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CLINICAL RESEARCH

Evaluation of a second-generation intercostal extravascular implantable cardioverter defibrillator lead with a pectoral pulse generator for sensing, defibrillation, and anti-tachycardia pacing

Shephal K. Doshi [1], Reinoud E. Knops [2], Adrian Ebner[3], Michael Husby [4], Alan Marcovecchio [4], Rick Sanghera [4], Don Scheck[4], and Martin C. Burke [2,4,5]*

[1]Department of Electrophysiology, Pacific Heart Institute, Santa Monica, CA, USA; [2]Department of Clinical and Experimental Cardiology, Amsterdam UMC, Academic Medical Center, Meibergdreef 9, Amsterdam, The Netherlands; [3]Cardiovascular Department, Sanatorio Italiano, Asunción, Paraguay; [4]Research and Development Department, AtaCor Medical, Inc., 905 Calle Amenecer #360, San Clemente, CA 92673, USA; and [5]Childers Electrocardiology Lab, CorVita Science Foundation, 1006 S Michigan Ave, Suite 500, Chicago, IL 60605, USA

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Aims

Intercostal extravascular implantable cardioverter defibrillator (EV-ICD) leads may work better in contact with the pericardium thereby directing pacing and defibrillation energy towards excitable myocytes. We report 3-month safety and performance outcomes with a second-generation intercostal EV-ICD lead paired with standard, commercially available ICD pulse generators (PGs).

Methods and results

Subjects undergoing a transvenous ICD (TV-ICD) procedure received a concomitant intercostal EV-ICD lead system. The intercostal EV-ICD lead was connected sequentially to a PG in a left pectoral and then a left mid-axillary location. Extravascular ICD lead assessment included sensing and defibrillation of induced ventricular arrhythmias and pacing capture. The intercostal EV-ICD system was followed in a 'recording-only' mode and the control TV-ICD system in 'therapy delivery' mode to compare stored events. Devices were evaluated prior to hospital discharge, 2 weeks, 1 month, 2 months, and 3 months post-implant. Defibrillation testing was repeated prior to lead removal; 20/20 (100%) were successfully implanted (median implant time of 9 min). Two major lead complications were reported over a mean of 82 days: (i) lead movement and (ii) infection of both the TV-ICD and EV-ICD systems. Intraoperative pacing capture was achieved with the integrated bipolar configuration in 19 of 20 (95%) subjects. Pacing capture with the EV-ICD system was tolerated in all subjects, with over 90% feeling no pain after a 1-month recovery from the procedure. Induced VF episodes were sensed in all subjects and defibrillated successfully in 17 of 17 patients (100%) with a left mid-axillary PG and 19 of 20 patients (95%) with a left pectoral PG. Sensing and defibrillation were successful in 18 of 18 (100%) tested prior to lead removal.

Conclusion

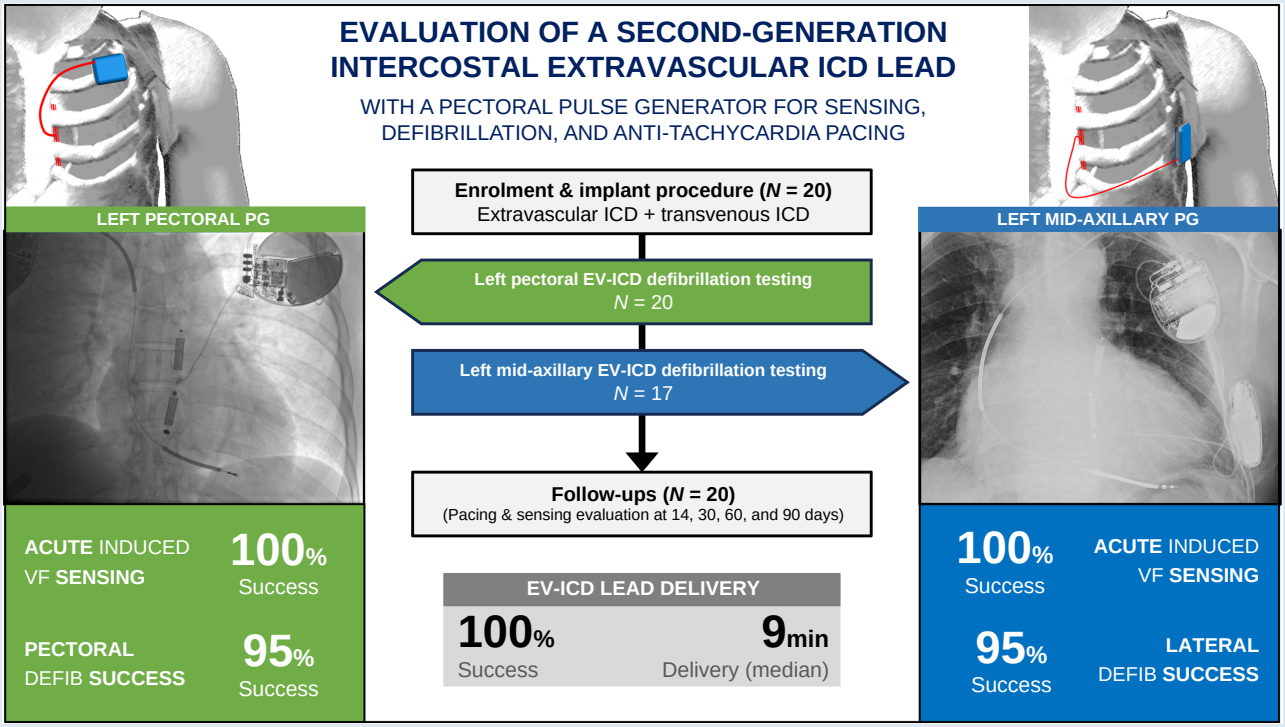
In this pilot experience with a second-generation intercostal EV-ICD lead implantation, sensing and defibrillation of induced VF were successful when paired with a standard ICD PG from either a left mid-axillary or pectoral pocket.

Clinical trial registration

NCT number: NCT05791032; URL: https://clinicaltrials.gov/study/NCT05791032

* Corresponding author. Tel: +1 (773) 432 4800. *E-mail address*: mburke@corvitahealth.org

Graphical Abstract



Keywords ICD • Extravascular • Defibrillation • Anterior mediastinum • Intercostal

What's new?

The data presented here provide further insight into the clinical science surrounding the burgeoning interest in extravascular defibrillation. The procedure presented provides new insights into an anterior approach along the left para-sternum with the following developments:

- Safety of placing an implantable cardioverter defibrillator (ICD) lead along the left para-sternum over the heart.
- Efficacy of sensing and defibrillating induced ventricular fibrillation.
- Pacing capture with a second-generation prototype ICD lead place along the left para-sternum over the heart.
- An acceptable patient sensation of high-output pacing with directed electrical impulses nearer to the heart in the anterior extravascular thoracic space.

Introduction

The implantable cardioverter defibrillator (ICD) is widely used for primary and secondary prevention of sudden cardiac death (SCD) among patients who are at high risk for, or who have a history of, ventricular tachyarrhythmia (VT) due to a variety of acquired or inherited cardiac conditions.[1,2] The mortality benefit conferred with transvenous ICDs (TV-ICDs) is not without risk of acute lead complications, including haemothorax, pneumothorax, cardiac perforation, and tamponade,[3–7] and delayed complications, which consist primarily of lead failures, venous thrombosis, and bloodstream infection.[8–13] In certain subpopulations, such as end-stage renal disease patients requiring dialysis, the risks of bloodstream infection and/or central venous stenosis outweigh potential benefit of TV-ICD implantation despite the high risk of SCD.[14] Additionally, TV-ICD lead placement may be precluded in patients with occluded or limited venous access, prior thoracic radiotherapy, or anomalous cardiac anatomy.[15,16] These shortcomings have spurred the development of alternative approaches that avoid vascular access and indwelling intravascular leads.[16–18]

Extravascular ICD (EV-ICD) systems provide an alternative to TV-ICDs. The commercially available subcutaneous ICD (S-ICD; Boston Scientific Corporation, Marlborough, MA, USA) has been shown to have low complication rates[19,20] and similar efficacy to the TV-ICD. However, the S-ICD requires implantation of a leadless pacemaker to provide pacing therapies and a unique ICD pulse generator (PG) capable of delivering higher energy shocks (80 J) and is, therefore, larger than modern TV-ICDs. Placement of extravascular defibrillation electrodes below the sternum and ribs facilitates less shock energy for defibrillation, smaller PGs, and the addition of pacing options not available with the S-ICD.[21] To that end, a substernal EV-ICD lead (Epsila EV™ MRI SureScan™ defibrillation lead, Medtronic, Inc., Minneapolis, MN, USA) has been developed for substernal implantation from a subxiphoid incision. Friedman *et al.*[22] reported successful substernal implantation in 299 of 316 subjects (95%) with no procedural complications observed. Shock termination of induced ventricular arrhythmias was successful in 298 of 302 subjects (98.7%) when connected to a custom EV-ICD PG (Aurora EV-ICD™ System, Medtronic, Inc., Minneapolis, MN, USA) placed into a left mid-axillary pocket. However, inadequate distal lead fixation with the substernal EV-ICD lead design makes it susceptible to migration in the cranial-caudal axis, which has resulted in oversensing of P waves when the sensing electrodes migrate to a location over the left atrial appendage.[22,23]

Additionally, the substernal implant approach requires tunnelling close to the dorsal side of the sternum, which typically places electrodes at a distance from the pericardium. That distance greatly increases the amount of electrical current required for pacing capture, often resulting in pain during pacing and thus defeating the purpose of anti-tachycardia pacing (ATP) as a pain-free means of terminating VTs. These disadvantages are addressed by the new intercostal EV-ICD lead (Atala™ EV-ICD lead, AtaCor Medical, Inc., San Clemente, CA, USA), which is designed to (i) prevent lead movement along the cranial-caudal axis; (ii) minimize pacing current demand by placing electrodes in contact with the pericardium; and (iii) minimize current flow back towards skeletal muscle of the chest wall by backing pacing electrodes with an insulative substrate.

The new intercostal EV-ICD lead is uniquely designed to access the mediastinum via an anterior, left parasternal approach using a custom delivery tool. Published acute and 3-month results[23] from the first design iteration demonstrated safety and feasibility, with successful sensing, detection, and defibrillation of induced ventricular arrhythmias in 27 of 27 (100%) subjects implanted with an intercostal EV-ICD lead connected to a commercially available ICD PG placed in a left mid-axillary pocket. This report describes acute and 3-month safety and performance of the second-generation intercostal EV-ICD lead system designed to further improve pacing capture.

Methods

Study design

The Sub Chronic Evaluation for ATP with an Extravascular Placed ICD Lead Study (STEP ICD Study; NCT05791032) was a prospective, single-centre, exploratory, early feasibility, non-randomized study. The STEP ICD Study was approved by the ethics committee (El Comité de Ética de la Investigación del Instituto Paraguayo de Estudios Sociales) and complied with Paraguayan national regulations and the Declaration of Helsinki. All subjects gave informed consent prior to study enrolment.

The STEP ICD Study did not attempt to gain ethics approval in the USA or EU for these studies due to the perceived Food and Drug Administration (FDA; Washington DC, USA) and Notifying Body (European Union) requirements for early prototype EV lead systems. The time and resources necessary to complete the feasibility testing in Paraguay was more efficient in moving from one prototype to the next. A reality in Paraguay is that there were many patients in need of ICD therapy who were unable to have access for a variety of cardiomyopathies including ischaemic, Chagas disease, arrhythmic right ventricular cardiomyopathy (ARVC), and non-ischaemic disease. Hence, the governmental regulatory body and ethics committee were more liberal that more affected citizenry could access ICD implants *de novo* or as a PG change despite economic hardship. The novelty of this EV ICD approach using commercially available ICD systems warranted a series of small feasibility studies where having the matched sensing events with the TV ICD standard of care allows our clinical science team to move through three prototype leads making iterative improvements very quickly. Another clinical reason was that there were no animal or non-human models to substitute for the STEP ICD 20 patient cohort.

Subjects undergoing a TV-ICD procedure received a concomitant investigational intercostal EV-ICD lead coupled with a passive commercially available ICD PG from one of four manufacturers (Abbott Laboratories, Chicago, IL, USA; Biotronik, Berlin, DE; Boston Scientific Corporation, Marlborough, MA, USA; Medtronic, Inc., Dublin, IE) for induced ventricular arrhythmia testing in both a left pectoral pocket and left mid-axillary pocket. The PGs were identically paired for acute defibrillation testing pectoral and lateral. The PGs were not matched for chronic sensing as only Boston Scientific and Medtronic could sense with therapies off. The PG mismatches for chronic implant data were seen in 8/20 (40%) patients (see *Table 1*). Sensing programming was selected (rate cut-off and discrimination algorithms) as close as possible when PG mismatching was necessary. Echocardiography before and after intercostal EV-ICD lead deployment was used to check for pericardial effusions. Electrical parameters, including R-wave amplitude, pacing impedance, and pacing capture threshold, were measured with a standard pacing system analyser (PSA) in dedicated bipolar and integrated bipolar vectors. Subjects were discharged with the investigational intercostal EV-ICD system in a 'record-only' mode and the control TV-ICD system in an active 'therapy delivery' mode. Detection zones were matched to allow comparison of stored events between the two systems over the follow-up period. Postoperative follow-up visits were conducted at hospital discharge, 2 weeks, 1 month, 2 months, and 3 months. Device evaluations were conducted at each follow-up visit to collect standard electrical measurements and download recorded device information. At the final follow-up visit, defibrillation testing was repeated with an abbreviated protocol, and the investigational intercostal EV-ICD system was explanted. Subjects remained in the study for an additional 30 days to monitor for latent adverse device effects.

Table 1 Pulse generator pairing for acute and chronic testing

	PG used for acute EV defibrillation testing	ICD manufacturers used for paired sensing analysis	
n		EV-ICD (therapy OFF)	TV-ICD (therapy ON)
6	Boston Scientific	Boston Scientific	Boston Scientific
6	Medtronic	Medtronic	Medtronic
6	Abbott	Boston Scientific	Abbott
2	Biotronik	Boston Scientific	Biotronik

EV-ICD, extravascular implantable cardioverter defibrillator; PG, pulse generator; TV-ICD, transvenous implantable cardioverter defibrillator.

Study population

Eligible subjects included adult patients at least 18 years old who were scheduled to undergo *de novo* or replacement ICD procedures. Key exclusions from the study included the following: subjects with known structural abnormalities of the thorax; subjects with a prior sternotomy or prior surgery disrupting the pericardium or tissue outside the pericardium; prior chest radiation, pericardial disease, or mediastinitis; severe lung disease or known obstruction of the intended insertion location; and New York Heart Association function classification IV.

Endpoints

The primary performance endpoint was successful sensing and termination of induced ventricular arrhythmias up to 3 months post-implant. The primary safety endpoint was the incidence of adverse device effects. As a feasibility study, endpoint results were reported with standard summary statistics without pre-specified hypothesis tests. Secondary endpoints included pacing performance of the intercostal EV-ICD lead measured with an external PSA as well as using commercially available ICD PGs and the assessment of pacing sensation/pain during standard device checks (without anaesthesia) in follow-up.

Intercostal extravascular implantable cardioverter defibrillator lead description and implantation

The intercostal EV-ICD lead system (AtaCor EV-ICD Lead System, AtaCor Medical, Inc., San Clemente, CA, USA) is designed for anterior delivery of an extravascular defibrillator lead through an intercostal space along the left parasternal margin over the heart. The delivery tool is specific to the intercostal EV-ICD lead allowing for safe delivery against the outer layer of the pericardium over the heart. The intercostal EV-ICD lead has 564.6 mm^2 of defibrillation coil surface area divided between two symmetrical, electrically connected coil segments (see *Graphical Abstract*). The pace/sense electrodes allow various options for pace/sense vectors, including dedicated bipolar (near field, between the two pace/sense electrodes), integrated bipolar

(between either pace or sense electrode and the defibrillation coil) and far-field sensing vectors. The DF-4 standard lead connector is designed for compatibility with commercially available ICD PGs.

Implant procedures were previously described in detail.[24] In brief, patients were placed under general anaesthesia in a hybrid cardiac suite by experienced electrophysiologists with prior didactic and hands-on training and were overseen by a cardiovascular surgeon. Surgical preparation of subjects included placement of external defibrillator pads, standard electrocardiogram (ECG) electrodes, and an arterial line.

The TV-ICD procedure (*de novo* or replacement) was performed prior to initiation of the intercostal EV-ICD lead implant procedure, making the TV-ICD lead available for backup pacing and/or induction of VF for acute testing. An echocardiogram was performed to assess pericardial effusion following transvenous lead implant.

The incision for the intercostal EV-ICD lead was made over the target intercostal space adjacent to the left sternal margin, an area that typically resides within the cardiac notch of the left lung targeting the convexity of the heart to the sternum in the lateral 90° fluoroscopy view. The incision was made vertically along the left parasternal margin to allow for access to a choice of intercostal spaces. An 18-gauge needle was used to pierce the endothoracic fascia of the ribs and to pass a 0.035 J tip wire into the anterior mediastinal space above the heart. A custom EV-ICD dilator tool (AtaCor Medical, Inc., San Clemente, CA, USA) was inserted over the wire to expand the fascia and create tissue space for the EV-ICD delivery tool. The intercostal EV-ICD lead was preloaded into the EV-ICD delivery tool and locked in place and the blunt tip of the tool was advanced to the area anterior of the pericardium while being monitored using 90° lateral fluoroscopy. The deployment actuator was then unlocked, and the lead coils of the intercostal EV-ICD lead were deployed smoothly onto the pericardium in a superior and inferior direction. Following delivery tool removal, the intercostal EV-ICD lead was secured to the anterior chest fascia and tunnelled to the left pectoral pocket or left mid-axillary pockets.

Defibrillation testing

All subjects with successful intercostal EV-ICD lead placement underwent intraoperative defibrillation testing with the PG in the left pectoral location. Subjects with intercostal EV-ICD leads pre-determined to be connected to a left mid-axillary ICD PG ($n = 17$) were tested first in the left pectoral location with an abbreviated defibrillation safety margin test protocol without tunnelling the lead under the skin. Subsequently, EV-ICD leads were tunnelled to the PG in the left mid-axillary location for step-down defibrillation testing. Subjects pre-determined to be connected to a left pectoral PG ICD ($n = 3$) were tested using a step-down defibrillation protocol in the left pectoral location only, without any testing in the left mid-axillary location.

Ventricular arrhythmias were induced using the intercostal EV-ICD lead, TV-ICD lead, or temporary pacing wire. Induced episodes were sensed and treated with the intercostal EV-ICD lead and automatic sensing and detection algorithms integral to the connected commercially available ICD PG.

Pacing, sensation, and anti-tachycardia pacing testing

The second-generation intercostal EV-ICD lead design was an iterative advance to further improve pacing performance compared with the lead system previously described.[24] Pacing data were systematically collected in different vectors to understand directed current fields from outside the heart. In selected cases, patients with cardiomyopathies leading to monomorphic VTs underwent programmed stimulation inductions to assess capability of extravascular directed fields of pacing to terminate VT via overdrive pacing. In ambulatory follow-up, each patient visit included pacing capture threshold testing as well as sensation from maximum output of the PGs used. Sensation/pain was characterized as no sensation, sensation only, tolerable pain, or intolerable pain at maximum pacing output in the supine and upright positions.

Sensing evaluation and implantable cardioverter defibrillator programming

Sensing and detection algorithms represented by various ICD manufacturers were evaluated during induced ventricular arrhythmia testing at post-discharge prior to lead removal, as well as during ambulatory activity by concomitant TV-ICD and intercostal EV-ICD systems that were programmed with matching tachycardia cut-off rates activated in both devices. The TV-ICD system remained with therapy active and the intercostal EV-ICD system with therapies off.

Statistical analysis

Descriptive statistics were used for demographics, medical history, procedure times, electrical parameters, induced episode sensing, and lowest successful defibrillation testing. The study was not powered for pre-specified statistical hypothesis tests.

Results

Twenty-one subjects were enrolled between September 2023 and January 2024 and 20 subjects underwent an intercostal EV-ICD lead implant procedure. One subject was withdrawn by the investigator prior to the procedure due to anaesthesia risk. The disposition of all study subjects is shown in *Figure 1*. All the patients were enrolled in Paraguay and the entire study was performed in Paraguay.

The study cohort was predominantly male (80%) with a mean age of 57 (range 26–84) years. The mean body mass index was 29 kg/m^2 (range 21–35). The main indication for ICD therapy was secondary prevention (65%) with non-ischaemic cardiomyopathy reported in 58% of subjects. Baseline characteristics are presented in *Table 2*.

Implantation procedure

Two physicians performed 20 successful implantation procedures with a median time from incision to the final placement of the intercostal EV-ICD lead (before tunnelling and suturing) of 9 min (Interquartile Range [IQR] 7, 15). Using a PSA programmed with a 1.5 ms pulse width, pacing capture was demonstrated in 19 subjects (95%) using the integrated bipolar configuration (pace/sense cathode to coil) and in 17 subjects (85%) using the dedicated bipolar configuration (pace/sense cathode to pace/sense anode). Mean intraoperative R-wave amplitude, pacing impedance, and pacing capture threshold are presented in *Table 3*.

Defibrillation testing

Intraoperative defibrillation testing was conducted with PGs from Abbott Laboratories ($n = 6$), Biotronik ($n = 2$), Boston Scientific ($n = 6$), and Medtronic ($n = 6$). Successful defibrillation was observed in 17 of 17 (100%) subjects with a left mid-axillary PG position (mean lowest defibrillation energy of 14.5 J, delivered). The percentage of subjects successfully converted at incrementally higher energies is shown in *Figure 2*. With the left pectoral PG position, defibrillation was achieved in 19 of 20 (95%) subjects. In one subject with a large body habitus (2 m tall and 33 kg/m^2 body mass index), defibrillation was not achieved with left pectoral PG location; however, subsequent testing with the PG in the left mid-axillary position resulted in successful defibrillation with 10 J. Mean intraoperative shock impedance was 76 Ω ($n = 42$ shocks; SD 15; range 54–110 Ω) in shocks delivered from a left mid-axillary ICD PG and 73 Ω ($n = 35$ shocks; SD 13; range 50–93 Ω) in shocks delivered from a pectoral ICD PG. Of note, one induced ventricular arrhythmia was successfully pace terminated with ATP, as shown in *Figure 3*.

At the intercostal EV-ICD lead removal visit (mean of 82 days post-implant), defibrillation was successful in 18 of 18 (100%) subjects tested and successful with a 10 J safety margin in 16 of 18 (89%) subjects. Two subjects were not tested at the lead removal visit at the discretion of the investigator for medical reasons (one subject with infection of both the TV-ICD and EV-ICD Systems on Day 6 and one subject with sinus node dysfunction at the lead removal visit). Mean shock impedance at the lead removal visit was 66 Ω ($n = 17$ shocks; SD 14; range

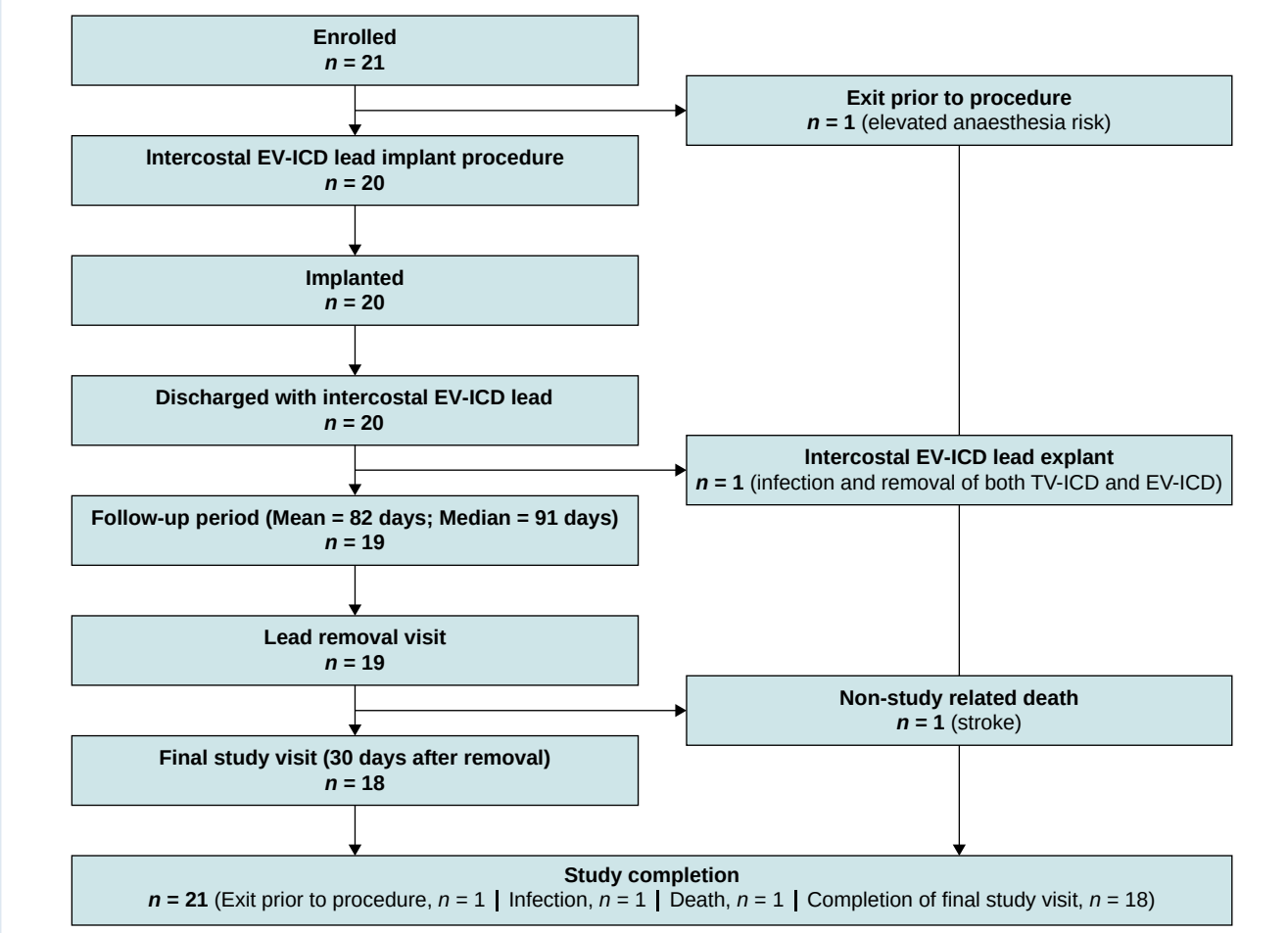


Figure 1 The STEP ICD Study enrolled patient disposition. EV-ICD, extravascular implantable cardioverter defibrillator; TV-ICD, transvenous implantable cardioverter defibrillator.

46–94 Ω) in shocks delivered from a left mid-axillary ICD PG and 64 Ω ($n = 5$ shocks; SD 13; range 57–88 Ω) in shocks delivered from a left pectoral ICD PG.

All 20 (100%) subjects demonstrated the ability to automatically sense, detect, and shock induced ventricular arrhythmias. A complete summary of detection time and time to therapy is presented in *Table 4*.

Ambulatory sensing

Ambulatory sensing performance of the intercostal EV-ICD lead was assessed by comparing stored events from the investigational passive intercostal EV-ICD lead system with those of the control active TV-ICD system to determine if the intercostal EV-ICD lead introduced challenges for sensing architectures of the commercially available PGs.

In 18 of 20 (90%) subjects, sensing performance matched between systems, indicating excellent performance of the intercostal EV-ICD lead compared with transvenous. Two subjects had differing stored events between the systems: (i) in one subject, two non-sustained ventricular tachycardia episodes were appropriately recorded only by the intercostal EV-ICD lead system due to a mismatch of ICD manufacturer of the EV-ICD and TV-ICD, which used different duration criteria for arrhythmia declaration; and (ii) in one subject, the intercostal EV-ICD system alone recorded six episodes due to non-cardiac signals (noise). Notably, the sensitivity had been programmed to the most sensitive setting with the amplitude attenuation filter turned off.

There were no sustained ventricular arrhythmias documented by either the intercostal EV-ICD or TV-ICD systems in the study. In two subjects, the intercostal EV-ICD and TV-ICD systems both sensed a high ventricular rate from a conducted supraventricular tachycardia (SVT), leading both systems to inappropriately declare episodes based on incorrect PG rhythm discrimination algorithm decisions. The intercostal EV-ICD lead and transvenous lead demonstrated equivalent performance in terms of signal transmission to the ICD PG.

Rate sense/pacing

In the integrated bipolar pacing configuration, capture was achieved with the intercostal EV-ICD lead system in 19 of 20 (95%) subjects at implant (mean threshold = 5.7 V, SD 3.3) and 19 of 20 (95%) at explant (mean threshold = 7.4 V, SD 4.0). In the dedicated bipolar configuration, capture was achieved in 17 of 20 (85%) subjects at implant (mean threshold = 8.5 V, SD 4.3) and in 15 of 20 (75%) subjects (mean threshold = 10.1 V, SD 4.8) at explant. Of note, one induced ventricular tachycardia was pace terminated with ATP from the EV-ICD lead. A summary of all sensing and pacing measurements taken with the intercostal EV-ICD lead system throughout the study is shown in *Table 5*. Only one (5%) subject reported intolerable pacing sensation

at the pre-discharge visit, which diminished to sensation only by the lead removal visit. Over 90% of subjects felt no pain at all after a 1-month recovery from the implant procedure (*Figure 4*). There were no reports of intolerable pacing sensation after the pre-discharge visit.

Extravascular implantable cardioverter defibrillator safety

Two major intercostal EV-ICD lead complications were reported in the study: (i) one subject required a lead revision on Day 1 due to lead movement and (ii) one subject required explant procedures to remove both the TV-ICD and EV-ICD systems on Day 6 following the discovery of infection at each PG incision site. The subject was discharged on oral antibiotic therapy to resolve the infection before study exit and evaluation for a new TV-ICD system. There were no new or worsened pericardial effusions related to the intercostal EV-ICD lead or its delivery as confirmed by echocardiography. One subject died during the post-explant follow-up period due to a stroke unrelated to the intercostal EV-ICD lead system or procedure.

Table 2 Baseline patient characteristics

Attribute	Implanted subjects $n = 20$
Female, no. (%)	4 (20%)
Age, mean (SD), year	57 (15)
Height, mean (SD), cm	173 (9)
Weight, mean (SD), kg	86 (15)
BMI, mean (SD), kg/m^2	29 (4)
LVEF, mean (SD), %	54 (14)
ICD indication	
Primary, no. (%)	7 (35%)
Secondary, no. (%)	13 (65%)
Heart failure class, no. (%)	
None, no. (%)	4 (20%)
NYHA Class I, no. (%)	3 (15%)
NYHA Class II, no. (%)	12 (60%)
NYHA Class III, no. (%)	1 (5%)
Coronary artery disease, no. (%)	4 (20%)
Myocardial infarction, no. (%)	7 (35%)
Atrial fibrillation, no. (%)	3 (15%)

BMI, body mass index; ICD, implantable cardioverter defibrillator; NYHA, New York Heart Association; LVEF, left ventricular ejection fraction.

Discussion

Major findings

This study of a second-generation intercostal EV-ICD lead inserted via the anterior mediastinum through an intercostal space along the left parasternal margin provides further evidence of safety and feasibility. The intercostal EV-ICD lead demonstrated appropriate sensing and defibrillation of induced ventricular arrhythmias using commercially available DF-4 compatible ICD PGs placed within a left mid-axillary or left pectoral pocket. Automatic sensing of induced and spontaneous ventricular arrhythmias was reliably achieved using ICD PGs from multiple manufacturers, representing a variety of sensing and detection algorithms. Particularly interesting in these data is the performance of the left pectoral pocket as a viable option using the intercostal EV-ICD lead system. All commercially available EV-ICD systems[21–28] require a left mid-axillary chronic pocket in their final design limiting implanters to this operative platform. Expanding the operative approach to include the left pectoral pocket gives patients and implanters more clinical options and logically advances EV-ICD system use.

Defibrillation energy

Defibrillation energy requirements in this study are similar to transvenous and the substernal EV-ICD lead system.[21–23,26–28] Results from the STEP ICD Study demonstrate that a 10 J safety margin can be reliably achieved with the second-generation intercostal EV-ICD lead connected to standard ICD PGs placed in a left mid-axillary position or, in most patients, a left pectoral position. Flexibility in PG pocket location allows for the use of alternate shock vectors, which may be useful for troubleshooting, and may avoid the need for an additional incision in replacement procedures with patients with fractured TV-ICD leads. The long-term/chronic performance of the substernal EV-ICD system, with similar shock vector and PG location, demonstrated similar acute testing defibrillation energy requirements as compared with the STEP ICD data presented here.[28]

Implant, lead design, and extraction safety

This study adds to the safety profile of the intercostal EV-ICD lead implant procedure. The unique anterior chest implantation approach employed by the intercostal EV-ICD continues to prove straightforward, with 100% implant success and a median implant time of 9 min, which compares favourably with published data from other EV-ICD systems.[21–27] Intercostal EV-ICD lead placement in contact with the pericardium contrasts with the Epsila EV™ MRI SureScan™ (Medtronic, Inc., Minneapolis, MN, USA) substernal lead implantation procedure,

Table 3 Intraoperative pacing measurements by varying electrode vector (PSA)

	R-wave amplitude (mV)		Pacing impedance (Ω)		Capture at PSA max output (mA)		Capture Threshold (mA)	
	Mean (SD), *n*		Mean (SD), *n*		No. (%), *n*		Mean (SD), *n*	
	Dedicated Bipolar	Integrated Bipolar	Dedicated Bipolar	Integrated Bipolar	Dedicated Bipolar	Integrated Bipolar	Dedicated Bipolar	Integrated Bipolar
Intraoperative measurement	3.4 (1.7), 20	2.8 (1.7), 20	1008 (340), 20	497 (265), 20	17 (85%), 20	19 (95%), 20	8.5 (4.3), 17	5.7 (3.3), 19

PSA, pacing system analyser.

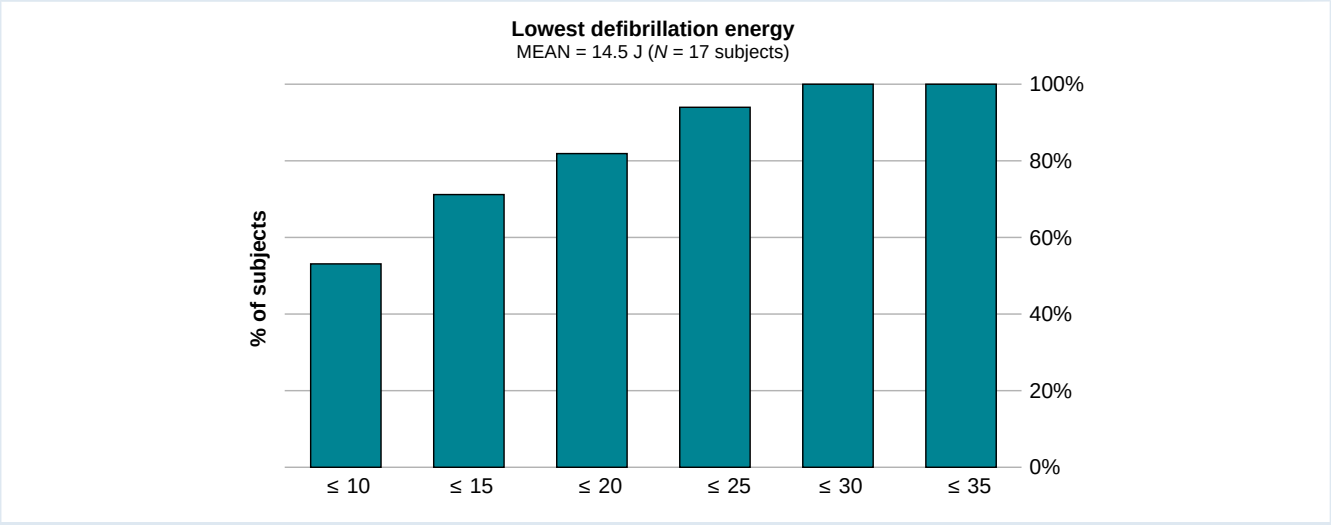


Figure 2 Acute defibrillation performance with a mid-axillary PG. Cumulative percentage of subjects successfully converting induced ventricular fibrillation at incrementally higher energy levels from a mid-axillary implanted PG. The maximum energy from the implanted PGs ranged from 36–41 J. J, Joules.

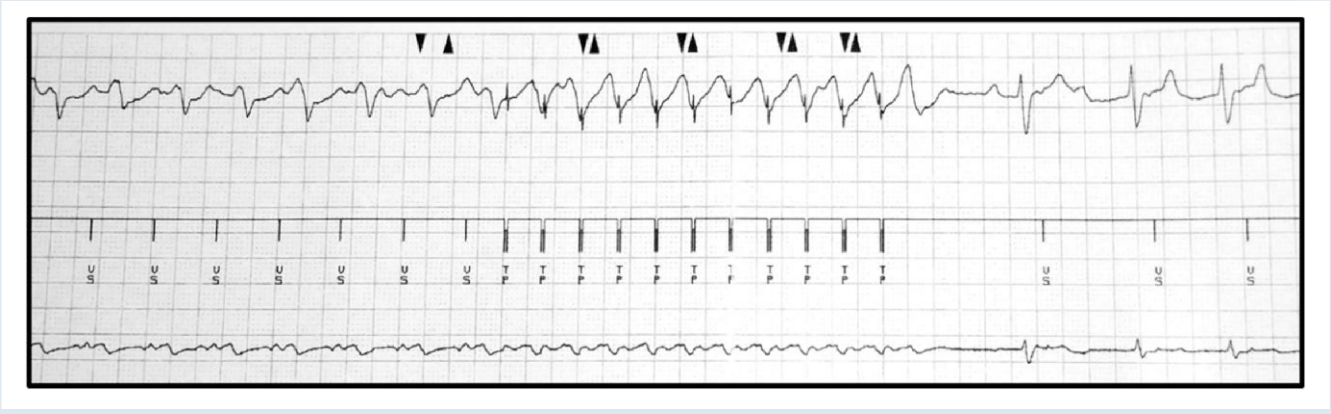


Figure 3 Extravascular ICD pace termination of induced ventricular tachycardia post-implant. The recorded electrogram illustrates an ATP entrainment of induced (programmed stimulation) monomorphic ventricular tachycardia at a cycle length of 480–520 ms. The top ECG is a surface lead. The middle tracing is the device's marker channel. The bottom ECG is an extracardiac electrogram. The slow ventricular tachycardia is entrained with overdrive pacing at 350 ms and exhibits a Type I termination to sinus rhythm post extracardiac pacing.

Table 4 Induced ventricular arrhythmia detection time and time to therapy

Detection time (seconds)		Time to therapy (seconds)	
Mean (SD), *n*	**Median (range)**	**Mean (SD), *n***	**Median (range)**
5.7 (2.0), 74	5.2 (4.2, 7)	11.0 (3.2), 73	10.9 (9.4, 12.7)

which requires the lead to be placed at a distance from the heart during the implant procedure by closely following the dorsal side of the sternum.

With the intercostal EV-ICD pace/sense electrodes placed on an insulative backing, pacing current is directed towards the heart and impeded in the direction of the skeletal muscles. This contrasts with the use of ring electrodes on the substernal EV-ICD lead, which create a circular pacing field that can capture the skeletal muscles of the chest wall, potentially causing more pain with pacing as well as sensing fields that include non-cardiac and unintended cardiac signals such as P waves.[22] P-wave oversensing was not seen with any patients with the intercostal EV-ICD lead implanted. The STEP ICD Study, in combination with prior feasibility studies,[24] demonstrates robust chronic sensing when R waves are greater than 1 mV at implant. Inappropriate recorded events were from non-cardiac signals when the R waves were lower than 1 mV.

The second-generation intercostal EV-ICD lead features shorter coil segments than the original version, which potentially lowers the risk of pneumothorax without affecting defibrillation performance. The new

Table 5 Pacing and sensing measurements using implanted commercial ICD PGs

	R-wave amplitude (mV)		Pacing impedance (Ω)		Low-voltage shock impedance (Ω)		Capture at max output	Pacing capture threshold (V)	
	Mean (SD), *n*	Median (range)	Mean (SD), *n*	Median (range)	Mean (SD), *n*	Median (range)	No. (%), *n*	Mean (SD), *n*	Median (range)
Implant	3.6 (2.1), 20	3.3 (0.9, 10.5)	876 (405), 20	808 (390, 2160)	72 (15), 20	73 (46, 110)	10 (50%), 20	5.0 (2.0), 10	4.3 (3.1, 8.0)
Pre-discharge	3.3 (1.6), 19	3.3 (1.1, 6.8)	526 (215), 19	456 (304, 1161)	54 (10), 19	54 (37, 80)	11 (61%), 18	5.4 (1.6), 11	5.0 (3.3, 8.0)
14 days	3.4 (2.0), 18	3.2 (0.6, 6.6)	540 (143), 18	509 (305, 885)	57 (11), 18	58 (38, 83)	2 (13%), 16	8.0 (0.0), 2	8.0 (8.0, 8.0)
30 days	3.3 (2.1), 18	2.6 (0.9, 7.5)	627 (164), 18	571 (428, 963)	62 (12), 18	61 (36, 91)	3 (17%), 18	5.0 (2.8), 3	5.5 (2.0, 7.5)
60 days	4.9 (2.2), 11	4.6 (0.9, 8.1)	752 (206), 11	700 (589, 1269)	76 (16), 11	72 (58, 115)	3 (27%), 11	4.8 (1.1), 3	4.3 (4.0, 6.0)
90 days	4.1 (2.0), 16	3.7 (1.6, 7.8)	727 (184), 16	656 (557, 1168)	70 (16), 16	69 (49, 99)	2 (13%), 15	6.3 (1.8), 2	6.3 (5.0, 7.5)
Subject's final follow-up	3.8 (1.9), 20	3.2 (1.3, 7.8)	681 (196), 20	632 (399, 1168)	67 (17), 20	67 (36, 99)	4 (21%), 19	5.3 (1.6), 4	4.8 (4.0, 7.5)

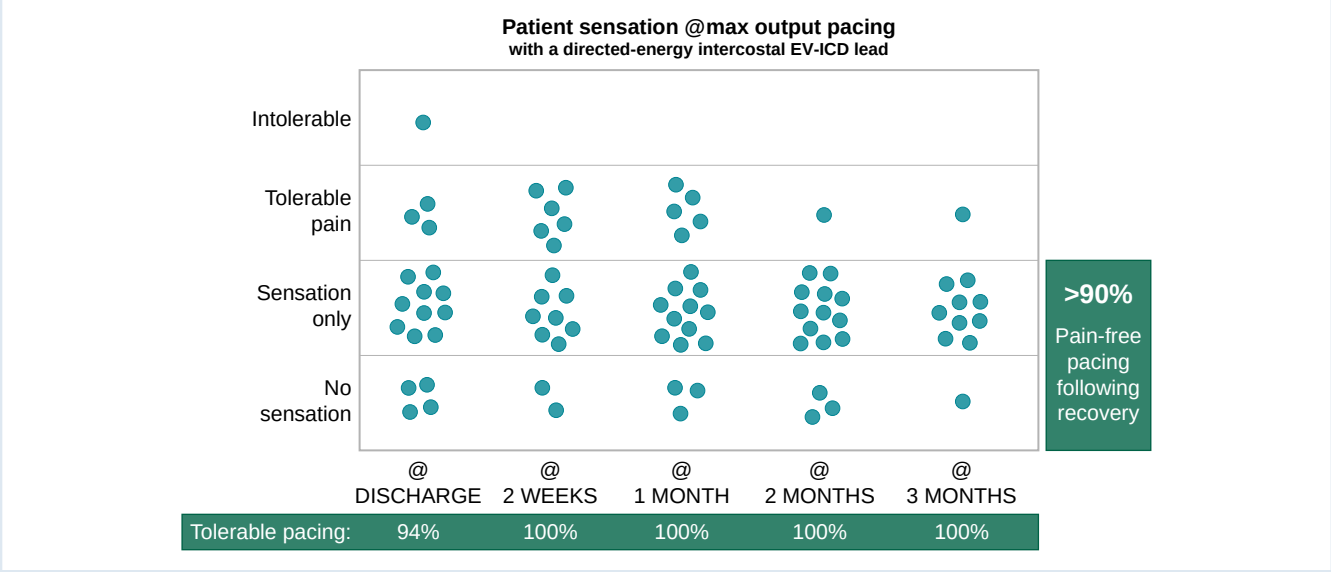


Figure 4 Patient-reported pacing sensation at maximum output of the EV-ICD PG. This graphic shows the patient reported sensation during maximum pacing output from the implanted commercial ICD PG connected to the EV-ICD lead over the entire term of implant. The trend demonstrates a lack of intolerable pain during pacing post discharge. The pacing sensation shows a clear improvement in tolerability and sensation to high-output pacing over time. EV-ICD, extravascular implantable cardioverter defibrillator; Intolerable, intolerable pain; MAX, maximum.

intercostal EV-ICD lead is also easier[24] to extract than the original with every lead completely extracted without complication after 90 days of implant. Sagi *et al.*[29] analysed the removal of the substernal EV-ICD lead with a mean indwell time of over 12 months demonstrating a 93.1% removal rate and a successful re-implant in 11/11 patients achieved. There were no serious complications. The EV-ICD lead design, including design features for successful extraction when clinically necessary, is extremely important.

Pacing success and sensation

The second-generation intercostal EV-ICD lead used in the STEP ICD Study includes a pacing cathode electrode located on the inferior paddle of the lead, which improved pacing performance over the first-generation design with the cathode recessed between the paddles. Pacing capture thresholds in the STEP ICD Study are comparable with the primary pacing vector (ring 1 to coil) of the substernal Aurora EV-ICD™ System (Medtronic, Inc., Minneapolis, MN, USA), which reported[22] pacing capture thresholds 4.9 ± 2.0 V (1.5–8.0 V, $n = 239$) at implant and 5.5 ± 2.0 V (1.0–8.0 V, $n = 155$) at 6 months, with pacing sensation intolerance reported in 47/284 (17%) subjects. The much smaller STEP ICD Study demonstrated no instances of intolerable sensation/pain at device maximum outputs after discharge, suggesting an important benefit from placing the pacing electrodes on the pericardium, directing the pacing current towards the myocardium, and impeding current in the direction of skeletal muscle. The STEP ICD

Study pacing results provide the foundation for successful pacing and patient acceptance with a third-generation lead, which is currently under development for use in a pilot study and subsequent pivotal study.

Study limitations

This feasibility study of a second-generation intercostal EV-ICD lead is limited to a 3-month assessment of induced sensing and defibrillation within a single-centre implanting a small study group by two operators. Moving forward, the involvement of more operators is important to further characterize the safety of the intercostal EV-ICD lead insertion procedure. The planned longer-term follow-up of the anteriorly placed intercostal EV-ICD lead in a larger cohort as the sole implanted ICD system is essential.

Conclusions

The STEP ICD study showed that with a parasternal extravascular defibrillation lead placed in the mediastinum through an intercostal space, connected to various DF-4 commercially available ICD PGs, sensing was appropriate and both mid-axillary and left pectoral PG placement resulted in a successful defibrillation vector.

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Data availability

The data underlying this article will be shared at reasonable request to the corresponding author. Selected raw data are generally available at ClinicalTrials.gov using STEP ICD Study; NCT05791032.

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