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Catheter Ablation of Ventricular Arrhythmia guided by a High-Density Grid Catheter.

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Short title: Procedural Characteristics of **Advisor™ HD** Grid in Ventricular Arrhythmias

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Abstract

Introduction

Minimal data exists on the Advisor™ HD Grid (HDG) catheter and the Precision™ electroanatomic mapping system (EAM) for ventricular arrhythmia (VA) procedures. Using the HDG catheter the EAM uses the HD wave mapping and best duplicate software to compare the maximum peak-to-peak bipolar voltages within a small zone independent of wavefront direction and catheter orientation. The study aimed to summarise the procedural experience for VAs using the HDG catheter.

Methods

Clinical and procedural characteristics of VA ablation procedures were retrospectively reviewed that used the HDG catheter and the Precision^{TM} EAM over a 12-month period.

Results

Twenty-two patients, 18 with sustained ventricular tachycardia and 4 with premature ventricular contractions were included. Clinically indicated left and/or right ventricular (LV, RV, respectively), and aortic maps were created. LV substrate maps (n=13) used a median 1700 points (IQR$_{25-75\%}$ 1427-2412) out of a median 18,573 (IQR$_{25-75\%}$ 15,713-41,067) total points collected. RV substrate maps (n=11) used a median 1435 points (IQR$_{25-75\%}$ 1114-1871) out of a median 16,005 (IQR$_{25-75\%}$ 11,063-21,405) total points collected. Total point utilisation, used vs collected, was 9%. Mean mapping time was 43±17mins (substrate 34±18mins; activation/pace mapping 9±13mins). Acute success was achieved in 56 (86%) and short-term success achieved in 16 patients (73%) at median follow up of 145 days [IQR$_{25-75\%}$62-273 days]). There were no procedural complications.

Conclusion

HD wave mapping using the novel HDG catheter integrated with the Precision^{TM} EAM is safe and feasible in VA procedures in the LV, RV and Aorta. Mapping times are consistent with other multi-electrode mapping catheters.

Keywords: Ventricular Arrhythmias, Electrophysiology, Catheter Ablation, Multi-electrode mapping, Electroanatomic mapping.

Introduction

High density multi-electrode mapping (MEM), when compared to point-by-point mapping is now established as the preferred method during catheter ablation of ventricular arrhythmias (VA). When compared to point-by-point mapping, a high-density mapping approach is associated with greater mapping resolution of scar and delineation of conducting channels, resulting in shorter procedure times, and superior arrhythmia-free survival.[1-3] A number of MEM catheters, integrated with electro-anatomic mapping systems (EAM) are now commercially available that allow rapid, ultra-high density data collection.[4] A novel, equally-spaced orthogonal electrode catheter, Advisor™ HD Grid Sensor Enabled (HDG; Abbott Medical, Abbott Park, IL, USA) integrated with an EAM (Precision™, Abbott Medical, Abbott Park, IL, USA) has become clinically available. The EAM uses a novel algorithm, HD Wave solution,[5] that seeks to find the maximal voltage within a small region of bipolar electrode recording sites. During mapping the largest bipolar EGM is selected, independent of catheter orientation or direction of wavefront (Figure 1). There is limited published data on the utility of this system. We report the clinical and procedural characteristics of catheter ablation of VAs guided by mapping utilising the novel Advisor™ HDG catheter.

Methods

Between April 2018 and May 2019, 22 patients presenting with VA that had EAM performed with Precision™ and the HDG catheter were identified. Written informed consent was obtained in all cases as part of routine clinical care. Analysis of this data was approved by the Human Research Ethics Committee of Westmead Hospital. Clinical data, including detailed information from EAM were reviewed. Patient follow up data was obtained at the end of the study period.

Mapping and radiofrequency ablation

Preparation

Procedures were performed under either conscious sedation or general anaesthesia as previously described.[6-8] An SL3 sheath (Abbott Medical) was used to perform coronary sinus (CS) venography and a decapolar catheter inserted into the CS. A quadripolar catheter was deployed to the right ventricle (RV) apex. Intracardiac echocardiography (ICE; ViewFlex™ Xtra, Abbott Medical) was routinely used for direct visualisation of catheter position and monitoring of acute complications. Antiarrhythmic drug (AAD) therapy was withheld for 5 doses prior to the planned catheter ablation (except in the case of an emergent procedure). Systemic anticoagulation was administered after sheath insertion using intravenous unfractionated heparin to maintain an activated clotting time ≥400 seconds prior to left ventricular (LV) access, unless epicardial access was planned. If an epicardial approach was planned, anticoagulation was commenced after safe epicardial access was established. Implanted cardioverter defibrillators (ICDs) were re-programmed to disable therapies prior to ablation. The endocardial LV was accessed either transeptally (large curve Agilis™, Abbott Medical), or anterogradely (SL1 8.5Fr, Abbott Medical), or both. In patients with previously failed endocardial catheter ablation or if pre-procedural imaging strongly indicated intramural/epicardial substrate, epicardial access (via a percutaneous approach) was obtained. Coronary angiography was performed prior to epicardial ablation to avoid coronary artery injury. High output pacing (10 milliAmps [mA] and 9 milliseconds [ms] output) was performed to exclude phrenic nerve stimulation.

VA Induction protocol

Programmed electrical stimulation (PES) was performed in all cases by pacing from a 400ms drive train and up to 4 extra-stimuli, beginning at 300ms and decrementing by 10ms down to ventricular refractoriness. LV stimulation was used if VA was non-inducible after RV stimulation. PES was followed by burst RV pacing down to ventricular refractoriness. PES and burst RV pacing were repeated using highest tolerated dose of isoprenaline (2 microgram bolus and up to 40 micrograms/minute infusion). To maintain perfusion pressure, haemodynamic stability was achieved with inotropic or mechanical circulatory support, initiated at the start sustained VA. The induction protocol was repeated post ablation.

HD Grid catheter design

The HDG is an asymmetric deflecting, irrigated 16-electrode MEM catheter arranged in a four-by-four electrode configuration with an interelectrode distance of 3 mm edge-to-edge of 1mm electrodes (Figure 1). Four splines are orientated parallel to each other with electrodes along the splines. Electrodes on an adjacent spline are equally spaced (Figure 1A).[9] Irrigation ports are located at the junction of the distal main catheter body and the HD grid splines and irrigated via a pressure bag with heparinised saline at a minimum of 2 mL/min. Bipolar electrograms can be created in a linear or across spline configuration to enable bipolar EGM creation at orthogonal orientations. A diagonal configuration is not used due to the differences in spacing compared to the linear and across configurations. This difference using the 4 mm center to center of each electrode of the diagonal measurement is 5.6mm. The HDG allows 'real-time' confirmation of endocardial tissue apposition as the array flexes from the shaft when it is in direct contact with the adjacent tissue which can be confirmed with ICE (Figure 2 and Supplemental Video 1).

HD Wave Solution

The HD Wave solution combines the HDG catheters ability to collect orthogonal electrograms from the same location and the Best Duplicate Algorithm (BDA).[5] The BDA selects the EGM with the best combined timing and voltage, favouring those EGMs with large voltages that are close to average timing.[10] (Figure 1B-D). Duplicate EGMs are stored in the system and can be assessed to ascertain the amount of compared EGMs per single site.

Electro-anatomical mapping

Three-dimensional (3D) EAM of the RV or LV (or both) was performed with the HDG in all cases. In the EAM system and Cardiolab EP recording system (General Electric Healthcare, Chicago, Illinois), band pass filtering was performed 30-500 Hz.

An endocardial and/or epicardial 3D-shell of chamber geometry was constructed for each ventricle with electrogram recordings during either sinus rhythm, implanted device pacing or RV pacing. Shell creation was performed with a magnetic and impedance tracked catheter with continuous field scaling at time of acquisition. Automated point acquisition utilising QRS morphology matching with a high correlation value >96% was used to exclude mechanical catheter ectopy, comparable to other EAM.[(11)] Sinus rhythm or paced rhythm was used for all substrate maps. If atrio-ventricular (AV) conduction was preserved, coronary sinus pacing was performed at 600ms. If AV conduction was impaired, dual chamber pacing and/or biventricular pacing (BiV) at 600ms was performed. Activation maps of each ventricular tachycardia (VT) were obtained if the rhythm was sustained and hemodynamically tolerated. When activation mapping was not feasible, pacing correlation maps for the clinical VT were attempted. Fill threshold (projection of colour from each mapping point) was set at 7 units for all cases. Internal and external distances from the ventricle shell were set at 7 mm. Conventional ventricular $V_{p\text{-}p}$ bipolar substrate voltage parameters were used (dense scar: <0.5 millivolts [mV], low voltage: 0.5 mV-1.5 mV, normal >1.5 mV).[(12)] Unipolar low-voltage was defined as electrogram amplitude <8.3 mV (LV) and <5.5 mV (RV).[(13, 14)]

The chamber mapped was based on the characteristics of the induced or spontaneous VA. To prevent overestimation of low voltage areas at peri-annular locations, sites within 1 cm of the annulus were excluded from measurements.[(13)]

Endpoints and success of ablation

Ablation was performed using irrigated catheters TactiCath™ SE or Flexability™ (Abbott Medical). If a contact force (CF) catheter was used, the endpoint of each ablation lesion was controlled with ≥10g CF aiming for an impedance drop of ≥20 ohms and maximum power of 50 Watts (W), applied in a temperature-controlled mode. Ablation lesions were repeated until the site was electrically unexcitable with pacing at 10mA at 9ms pulse width.

Ablation was guided by substrate and/or activation mapping. Ablation targeted presumptive isthmus and exits, based on activation and entrainment mapping, if the VT was hemodynamically tolerated.[(6)] If the VT was not tolerated, non-inducible or non-sustained, a substrate-based ablation was performed for scar-related VTs. The specific approach targeted presumptive channels and exits as determined by paced QRS morphology matched against the VT QRS morphology with a stimulus-to-QRS interval >40 ms, abnormal fractionated potentials, double potentials, late potentials during sinus and paced rhythm, and late abnormal ventricular activities.[(6)] Focal VT that was not tolerated or non-sustained, both pace mapping and short periods of induction to confirm activation guided the putative ablation site. Spontaneous VT defined as any inducible VT that had a 12-lead ECG morphology and rate (within 20 ms) matching a VT that had documented to have occurred spontaneously before ablation.[(6)] PVC targeted ablation was guided by activation and high-density pace mapping.

Acute success was defined as non-inducibility of all inducible VTs using the outlined PES induction protocol,[(6, 15)] and repeated with an isoprenaline infusion up to 40 mcg/min. Acute PVC success was defined as suppression of all morphologies targeted, reinduction was attempted with PES, burst RV pacing to ERP, repeated with an isoprenaline infusion up to 40 mcg/min.

Outcomes

Acute procedural outcomes were reported as complete success (non-inducibility of any VT or PVC, spontaneous or non-spontaneous), partial success (elimination of at least 1 spontaneous VT or PVC), and failure (residual inducibility of spontaneous VT or PVC).[(6)] Recurrence of VT was defined as the occurrence of spontaneous sustained VT causing symptoms or requiring ICD therapies (shocks or ATP). Recurrence of PVCs were detected by 5 day Holter monitoring at 6 weeks, 3, 6 and 12 months' follow up. Survival free of any ventricular arrhythmia (VA) and overall survival via ICD diagnostics or Holter monitoring was reported in follow up; (2) arrhythmia control defined as any reduction in the number of VA episodes or number of AADs required for arrhythmia control during follow-up; (3) overall survival; and (4) survival free of death or cardiac transplantation.

Follow-up

In regards to post ablation ICD reprogramming, two VT treatment zones were programmed. The first zone was programmed below the rate of the slowest VT (with or without ATP) and the second zone programmed at a minimum detection rate >188 beats per minute programmed to deliver a shock (with or without ATP). All patients were enrolled to a remote monitoring service, managed by Westmead Hospital. All ICD activations were recorded, logged and transmitted to the clinic, which prompted an in-office visit for detailed evaluation of clinical and device data. Hospital medical records and outpatient clinic assessments were used to complete clinical follow up. Where a patient didn't have an implanted device, multiple in-clinic appointments and Holter monitors were used.

Statistical analysis

Statistical Package for the Social Sciences for Windows (SPSS) was used for analysis. Continuous variables were expressed as mean ± SD if normally distributed; median and interquartile range 25% to 75% ($IQR_{25\text{-}75\%}$).

Results

Baseline Characteristics

Twenty-two patients were included (aged 56 ± 18years; 15 male, mean LVEF 41 ± 22%, Table 1). 18 patients (82%) had VT and 4 (18%) had monomorphic PVCs. There were 7 patients with no structural heart disease, 10 with ischemic cardiomyopathy and 5 with non-ischemic cardiomyopathy (3 idiopathic DCM, 1 ARVC, 1 PVC-induced). Indications for VA ablation included 18 (55%) patients sustained VT (82%) and 4 (18%) for symptomatic/high ectopic burden of PVCs.

Ventricular Arrhythmia Characteristics

A total of 65 VAs were induced (median 1.5, $IQR_{25\text{-}75\%}$1-4). 55 (85%) were sustained VT, median cycle length 340ms ($IQR_{25\text{-}75\%}$ 250-424ms). Six sustained VTs were hemodynamically tolerated and able to be activation mapped. Four patients had PVC only ablation procedures. Predominant QRS axes consisted of RBBB 39 (60%), LBBB 19 (29%), QR 4 (6%) and RS 3 (5%) patterns in V_1 and inferior axis 33 (51%), superior axis 27 (42%) and horizontal frontal plane axis 5 (7%).

Procedural characteristics

All patients had a substrate map completed, either for RV, LV, and/or the aorta (Table 2). Epicardial mapping was attempted in 2, however, these were not included in the analysis, as the mapping was switched to a linear Duo-Decapolar^{TM} catheter (2-2-2 electrode spacing, Abbott Medical). Complete and partial activation maps for induced or spontaneous VAs were performed for 12 (18%), and 18 (28%) respectively. Complete and partial pacing correlation maps were performed in 13 (20%) and 12 (18%) respectively. Total procedure duration was 218 minutes ($IQR_{25\text{-}75\%}$ 200-253 mins). Total median mapping time with all catheters 76 mins ($IQR_{25\text{-}75\%}$ 53.5-98.75 mins). The median mapping times with the HDG was 42 mins ($IQR_{25\text{-}75\%}$ 33.25-55.25 mins), substrate mapping and activation/pace mapping with HDG was 34.5 mins ($IQR_{25\text{-}75\%}$ 20.25-44.5 mins) and 17 mins ($IQR_{25\text{-}75\%}$ 13-19.75 mins), respectively. Total median mapping time with other catheters, ablation and/or Duo-Decapolar was 37 mins ($IQR_{25\text{-}75\%}$ 16.25-56 mins) and substrate and activation/pace mapping respectively 14.5 mins ($IQR_{25\text{-}75\%}$ 10.25-19.75 mins) and 36 mins ($IQR_{25\text{-}75\%}$ 20-50mins). The Duo-Decapolar catheter was used in 2 (9%) patients to complete mapping. Measured radiation was 3.5 ± 4 (mSv) and 17±21 ($gycm^2$) for effective dose and dose area product respectively and median screening time of 18.5 mins ($IQR_{25\text{-}75\%}$ 14.75-21.3 mins). Idiopathic and structural heart disease patients procedural and EAM characteristics are shown in supplemental table 1.

Electro-Anatomical Mapping

HD Grid feasibility

The HDG was used in LV, RV and aortic cusps for chamber reconstruction, activation mapping and substrate delineation (Figure 3). Epicardial mapping was attempted in the epicardium with the HDG, however, it was noted that the Duo-Decapolar catheter was easier to manipulate in the epicardium due to the lack of lateral deflection the HDG provided. For LV endocardial mapping, transeptal and retrograde approach was used in 13 and 2 patients, respectively. A deflectable sheath was used (Agilis NxT 8.5F, Abbott Medical, Abbott Park, IL, USA) and allowed mapping of the endocardium with the HDG. Retrograde mapping in the aortic cusps was feasible in 2 patients where the HDG was able to map the individual cusps with direct advancement to the aortic annulus.(Supplemental Video 2). LV endocardial contact was confirmed via EAM visually displaying the HDG deforming against the endocardium, folding back on itself when advanced. During the mapping phase, no acute complications occurred with the HDG.

HD Grid manoeuvrability

The general approach to catheter manipulation, where the majority of electrodes are in contact with the wall, was to use a “paint brush” technique. To map the RV, we describe the following suggested approach. The RV endocardium is mapped by selecting the small curve to face the RVOT and the catheter advanced toward and against the anterior free wall, where the catheter suddenly jumps upwards into the pulmonary artery. From here, a combination of withdrawal, rotation and release of the small curve and/or use of the large curve will allow creation of outflow tract geometry (Supplemental Video 3). The RV infundibulum, peri-tricuspid regions are reached by orientating the catheter such that either the small or large curve is directed to one wall (e.g. free wall) and the other curve directed to the other wall (e.g. septum). Maximal use of the small and large curves, with clockwise and counter-clockwise rotation will allow basal septal and free wall RV geometry to the mapped. The RV basal para-hisian region and annular points are mapped by using the small curve and withdrawing the catheter back into the sheath. A deflectable sheath enhances accurate geometrical recreation of the RV. The RV apex may be challenging to due heavy trabeculation, however advancement of the catheter to the RV apex and use of the small and/or large curves will map the RV apex. Repeated “probing” back and forth with the catheter may be required to map the RV apex in between trabeculations. Significant ectopy can be seen when the catheter encounters the moderator band, limiting the mapping in the mid-apical inferior RV.

With LV mapping via the transeptal route, the HDG is naturally directed to the lateral basal LV wall. If the catheter is advanced with the aid of small curve, the catheter body is able to deform easily against the lateral wall, matching the contour of the endocardial surface. Withdrawal of the catheter away from the lateral wall toward the LV base is then followed by counter-clockwise rotation of the sheath with advancement of the catheter with the small curve at the base will disengage it from the lateral papillary muscle and allow advancement to map the LV septum and inferior base. With a tight small curve held intact at the inferior mid LV, the catheter can be rotated and “flipped” which allows mapping of the antero-septum, anterior walls by release the deflection and gentle clockwise and counter-clockwise rotation of the catheter. When at the anterior wall the small curve can then be maximally deflected and the catheter advanced to the LV apex. At the apex, the curve can release and with gentle clockwise and counter-clockwise rotation, the apex defined. Rotating the catheter so that the small curve points to the inferior apex and advancing it further will see it deform and curve up to match the contour of the infero-apical and mid inferior LV. Basal aspects of the LV can be mapped either directly by withdrawing the catheter back into the sheath and with clockwise and counter-clockwise rotation or by advancing a large amount of catheter into the LV and using large curve pointing to the base combined with gentle clockwise and counter-clockwise rotation (Supplemental Video 4).

EAM features

EAM characteristics are found in Supplemental table 2. In total, 28 chambers were mapped; 11 RV, 13 LV, 2 aortic cusps and 2 epicardial surfaces. Rhythm of substrate map collection was sinus rhythm in 16 (73%), atrial paced in 4 (18%) and RV pacing in 2 (9%). A median of 1435 ($IQR_{25-75\%}$ 1114-1871) points were used out of median 16,005 ($IQR_{25-75\%}$ 11,063-21,405) total points collected (8.9% used) to define the substrate in the RV. A median 1700 ($IQR_{25-75\%}$ 1427-2412) points were used out of 18,573 ($IQR_{25-75\%}$ 15,713-41,067) points in the LV substrate maps. This equates to 8.9% and 9.1% of total points collected were used in RV and LV substrate maps. One of the epicardial surfaces was mapped with the HDG, the second was mapped with a Duo-Decapolar catheter. Total surface area of the RV 126.9 cm^2 ($IQR_{25-75\%}$ 100.28-143.53 cm^2) and LV 136.5 cm^2 ($IQR_{25-75\%}$ 115.1-144.1 cm^2). Bipolar substrate area (<1.5mV) was identified in the RV and LV median 15.7cm^2 [$IQR_{25-75\%}$ 8.73-21.53 cm^2] and 49.2 cm^2 [$IQR_{25-75\%}$ 32-64.5 cm^2], respectively. Bipolar dense scar (<0.5mV) was identified in the RV and LV median 3.35 cm^2 [$IQR_{25-75\%}$ 1.35-4.9cm^2] and 16 cm^2 [$IQR_{25-75\%}$ 5.3-31.1 cm^2], respectively. Unipolar substrate (<5.5 or 8.3mV) area was identified in RV and LV median 23.1 cm^2 [$IQR_{25-75\%}$ 9.93-33.85cm^2] and 70.2 cm^2 [$IQR_{25-75\%}$ 45.4-99.1cm^2] respectively. Individual sites of duplicate EGMs had up to 331 and 177 points in the RV and LV respectively. Duplicate EGM locations with >10 points were predominantly in the basal anterolateral, basal anteroseptal, basal inferoseptal and basal inferior in the LV and basal and mid sections of the RV.

Catheter ablation and Acute Procedural Outcomes

Acute success was achieved for 56 (86%) of the induced or spontaneously occurring VA. Failure occurred in 5 (8%) and 4 (6%) were not targeted. Ablation was given at sites of earliest activation and sites in low voltage regions. Median total ablation time was 23 mins ($IQR_{25-75\%}$ 13-35.75 mins), and ablation times for idiopathic and structural heart disease patients was 13 mins ($IQR_{25-75\%}$ 10-19 mins) and 34 mins ($IQR_{25-75\%}$ 15-47.5 mins) respectively. Failure was due in 1 patient to the earliest site located at the His bundle, and the remaining all presumed to be epicardial foci. Acute and mid-term outcomes shown in Supplemental table 3.

Outcomes and follow up

At a median follow-up of 145 days ($IQR_{25-75\%}$, 62-273 days), 6 patients (27%) had VA recurrence regardless of a 30 day blanking period. Median time to VT recurrence was 10 days ($IQR_{25-75\%}$, 3.5-19.5 days) with repeat catheter ablation in 5 patients (83%), one patient requiring a further third procedure. Median time to repeat catheter ablation was 20 days ($IQR_{25-75\%}$, 8-52 days). Of the 6 patients with recurrence, 5 recurred with in 30 days. Of the 5 that had recurrence with in 30 days, 2 had repeat procedures on day 52 and 102 respectively. These 2 patients recurred on day 22 and 2 respectively. At the end of follow-up, 2 patients had died. In one case, the patient died within 30 days following re-admission with multi-organ dysfunction *without* recurrent ventricular arrhythmias. In the second case, the cause was sudden death attributed by recurrent ventricular arrhythmia. No patient was referred for cardiac transplantation and no ventricular assist devices were placed. No peri-procedural complications occurred. 7 (32%) of patients had a reduction in anti-arrhythmic drug (AAD) therapy, 10 (45%) had no change in AADs, 2 (9%) changed to different AADs and 3 (14%) had an increase in AADs. In the patients with increased AAD therapy, one commenced beta-blocker therapy while an inpatient due to an early recurrence, the second was discharged on a beta-blocker for ICM but did not have a recurrence and the third patient had an early recurrence and commenced amiodarone whilst an inpatient. Two patients changed AADs, both from amiodarone to sotalol without recurrence.

Discussion

This study is reporting on the clinical use of the HDG and BDA in catheter ablation of VAs. The study conveys the following new findings:

(1) Integration of an equally spaced grid catheter with an EAM system is safe and feasible for substrate identification in a heterogeneous group of patients with ventricular arrhythmias;

(2) Time to create high-density substrate or activation maps is similar in comparison with other MEM catheters.[1, 2, 5, 8, 11, 16-20]

(3) Points used and points collected differed significantly, underpinned by the BDA whereby the largest bipolar V_{p-p} is selected independent of depolarising wavefront and catheter orientation.

Advantages and disadvantages of the HDG

In our experience, crossing the aortic, mitral and tricuspid valves and mapping of the RV, LV and aortic regions proved to be safe and feasible with the HDG catheter. Utilisation of the deflectable sheath facilitated ease of crossing the mitral and tricuspid valves. The HDG was challenging to manipulate around papillary muscles of the LV and beyond the moderator band making the RV apex consistently difficult to reach all aspects of. This contributed to an extra 14.5 mins of substrate mapping required with a non-HDG catheter. A single case report of its use in the epicardium is described by Bellmann et al,[21] however, in our experience, mapping epicardially with the HDG was limited and its feasibility is unknown for this location currently. Complications across multiple studies, including a recent meta-analysis post ventricular tachycardia ablation, report a rate between 8-10%.[22] We found no peri-procedural complications in our cohort of study patients. Pace mapping through the HDG, as with any multi-electrogram producing catheter, proved to be challenging due to the sheer amount of poles available for pacing. Orientation and contact were often difficult for identification of the electrodes position when pace mapping.

Prior studies

Okubo et al recently published the HDG catheter and BDA use in identifying late potentials and diastolic isthmuses in a structural heart disease population with VT.[5] The HD wave solution generated substrate maps showed a significantly smaller low voltage area in comparison to linear and across spline EGM configurations. In an animal infarct model, Takigawa et al demonstrated using the BDA provided a higher accuracy for scar discrimination compared to not using the algorithm regardless of EGM collection configuration; along, across or the diagonal between electrodes.[23]

Other commercially available MEM and EAM systems

Procedural characteristics of other commercially available MEM catheters for ventricular arrhythmias are displayed in Table 3. Total substrate mapping time of 34.5 mins with the HDG catheter was consistent with the published range of 23 – 55.6 mins.[1, 2, 16-20] Viswanathan et al reported their initial evaluation of the Orion™ 64-electrode mini-basket mapping catheter and EAM (Rhythmia™, Boston Scientific, Marlborough, MA, USA) for VAs in a retrospective study across two centres. Total substrate mapping and activation times were reported for 20 patients, respectively 24 minutes (14:59-34:22 mins) and 9 minutes (04:12-16:14 mins). Liu et al, evaluated the same catheter in predominantly right sided outflow tract procedures and showed reduced mapping and ablation times. The mapped rhythms were predominantly activation mapped and did not necessitate an additional substrate map. In a single centre, non-randomised, observational study comparing point by point mapping with an ablation catheter and a MEM catheter, Pentaray™ (Biosense Webster, Irvine, CA, USA), in patients with structural heart disease, mapping time of the MEM catheter was significantly longer at 55.6±34.4mins.[16] Acosta et al, in a single centre, randomised study compared point by point mapping with an ablation catheter and the Pentaray™ for substrate mapping in the LV, total mapping time was 24±8mins,[2] compared to our median of 34.5 (20.25-44.5). In our study group we included both RV and LV substrate maps in 3 patients compared to LV only.

Points Collected

The total points collected with the HDG catheter is far greater than used and displayed on the map. Only 9% of the total points acquired were used. This discrepancy could be explained by two conditions; (i) internal and external distance from the surface of the EAM anatomical reconstruction may contribute to exclusion of points (our filtering was set to 7mm from internal and external surfaces), (ii) the BDA methodology, which compares the bipolar V_{p-p} amplitudes for all points generated from the positive electrode's location, only using the largest amplitude. These excluded points are available for review and if a displayed point is removed the BDA automatically checks for the next best EGM. At a single point location we observed up to 331 duplicated EGMs. Whilst this contributed to a high level of point redundancy it did provide a comprehensive interrogation of the largest amplitude EGM at singular sites. The total used points for endocardial substrate mapping in our study cohort was much larger than published for Pentaray™ and Duo-Decapolar™ catheters,[2, 19] only Viswanathan et al had more points collected with the Orion™ mini-basket. Discrepancies in automated collection algorithms between the EAM systems may also contribute to the sizeable difference in points used versus total points collected.

Study Limitations

This study was a non-randomised retrospective analysis of a series of patients undergoing VA ablation. The study cohort is small which included procedural characteristics of all VAs, PVC and sustained VT patients in structural heart disease and normal hearts. The values for low voltage substrate identification are unknown with this catheter in human clinical studies and the utilisation of the standard 3.5mm catheter tip derived cut off was used (<0.5mV dense scar, 0.5-1.5mV border zone and >1.5mV normal myocardium). Tung et al have previously described the impact of wavefront propagation on the detection of scar and scar border zones.[24] The influence of the bipolar EGM on low voltage characterisation with different wavefront propagation angles is an issue that the HDG integration to the EAM attempts to resolve. Due to the low number of substrate maps performed with RV pacing compared to sinus rhythm or atrial pacing our study was not powered to compare wavefront propagation effects on substrate delineation. A control group of patients with standard catheters was not used for mapping, therefore comparisons between standard and HDG catheters, the ability to localise and delineate the VT isthmus was not possible with the current study.

Conclusion

This is the first reported clinical use of the novel HDG catheter in VA procedures. Utilisation of the HDG catheter integrated with an EAM system is capable of rapidly annotating the largest bipolar $V_{p\text{-}p}$ amplitude to create high-density substrate and activation maps. HDG appears safe and feasible in catheter ablation of both scar-related and idiopathic VAs. Discrepancy of points used, and points collected is related to the BDA methodology. Further studies are needed on outcomes of VA procedures with this catheter.

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Figure legend

Figure 1: A) Abbot HD™ Grid 4 x 4 equal spaced electrode array catheter. 1mm electrodes with 3mm spacing between electrodes along catheter and across adjacent electrodes. B) Electrograms C3-D3 and C3-C4. C) At green arrow, the selection is of largest V_{p-p} (2.23mV) generated from the across spline bipole, C3-D3. D) Using the alternative bipole generated linearly along spline C3-C4 V_{p-p} (0.83mV) markedly reduced and changes the border zone delineation. V_{p-p} = Peak-to-peak Voltage

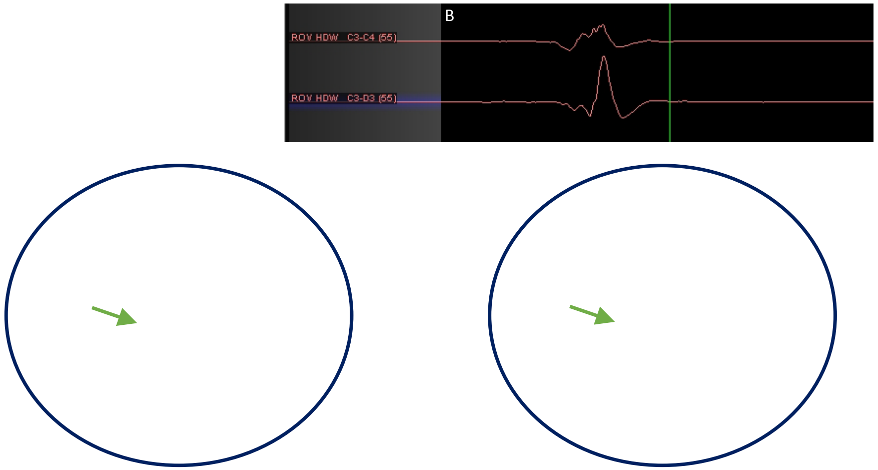

Figure 2: Advisor^{TM} HD grid positioned under ICE guidance. HD Grid positioned at blue arrow. A) Approaching LV septum. B) Against the LV septum. C) Lying on top of the posteromedial papillary muscle of the LV. Catheter deformation when in contact with myocardium by EAM. D) RAO and PA views. Catheter deformation in the RVOT. E) Superior and PA views of catheter deformation and position in the Aortic cusps. *ICE = Intra-Cardiac Echocardiography, EAM = Electro-anatomic Mapping system.*

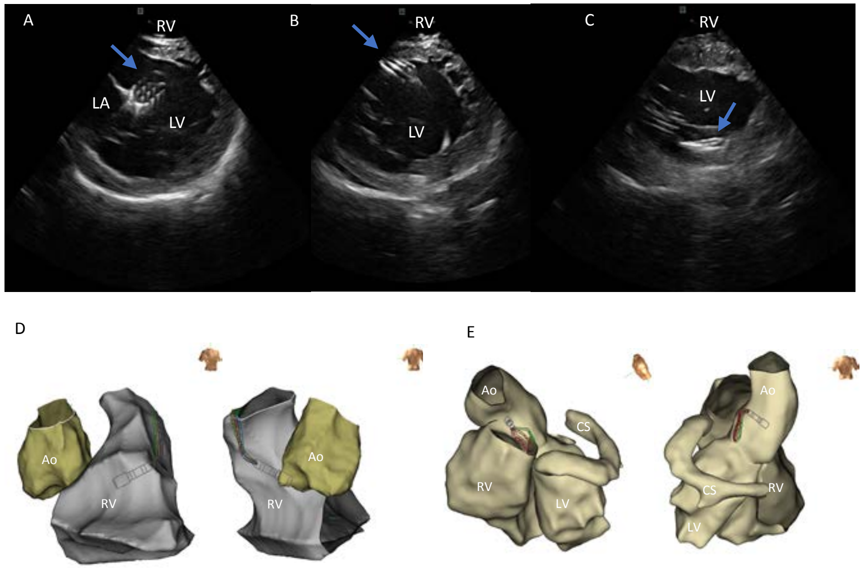

Figure 3: Electroanatomic mapping. A) LAO and RAO Bipolar Substrate map of LV. B) Superior and Left posterolateral views of Activation map of RV. Earliest site (White region) localized to superior tricuspid annulus.

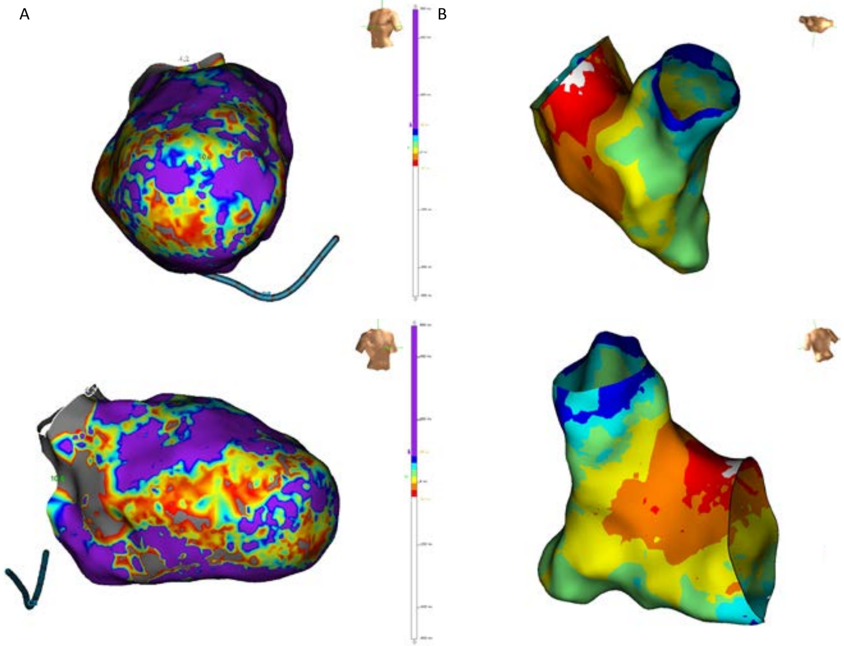

Table 1: Baseline Characteristics

Variable (N=22)	
Age, mean±SD, y (range)	56 ± 18 (17-84)
Male sex, %	15 (68)
Imaging	
LV ejection fraction at time of procedure, %, mean±SD	41±22
LV end diastolic diameter at time of first procedure, mm, mean±SD	53±13
RV dilatation/dysfunction (>mild), %	4 (18)
Cardiac MRI, %	6 (27)

Previous VT ablation procedure, %	3 (14)
ICD, %	11 (50)
Cardiomyopathy Aetiology	
Ischemic	10 (45)
Idiopathic dilated	3 (14)
PVC induced	1 (5)
ARVC	1 (5)
No cardiomyopathy	7 (32)
Indication for VA ablation, %	

Recurrent ICD shocks for VT/VF	3 (14)
Sustained VT	12 (55)
VT Storm	3 (14)
PVC	4 (18)
Anti-arrhythmic therapy (pre-ablation), %	
Amiodarone	7 (32)
Sotalol	2 (9)
Mexiletine	2 (9)
B-blocker	11 (50)

Calcium Channel Blocker	2 (9)
Flecainide	1 (5

Abbreviations: SD = Standard Deviation, LV = Left Ventricle, RV = Right Ventricle, MRI = Magnetic Resonance Imaging, VT = Ventricular Tachycardia, ICD = Implanted Cardiac Defibrillator, PVC = Premature Ventricular Contraction, ARVC = Arrhythmogenic Right Ventricular Cardiomyopathy, VA = Ventricular Arrhythmia, VF = Ventricular Fibrillation.

Table 2: Procedural Characteristics

Procedural Data	
Ventricular Arrhythmias (N =65)	
Number of VAs, median (IQR_{25-75})	1.5 (1-4)
Number of VTs, %	55 (85)

Cycle length, median (IQR_{25-75})	340 (250-424)
PVCs, %	10 (15)
VA recorded (n=65)	
RBBB, %	39 (60)
LBBB, %	19 (29)
QR, %	4 (6)
RS, %	3 (5)
Inferior axis, %	33 (51)

Superior axis, %	27 (42)
Other axis, %	5 (7)
Radiation	
DAP (gycm2)	17 ± 21
Effective dose (mSv)	3.5 ± 4
Fluoroscopy Time, median (IQR_{25-75}) (Mins)	18.5 (14.75-21.3)
Procedural Duration (Mins)	
Total time, median (IQR_{25-75})	218 (200-253)

Mapping time HDG, median (IQR_{25-75})	42 (33.25-55.25)
Substrate Mapping time HDG, median (IQR_{25-75})	34.5 (20.25-44.5)
Activation and Pace Mapping time HDG, median (IQR_{25-75})	17 (13-19.75)
Mapping time other catheter, median (IQR_{25-75})	37 (16.25-56)
Substrate Mapping time other catheter, median (IQR_{25-75})	14.5 (10.25-19.75)
Activation and Pace Mapping time other catheter, median (IQR_{25-75})	36 (20-50)
Ablation time, median (IQR_{25-75})	23 (13-33.75)
Alternative mapping catheter used, %	2 (9)

Substrate rhythm mapped	
Sinus rhythm, %	16 (73)
Atrial paced, %	4 (18)
RV pace, %	2 (9)
EAM	
RV mapped, %	11 (50)
LV mapped, %	13 (59)
RV and LV mapped, %	3 (14)

Epicardial mapped, %	2 (9)
Surface area of RV (cm2), median (IQR_{25-75})	126.9 (100.28-143.53)
RV EAM points used, median (IQR_{25-75})	1435 (1114-1871)
RV EAM points collected, median (IQR_{25-75})	16005 (11063-21405)
RV Scar <0.5mV area Bipolar (cm2), median (IQR_{25-75})	3.35 (1.35-4.9)
RV Scar <1.5mV area Bipolar (cm2), median (IQR_{25-75})	15.7 (8.73-21.53)
RV Scar <5.5 area Unipolar (cm2), median (IQR_{25-75})	23.1 (9.93-33.85)
Surface area of LV (cm2), median (IQR_{25-75})	136.5 (115.1-144.1)

LV EAM points used, median (IQR_{25-75})	1700 (1427-2412)
LV EAM points collected, median (IQR_{25-75})	18573 (15713-41067)
LV Scar <0.5mV area Bipolar (cm2), median (IQR_{25-75})	16 (5.3-31.1)
LV Scar <1.5mV area Bipolar (cm2), median (IQR_{25-75})	49.2 (32-64.5)
LV Scar <8.3mV area Unipolar (cm2), median (IQR_{25-75})	70.2 (45.4-99.1)

Abbreviations: VA = Ventricular Arrhythmia, VT = Ventricular Tachycardia, IQR_{25-75} = Interquartile range 25-75, PVC = Premature Ventricular Contraction, RBBB = Right Bundle Branch Block Morphology, LBBB = Left Bundle Branch Block Morphology, DAP = Dose Area Product, HDG = Advisor™ HD grid, RV = Right Ventricle, EAM = Electro-Anatomic Mapping, LV = Left Ventricle.

Table 3: Procedural Characteristics of MEM Catheters in literature.

Study	Study design	MEM catheter	Patients mapped with MEM catheter	Patient substrate aetiology (ICM/NICM/Normal Heart/ADCH)	Total used LV substrate mapping points	Total Used Points Endocardial Substrate(LV and/or RV)	Total Mapping time (mins)	Total Substrate Mapping time with MEM catheter (mins)	Total Activation and pace mapping time with MEM catheter (mins)	Ablation Time (mins)	Total Procedure Time (mins)	Total Fluoroscopy Time (mins)
Viswanathan 2017†	Two centre, Retrospective	Orion^{TM}	19	12 / 3 / 2 / 2	10219 ± 5194	10219 ± 5194	47.9 ± 25.3	37.2 ± 19.8	30.5 ± 22.4	-	250.3 ± 88.9	41.8 ± 18

Liu 2019‡	Single centre, Prospective	Orion^{TM}	26	.- / - / 26 / -	-	2050 ± 1338	16.4 ± 6.6	-	-	4 ± 1.9	-	-
Maagh 2017	Single centre, Retrospective	Pentaray^{TM}	26	18 / 8 / - / -	-	1085.9 ± 726.1	55.6 ± 34.4	55.6 ± 34.4	-	50.7 ± 30.1	175.4 ± 52.0	22.1 ± 13.7
Maagh 2018	Single centre, Retrospective	Pentaray^{TM}	26	18 / 8 / - / -	-	1085 ± 726	55.6 ± 34.4	55.6 ± 34.4	-	50.7 ± 30.1	175.4 ± 52.0	22.1 ± 13.7
Acosta 2018	Single centre, Prospective Randomized controlled	Pentaray^{TM}	10	10 / - / - / -	731 ± 274	731 ± 274	-	23 ± 9	-	12(7-20)	-	-
Yamashita 2016	Single centre, Retrospecti	Pentaray^{TM}	73	73 / - / - / -	-	658 (378-1062)	-	-	-	34 (23-53)	271 ± 71	-

	ve											
Jais 2012	Two centre, Prospective	Pentaray™	35	56 / 14 / - / -	-	-	-	-	-	23 ±11	148 ± 73	42 ± 20
Berte 2015	Single centre, Prospective	Pentaray™	9	4 / 5 / - / -	-	739 ± 536	Upto 30mins	-	-	-	-	-
Cano 2017	Single centre, Prospective	Pentaray™	59	37 / 20 / - / -	2150 ± 1477	-	38 ± 15	-	-	24.2 ± 21.4	177 ± 53	6.4 ± 5.8
Tung 2011	Two centre, Prospective	Duo-Decapolar™	17	15 / 2 / - / -	819 ± 357	-	31 ± 7	-	-	39.5 ± 17.7	329 ± 91	-
Okubo	Single centre, Retrospective	**HD Grid™**	41	24 / 16 / - / 1			47.3 ± 22.7	24.4 ± 12.6			192 ± 54	46 ± 13

Current study	**Single centre, Retrospective**	**HD Grid™**	**22**	**10 / 5 / 7 / -**	**1700 (1427-2412)**	**3392 ± 942**	**42 (33.25-55.25)**	**34.5 (20.25-44.5)**	**17 (13-19.75)**	**23 (13-33.75)**	**218 (200-253)**	**18.55 (14.75-21.3)**

MEM = Multi-Electrode Mapping catheter, LV = Left Ventricle, RV = Right Ventricle, ACHD = Adult Congenital Heart Disease, ICM = Ischaemic Cardiomyopathy, NICM = Non-Ischaemic Cardiomyopathy.

†Values calculated from supplemental data of Viswanathan publication. Activation and pace mapping values calculated from VE and VT maps

‡ RVOT type Ventricular arrhythmias only targeted