. Long-Term Results From a Pilot Study. J Cardiovasc Electrophysiol 2025:1–8. https://doi.org/10.1111/jce.16741.

[26] Knutson NC, Samson PP, Hugo GD, Goddu SM, Reynoso FJ, Kavanaugh JA, et al. Radiation Therapy Workflow and Dosimetric Analysis from a Phase 1/2 Trial of Noninvasive Cardiac Radioablation for Ventricular Tachycardia. Int J Radiat Oncol Biol Phys 2019;104:1114–23. https://doi.org/10.1016/j.ijrobp.2019.04.005.

[27] Zeppenfeld K, Rademaker R, Al-ahmad A, Carbucicchio C, Chillou C De, Cvek J, et al. Patient selection , ventricular tachycardia substrate delineation , and data transfer for stereotactic arrhythmia radioablation : a clinical consensus statement of the European Heart Rhythm Association of the European Society of Cardiology and the Heart R. Europace 2024;27. https://doi.org/10.1093/europace/euae214.

[28] Borzov E, Efraim R, Suleiman M, Bar-Deroma R, Billan S, Xie J, et al. Implementing stereotactic arrhythmia radioablation with STOPSTORM.eu consortium support: intermediate results of a prospective Israeli single-institutional trial. Strahlentherapie Und Onkol 2025;201:126–34. https://doi.org/10.1007/s00066-024-02300-z.

[29] Lydiard, PGDip S, Blanck O, Hugo G, O'Brien R, Keall P. A Review of Cardiac Radioablation (CR) for Arrhythmias: Procedures, Technology, and Future Opportunities. Int J Radiat Oncol Biol Phys 2021;109:783–800. https://doi.org/10.1016/j.ijrobp.2020.10.036.

[30] Wang L, Fahimian B, Soltys SG, Zei P, Lo A, Gardner EA, et al. Stereotactic Arrhythmia Radioablation (STAR) of Ventricular Tachycardia: A Treatment Planning Study. Cureus 2016;8:6–

13. https://doi.org/10.7759/cureus.694.

[31] Zeng LJ, Huang LH, Tan H, Zhang HC, Mei J, Shi HF, et al. Stereotactic body radiation therapy for refractory ventricular tachycardia secondary to cardiac lipoma: A case report. PACE - Pacing Clin Electrophysiol 2019;42:1276–9. https://doi.org/10.1111/pace.13731.

[32] Benedict SH, Yenice KM, Followill D, Galvin JM, Hinson W, Kavanagh B, et al. Stereotactic body radiation therapy: The report of AAPM Task Group 101. Med Phys 2010;37:4078–101. https://doi.org/10.1118/1.3438081.

[33] Bellec J, Castelli J, Lafond C, Chajon E. ITV versus mid-ventilation for treatment planning in lung SBRT : a comparison of target coverage and PTV adequacy by using in-treatment 4D cone beam CT 2020:1–10.

[34] Bellec J, Rigal L, Hervouin A, Martins R, Lederlin M, Jaksic N, et al. Cardiac radioablation for ventricular tachycardia: Which approach for incorporating cardiorespiratory motions into the planning target volume? Phys Medica 2022;95:16–24. https://doi.org/10.1016/j.ejmp.2022.01.004.

[35] Kong FM, Ritter T, Quint DJ, Senan S, Gaspar LE, Komaki RU, et al. Consideration of dose limits for organs at risk of thoracic radiotherapy: Atlas for lung, proximal bronchial tree, esophagus, spinal cord, ribs, and brachial plexus. Int J Radiat Oncol Biol Phys 2011;81:1442–57. https://doi.org/10.1016/j.ijrobp.2010.07.1977.

[36] Blanck O, Buergy D, Vens M, Eidinger L, Zaman A, Krug D, et al. Radiosurgery for ventricular tachycardia: preclinical and clinical evidence and study design for a German multi-center multi-platform feasibility trial (RAVENTA). Clin Res Cardiol 2020;109:1319–32. https://doi.org/10.1007/s00392-020-01650-9.

[37] Grimm J, LaCouture T, Croce R, Yeo I, Zhu Y, Xue J. Dose tolerance limits and dose volume histogram evaluation for stereotactic body radiotherapy. J Appl Clin Med Phys 2011;12:267–92. https://doi.org/10.1120/jacmp.v12i2.3368.

[38] Videtic GM, Paulus R, Singh AK, Chang JY, Parker W, Olivier KR, et al. Long-term Follow-up on NRG Oncology RTOG 0915 (NCCTG N0927): A Randomized Phase 2 Study Comparing 2 Stereotactic Body Radiation Therapy Schedules for Medically Inoperable Patients With Stage I Peripheral Non-Small Cell Lung Cancer. Int J Radiat Oncol Biol Phys 2019;103:1077–84. https://doi.org/10.1016/j.ijrobp.2018.11.051.

[39] Prusator MT, Samson P, Cammin J, Robinson C, Cuculich P, Knutson NC, et al. Evaluation of Motion Compensation Methods for Noninvasive Cardiac Radioablation of Ventricular Tachycardia. Int J Radiat Oncol Biol Phys 2021;111:1023–32. https://doi.org/10.1016/j.ijrobp.2021.06.035.

[40] Marshall J, Bergman A, Karan T, Deyell MW. Toward the Use of Implanted Cardiac Leads or the Diaphragm for Active Respiratory Motion Management in Stereotactic Arrhythmia Radioablation. Radiat Oncol 2025;122:1344–55. https://doi.org/10.1016/j.ijrobp.2025.02.035.Int.

[41] Gupta A, Sattar Z, Chaaban N, Ranka S, Carlson C, Sami F, et al. Stereotactic cardiac radiotherapy for refractory ventricular tachycardia in structural heart disease patients: a systematic review. Europace 2025;27:1–17. https://doi.org/10.1093/europace/euae305.

[42] Cochet H, Tedrow UB, Maury P, Whitaker J, Woods C, Gandjbakhch E, et al. Ca-533-01 Multimodality Planning of Stereotactic Radio-Ablation for Ventricular Tachycardia: Results From the International Music Consortium. Hear Rhythm 2022;19:S57–8. https://doi.org/https://doi.org/10.1093/europace/euac053.370.

[43] Akdag O, Borman P, Uijtewaal P, Woodhead P, Kok J, Van Asselen B, et al. OC-0502 Real-time cardiorespiratory motion management for MRI-guided stereotactic arrythmia radioablation. Radiother Oncol 2021;161:S384–5. https://doi.org/10.1016/s0167-8140(21)06928-0.

[44] Chiu MH, Mitchell LB, Ploquin N, Faruqi S, Kuriachan VP. Review of Stereotactic Arrhythmia Radioablation Therapy for Cardiac Tachydysrhythmias. CJC Open 2021;3:236–47. https://doi.org/10.1016/j.cjco.2020.11.006.

[45] De Rose F, Franceschini D, Reggiori G, Stravato A, Navarria P, Ascolese AM, et al. Organs at risk in lung SBRT. Phys Medica 2017;44:131–8. https://doi.org/10.1016/j.ejmp.2017.04.010.

[46] Petit C, Escande A, Sarrade T, Vaugier L, Kirova Y, Tallet A. Radiation therapy in the thoracic region: Radio-induced cardiovascular disease, cardiac delineation and sparing, cardiac dose constraints, and cardiac implantable electronic devices. Cancer/Radiotherapie 2023;27:588–98. https://doi.org/10.1016/j.canrad.2023.06.027.

[47] Hanna GG, Murray L, Patel R, Jain S, Aitken KL, Franks KN, et al. UK Consensus on Normal Tissue Dose Constraints for Stereotactic Radiotherapy. Clin Oncol 2018;30:5–14. https://doi.org/10.1016/j.clon.2017.09.007.

[48] Trojani V, Grehn M, Botti A, Balgobind B, Savini A, Boda-Heggemann J, et al. Refining Treatment Planning in STereotactic Arrhythmia Radioablation: Benchmark Results and Consensus Statement From the STOPSTORM.eu Consortium. Int J Radiat Oncol Biol Phys 2025;121:218–29. https://doi.org/10.1016/j.ijrobp.2024.07.2331.

[49] Balgobind B V., Visser J, Grehn M, Marquard Knap M, de Ruysscher D, Levis M, et al. Refining critical structure contouring in STereotactic Arrhythmia Radioablation (STAR): Benchmark results and consensus guidelines from the STOPSTORM.eu consortium. Radiother Oncol 2023;189.

https://doi.org/10.1016/j.radonc.2023.109949.

[50] Amino M, Yoshioka K, Tanabe T, Tanaka E, Mori H, Furusawa Y, et al. Heavy ion radiation up-regulates Cx43 and ameliorates arrhythmogenic substrates in hearts after myocardial infarction. Cardiovasc Res 2006;72:412–21. https://doi.org/10.1016/j.cardiores.2006.09.010.

[51] Cochet H, Komatsu Y, Sacher F, Jadidi AS, Scherr D, Riffaud M, et al. Integration of merged delayed-enhanced magnetic resonance imaging and multidetector computed tomography for the guidance of ventricular tachycardia ablation: A pilot study. J Cardiovasc Electrophysiol 2013;24:419–26. https://doi.org/10.1111/jce.12052.

[52] Prakosa A, Arevalo HJ, Deng D, Boyle PM, Nikolov PP, Ashikaga H, et al. Personalized virtual-heart technology for guiding the ablation of infarct-related ventricular tachycardia. Nat Biomed Eng 2018;2:732–40. https://doi.org/10.1038/s41551-018-0282-2.

[53] Sanchez-Somonte P, Garre P, Vázquez-Calvo S, Quinto L, Borràs R, Prat S, et al. Scar conducting channel characterization to predict arrhythmogenicity during ventricular tachycardia ablation. Europace 2023;25:989–99. https://doi.org/10.1093/europace/euac257.

[54] Faga V, Dallaglio PD, Claver E, Rodriguez-Garcia J, San Antonio R, Rodriguez M, et al. Variations in threshold values for border zone and dense scar produce significant changes in scar parameters obtained by ADAS-3D. Hear Rhythm 2025;22:106–17. https://doi.org/10.1016/j.hrthm.2024.06.055.

[55] ter Bekke RMA, Hohmann S, Xie J, Grehn M, Verhoeven K, Volders PGA, et al. Transfer of arrhythmia substrate targets from the cardiac electroanatomical and imaging modalities to the planning computed tomography scan for stereotactic arrhythmia radioablation for refractory ventricular tachycardia – a state-of-the-art review on sof 2025;210. https://doi.org/10.1016/j.radonc.2025.111004.

[56] Grehn M, Mandija S, Miszczyk M, Krug D, Tomasik B, Stickney KE, et al. STereotactic Arrhythmia Radioablation (STAR): the Standardized Treatment and Outcome Platform for Stereotactic Therapy Of Re-entrant tachycardia by a Multidisciplinary consortium (STOPSTORM.eu) and review of current patterns of STAR practice in Europe. Europace 2023;25:1284–95. https://doi.org/10.1093/europace/euac238.

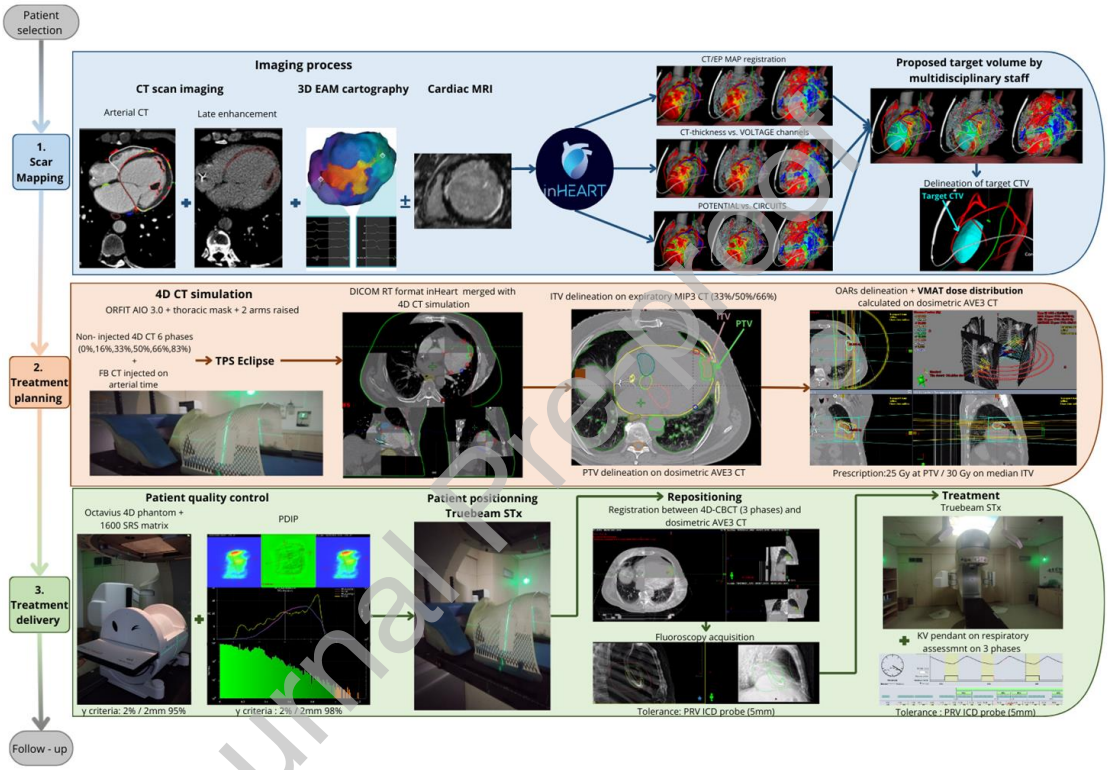


Figure 1: Clinical workflow developed for STAR. (CT = computed tomography, EAM = electro-anatomical mapping, MRI = magnetic resonance imaging, EP = electrophysiological, CTV = clinical target volume, 4D CT = four-dimensional CT, FB = free breathing, RT = radiotherapy, ITV = internal target volume, MIP3 CT = 3 phases maximum intensity projection CT, AVE3 CT = 3 phases average CT, PTV = planning target volume, TPS = treatment planning system, SRS = stereotactic radiosurgery, PDIP = portal dose image prediction, CBCT = cone beam CT, PRV = planning at risk volume, ICD = implantable cardioverter-defibrillator).

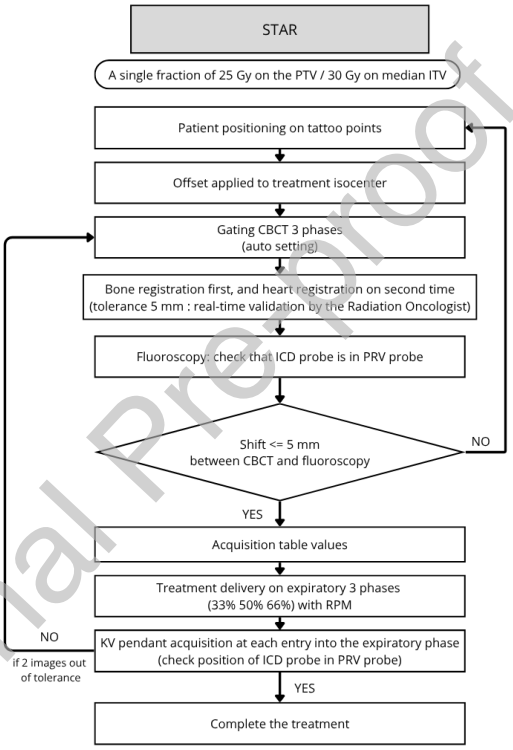
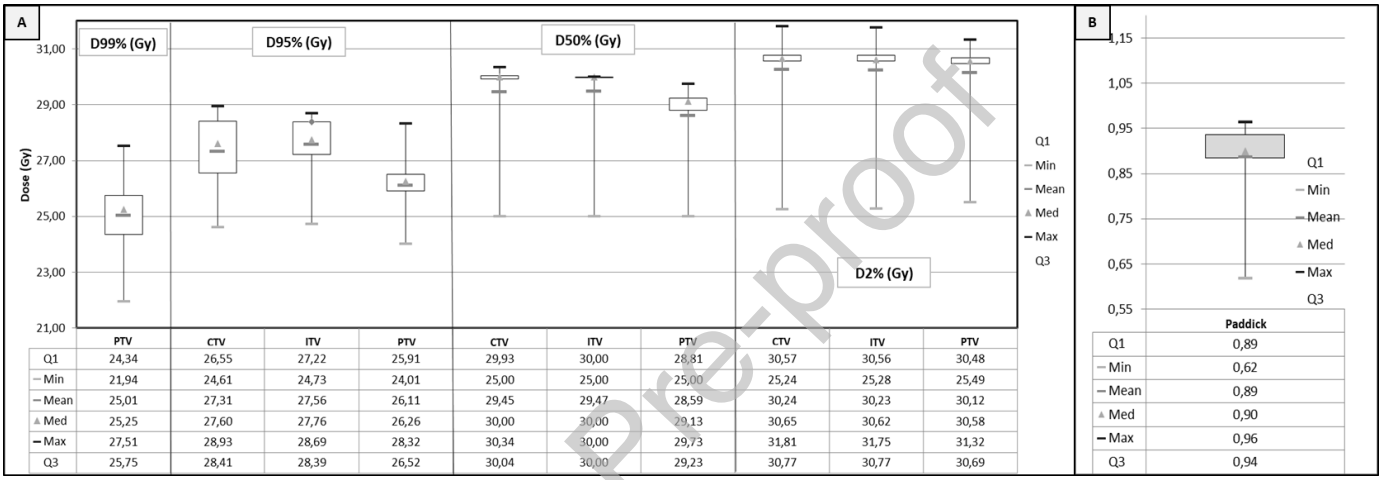


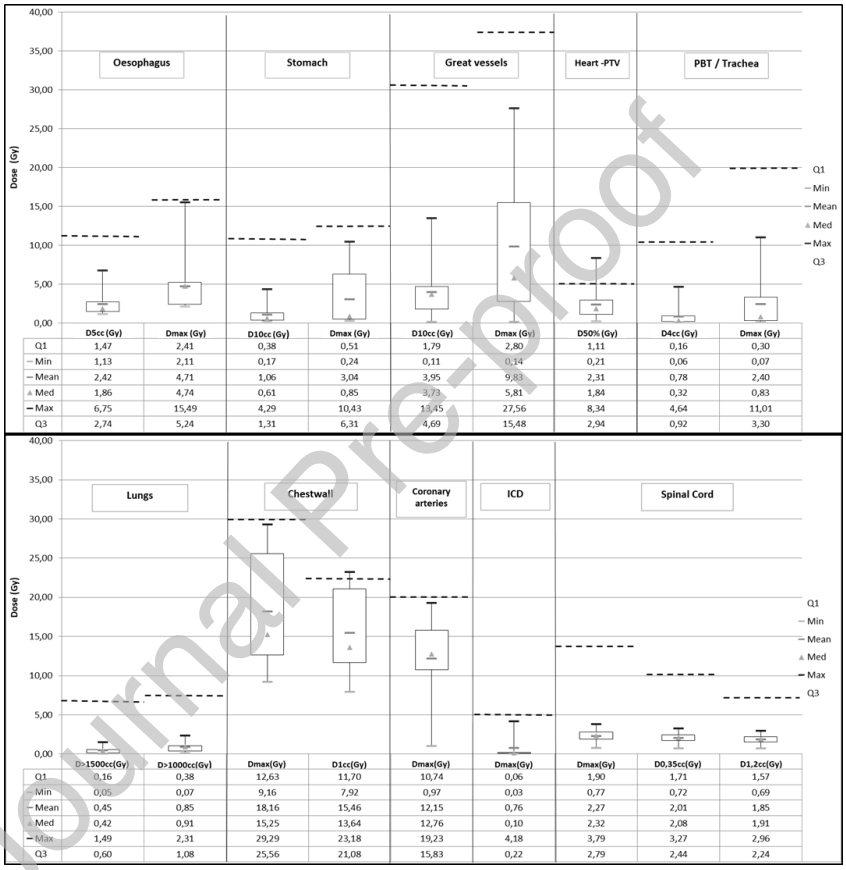
Figure 2: Decision flowchart for STAR on a Truebeam™ Stx linear accelerator. (ITV = internal target volume, PTV = planning target volume, CBCT = cone beam CT, ICD = implantable cardioverter-defibrillator, PRV = planning at risk volume, RPM = real time position management).



	PTV	CTV	ITV	PTV	CTV	ITV	PTV	CTV	ITV	PTV
Q1	24,34	26,55	27,22	25,91	29,93	30,00	28,81	30,57	30,56	30,48
Min	21,94	24,61	24,73	24,01	25,00	25,00	25,00	25,24	25,28	25,49
Mean	25,01	27,31	27,56	26,11	29,45	29,47	28,59	30,24	30,23	30,12
Med	25,25	27,60	27,76	26,26	30,00	30,00	29,13	30,65	30,62	30,58
Max	27,51	28,93	28,69	28,32	30,34	30,00	29,73	31,81	31,75	31,32
Q3	25,75	28,41	28,39	26,52	30,04	30,00	29,23	30,77	30,77	30,69

	Paddick
Q1	0,89
Min	0,62
Mean	0,89
Med	0,90
Max	0,96
Q3	0,94

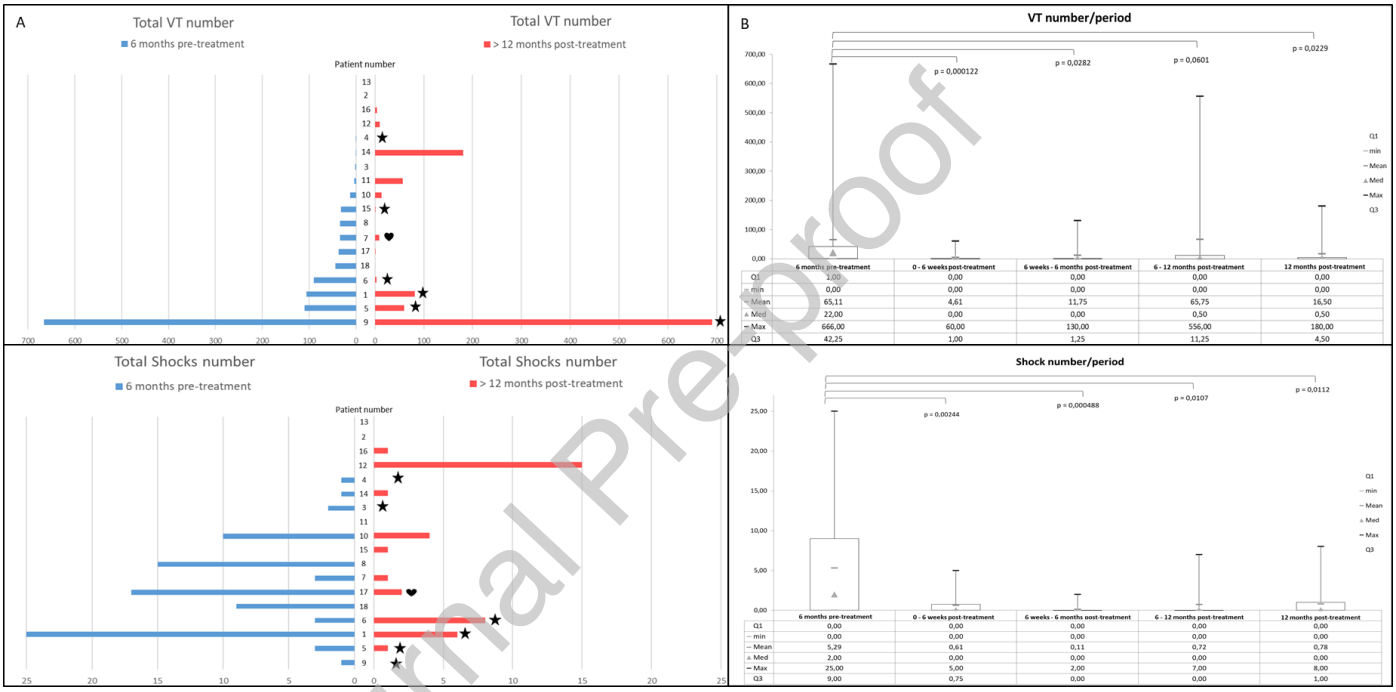
Figure 3: A. Box plots of doses received by CTV, ITV and PTV for the 18 patients treated. B. Box plots of Paddick Conformity index. (CTV = clinical target volume, ITV = internal target volume, PTV = planning target volume).



	D5cc (Gy)	Dmax (Gy)	D10cc (Gy)	Dmax (Gy)	D10cc (Gy)	Dmax (Gy)	D50% (Gy)	D4cc (Gy)	Dmax (Gy)
Q1	1,47	2,41	0,38	0,51	1,79	2,80	1,11	0,16	0,30
Min	1,13	2,11	0,17	0,24	0,11	0,14	0,21	0,06	0,07
Mean	2,42	4,71	1,06	3,04	3,95	9,83	2,31	0,78	2,40
Med	1,86	4,74	0,61	0,85	3,73	5,81	1,84	0,32	0,83
Max	6,75	15,49	4,29	10,43	13,45	27,56	8,34	4,64	11,01
Q3	2,74	5,24	1,31	6,31	4,69	15,48	2,94	0,92	3,30

	D>1500cc(Gy)	D>1000cc(Gy)	Dmax(Gy)	D1cc(Gy)	Dmax(Gy)	Dmax(Gy)	Dmax(Gy)	D0,35cc(Gy)	D1,2cc(Gy)
Q1	0,16	0,38	12,63	11,70	10,74	0,06	1,90	1,71	1,57
Min	0,03	0,07	9,16	7,92	0,97	0,03	0,77	0,72	0,69
Mean	0,45	0,85	18,16	15,46	12,15	0,76	2,27	2,01	1,85
Med	0,42	0,91	15,25	13,64	12,76	0,10	2,32	2,08	1,91
Max	1,49	2,31	29,29	23,18	19,23	4,18	3,79	3,27	2,96
Q3	0,60	1,08	25,56	21,08	15,83	0,22	2,79	2,44	2,24

Figure 4: Box plots of doses received by organs at risks. In dotted lines, the maximum tolerances for each organ. (ICD = implantable cardioverter-defibrillator)



VT number/period	6 months pre-treatment	0 - 6 weeks post-treatment	6 weeks - 6 months post-treatment	6 - 12 months post-treatment	12 months post-treatment
Q1	1,00	0,00	0,00	0,00	0,00
min	0,00	0,00	0,00	0,00	0,00
Mean	65,11	4,61	11,75	65,75	16,50
Med	22,00	0,00	0,00	0,50	0,50
Max	666,00	60,00	130,00	556,00	180,00
Q3	42,25	1,00	1,25	11,25	4,50

Shock number/period	6 months pre-treatment	0 - 6 weeks post-treatment	6 weeks - 6 months post-treatment	6 - 12 months post-treatment	12 months post-treatment
Q1	0,00	0,00	0,00	0,00	0,00
min	0,00	0,00	0,00	0,00	0,00
Mean	5,29	0,61	0,11	0,72	0,78
Med	2,00	0,00	0,00	0,00	0,00
Max	25,00	5,00	2,00	7,00	8,00
Q3	9,00	0,75	0,00	0,00	1,00

Figure 5: A: Evolution of total VT episodes and ICD shocks per patient before and after STAR. For the total VT number, patients are organized by recurrences during pre-treatment, ranging from greatest (bottom) to least (top). The patient number was kept the same for the total number of shocks to ensure consistency in the order, The heart symbol marks the transplanted patient, and stars denote deceased patients. B: Box plots of VT epidoses and ICD shocks per period. (VT = ventricular tachycardia).

Imaging Modality	Category inHEART	Name on inHEART	Segmented Structures on inHEART	Segmented Structures on Eclipse
Arterial CT (Angio-CT) on inHEART	**Left Heart Anatomy**	*LA ENDO*	Left atrial endocardium with pulmonary veins	
		LV ENDO	Left ventricular endocardium	
		LV EPI	Left ventricular epicardium	
		LV TRABEC	LV trabeculations and papillary muscles (PAPs)	
	Right Heart Anatomy	*RA ENDO*	Right atrial endocardium	
		RV ENDO	Right ventricular endocardium	
	Vessels	*AO*	Aortic arch	
		PAT	Pulmonary artery trunk	
		CS	Coronary sinus	
		PHRENIC LEFT	Left phrenic nerve	
		CORONARIES	Left and right coronary arteries	
	Other Structures	*FO*	Fossa ovalis	
		EPI	Left and right epicardium	
		GI TRACT	Gastrointestinal tract	
		AV NODE	Atrioventricular (AV) node	
	SBRT Target Volumes	*SBRT LV ENDO*	SBRT target: left ventricular endocardium (SBRT LV ENDO)	
		SBRT LV EPI	SBRT target: left ventricular epicardium (SBRT LV EPI)	
	Target	*Target CTV*	VT refractory	Target CTV
Late Enhancement CT on inHEART	**Arrhythmogenic Substrate**	*DARKCORE*	Fibrotic myocardial region ("darkcore") identified as the arrhythmia substrate	
MIP3 CT on Eclipse				ITV
AVE3 CT on Eclipse				PTV, Heart, Medullary canal, esophagus, great vessels, PBT, lungs, trachea, ICD probe, stomach, chest wall, ribs

Table 1: Segmented structures on inHEART and Eclipse for all treated patient. (SBRT = stereotactic body radiation therapy, CTV = clinical target volume, ITV = internal target volume, PTV = planning target volume, VT = ventricular tachycardia).

Organs	Constraints
PTV	D99% ≥ 25 Gy Acceptable deviation: D95% ≥ 25 Gy D2% ≤ 31,25 Gy (125% of the envelope dose)
ITV	Dose collected by 50% of the ITV = 30 Gy (100% DP) Dmax point must be located within the ITV

Organs	Constraints
Medullary canal	D0.35cc < 10 Gy
	D1.2cc < 7 Gy
	Dmax < 14 Gy
Esophagus	D5cc < 11.9 Gy
	Dmax < 15.4 Gy
Stomach	D10cc < 11 .2 Gy
	Dmax < 12.4 Gy
Great vessels	D10cc < 31 Gy
	Dmax < 37 Gy
Heart-PTV	D50% < 5 Gy
Trachea	D4cc < 10.5 Gy
Proximal bronchial tree	Dmax < 20 Gy
Lungs	D to>1500cc : < 7 Gy
	D to >1000cc : < 7.4 Gy
Chest wall	Dmax < 30 Gy D1cc < 22 Gy
Coronary arteries (IVA, Cx, IVD)	Dmax < 12-14 Gy (< 20 Gy on German consensus)
ICD	Dmax < 5 Gy

Table 2: Constraints used for organs at risk and ITV/PTV. (ITV = internal target volume, PTV = planning target volume, ICD = implantable cardioverter defibrillator)

Variable	N=18
Median age, y (range)	66 (45-90)
Sex, n (%)	
Male	18 (100)
Type of cardiomyopathy, n (%)	
Ischemic	15 (83.3)
Nonischemic	3 (16.7)
Median Left ventricular ejection fraction, % (range)	35 (10-64)
Median number of previous catheter ablation, n (range)	2 (1-4)
Device, n (%)	
ICD	17 (94.4)
Pacemaker	1 (5.6)
Current antiarrhytmic drugs, n (%)	
Amiodarone	4 (22.2)
β-blocker	2(11)
Amiodarone + β-blocker	9 (50)
Amiodarone + β-blocker + Mexiletine/Xylocaine	1 (5.6)
Sotalol + Mexiletine/Xylocaine	1 (5.6)
None	1 (5.6)
Median target volume, cc (range)	
Clinical target volume (CTV)	14.5 (4.3-32.6)
Internal target volume (ITV)	22.1 (5.2-49.2)
Planning target volume (PTV)	61.1 (20.9-109.8)
Median Heart volume, cc (range)	1459.1 (883.1-1726.7)

Table 3: Patients Demographics and targeting details. (ICD = implantable cardioverter defibrillator)