Epicardial Phrenic Nerve Displacement during Catheter Ablation of Atrial and Ventricular Arrhythmias: Procedural Experience and Outcomes

Running title: Kumar et al.; Epicardial Phrenic nerve displacement

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Abstract:

Background - Arrhythmia origin in close proximity to the phrenic nerve (PN) can hinder successful catheter ablation. We describe our approach with epicardial PN displacement in such instances.

Methods and Results - PN displacement via percutaneous pericardial access was attempted in 13 patients (age 49±16y, 9 females) with either atrial tachycardia (AT; 6 patients) or atrial fibrillation triggered from a superior vena cava focus (1 patient) adjacent to the right PN or epicardial ventricular tachycardia (VT) origin adjacent to the left PN (6 patients). An epicardially placed steerable sheath/4mm-catheter combination (5 patients) or a vascular or an esophageal balloon (8 patients) was ultimately successful. Balloon placement was often difficult requiring manipulation via a steerable sheath. In 2 VT cases, absence of PN capture was achieved only once the balloon was directly over the ablation catheter. In 3 AT patients, PN displacement was not possible with a balloon, however a steerable sheath/catheter combination was ultimately successful. PN displacement allowed acute abolishment of all targeted arrhythmias. No PN injury occurred acutely or in follow up. Two patients developed acute complications (pleuro pericardial fistula 1, pericardial bleeding 1). Survival free of target arrhythmia was achieved in all AT patients, however a non-targeted VT recurred in 1 patient at a median of 13 months’ follow up.

Conclusions - Arrhythmias originating in close proximity to the PN can be targeted successfully with PN displacement with an epicardially placed steerable sheath/catheter combination, or balloon, but this strategy can be difficult to implement. Better tools for phrenic nerve protection are desirable.

Key words: catheter ablation, ventricular tachycardia, atrial tachycardia, atrial fibrillation, phrenic nerve injury, epicardial access
Introduction

Collateral phrenic nerve (PN) injury can occur after endocardial catheter ablation of atrial fibrillation (AF), atrial tachycardias (AT), left sided accessory pathways, and epicardial ablation of ventricular tachycardia (VT). Right PN injury during ablation of atrial arrhythmias originating from the crista terminalis, superior vena cava (SVC) or the right upper pulmonary vein can be explained by the anatomic proximity of to the PN as it courses down the anterolateral wall of the SVC, with a distance as little as 0.3 ±0.5 mm and only the pericardium separating these structures. Similarly, VT originating from the basal inferolateral left ventricular epicardium, is often in close proximity to the course of the left PN, with a distance <3mm from the epicardial surface in up to 36% of patients. When present, PN injury can be varied in symptomatology (from asymptomatic to severe respiratory insufficiency) and temporality of recovery (median of 6-8 months but may take up to 28 months). Furthermore, PN may persist in up to 33% of patients in long term follow up causing significant morbidity.

A number of techniques for avoiding PN injury have been reported including pace mapping to identify sites close to the PN to avoid ablation, use of lower power settings (10 watts in one study) and PN displacement using an epicardially placed balloon, sheath/catheter combination, and pericardial injection of saline, air or both. The experience with PN displacement techniques is limited to animal studies, isolated case reports or small series of patients. Whilst these reports have been favorable in providing PN protection and arrhythmia cure, the particular technical challenges and limitations of these approaches have not been as well appreciated. In this study, we report our procedural experience as well as acute and medium term outcomes in 13 patients with debilitating atrial and ventricular arrhythmias originating in close proximity to the PN where PN displacement was used to assist with catheter
Methods

Of 6000 procedures catheter ablation for AF (n=2971), focal AT (n=319), SVT (n=685) and VT (n=2025) from January 2008 to December 2014, 13 patients (0.22%) with atrial or ventricular arrhythmias originating in close proximity to the PN in whom epicardial PN displacement was employed were included in this study. Of note, PN displacement was required in 13/298 (4.4%) procedures that required epicardial access. Procedures were performed according to protocols approved by the Brigham and Women’s Hospital Human Subject Protection Committee. The present study overlaps and expands on the population reported from our center previously.2 All patients gave written informed consent for their procedure.

Mapping of atrial arrhythmias

Intravenous conscious sedation was performed with midazolam and fentanyl for mapping of the atrial arrhythmias. Once the decision was made to obtain pericardial access, the patient was transitioned to general anesthesia, when available for patient comfort. Paralytic agents were not administered in order to avoid masking PN injury. Intracardiac catheters were inserted via the femoral veins, which included a 20-pole catheter placed along the lateral right atrium with the distal poles in the coronary sinus, His-bundle catheter, right ventricular apical catheter, a multipolar mapping catheter (circular mapping or a multi-spline catheter [Pentaray, Biosense Webster, Diamond Bar, CA, USA]), in addition to a mapping and ablation catheter. An electroanatomic mapping system (CARTO, Biosense-Webster) was used. Bipolar intracardiac electrograms (EGMs) were filtered between 30 and 500 Hertz, and recorded digitally with simultaneous 12-lead surface electrocardiograms (EKG). Site of origin of the AT was determined by examining P wave morphology and using activation mapping during AT that was
present in the baseline state or induced with burst atrial pacing with or without adrenergic stimulation (e.g. isoprenaline). Radiofrequency (RF) ablation was performed using an irrigated or a non-irrigated catheter (Navistar, Thermocool, Thermocool SF or Thermocool SmartTouch, Biosense Webster). For non-irrigated catheters, power was titrated up to 50 Watts and a temperature of 60°C. Based upon the discretion of the treating electrophysiologist, cryoablation was attempted prior to embarking on epicardial PN displacement.

Prior to ablation, unipolar pacing was performed with the ablation catheter at 10 milliamps (mA) and 2 millisecond (ms) pulse width was performed to exclude PN capture. If PN capture was present, sites adjacent to earliest activation where PN capture was absent were targeted, unless the patient had a prior failed ablation procedure using this approach. If this was not successful in abolishing the tachycardia, epicardial PN displacement was employed. PN displacement was performed based on symptom severity and impairment in quality life and patient preference with consideration of perceived benefits. Post ablation, burst and programmed atrial stimulation was repeated with or without high dose adrenergic stimulation to ensure arrhythmia non-inducibility.  

**Mapping of ventricular arrhythmias**

Our methods for mapping and ablation of ventricular arrhythmias have been previously reported. Briefly, programmed ventricular stimulation was performed to assess morphologies of induced VTs. Sustained monomorphic VT was defined as continuous VT for ≥30 seconds or one that required an intervention for termination (cardioversion, pacing or ablation). “Spontaneous VT” was defined as any inducible VT with an identical 12-lead EKG morphology and rate (within 20 milliseconds [ms]) to a VT that the patient presented with prior to ablation. If 12-lead EKGs of the presenting VT were not available prior to ablation, the rate
cut off and intracardiac EGMs from the implanted cardioverter defibrillator (ICD) were used.

“Undocumented VTs” were defined as inducible VTs that did not have an identical rate (>20 ms difference), 12-lead EKG morphology or ICD-derived EGM characteristics to the VT that the patient had presented with prior to ablation.24

Substrate mapping was performed with particular focus on the scar region facilitated by the CARTO electroanatomic mapping system (Biosense Webster). Areas of low voltage (<1.5 millivolt [mV]), dense (≤0.5mV)25 and electrically unexcitable scar21 were identified. Late potentials in the scar were tagged. Pace mapping was performed; areas of long stimulus to QRS (S-QRS) delays (>40 ms) and where pace mapping matched QRS morphology of an induced VT were tagged. If hemodynamically tolerated, VT was then re-induced and activation/entrainment mapping performed. If not tolerated, it was terminated with RFA, burst pacing or cardioversion and substrate mapping performed. Ablation targeted presumptive channels, exits within the low-voltage area including regions of long S-QRS (>40 ms).21 RFA was delivered with an irrigated catheter (ThermoCool, or ThermoCool SF; Biosense Webster) at a power of 25 to 50 Watts targeting an impedance drop of 10 to 20 ohms. Applications were repeated at target areas until they were rendered electrically unexcitable with unipolar pacing at 10 mA at 2-ms pulse width.21 Post ablation, programmed ventricular stimulation was repeated to confirm arrhythmia non-inducibility.

**Epicardial access and phrenic nerve protection approach**

Epicardial access was obtained by subxiphoid pericardial puncture as previously described.26 For AT ablation, only single epicardial access was obtained, unless the first epicardial access failed to provide PN displacement and the operator felt that a change of approach (e.g. from anterior to posterior pericardial access or vice versa) was necessary.
PN displacement strategies consisted of one or a combination of: (i) saline infusion into the pericardial space;17 (ii) epicardially placed balloon16 and/or (iii) epicardially placed sheath/non-irrigated 4 mm catheter combination.2 For the latter, we used a steerable non-irrigated 4 mm catheter to allow sufficient rigidity and size to enable PN catheter displacement. During endocardial ablation of atrial arrhythmias an epicardially placed balloon or sheath/catheter combination was positioned juxtaposed to the adjacent earliest endocardial site of activation such that PN capture was no longer present. Operator preference dictated which tool was applied first and in subsequent intra-procedural attempts if the first attempt was unsuccessful in PN displacement.

For epicardial VT ablation, single pericardial access, and the access was “double wired” to allow insertion of two sheaths over the wires; one access was for a mapping/ablation catheter delivered via a steerable sheath (Agilis, St. Jude Medical, St. Paul, Minnesota, USA), and the other for use of epicardial PN displacement, also delivered via a second steerable sheath. When epicardial ablation was deemed necessary, coronary angiography was performed before initial ablation. Unipolar pacing was performed with the ablation catheter at 10 mA, 2 ms pulse width was performed to determine if the site of origin was adjacent to the PN; if so, ablation was first attempted at an adjacent site where PN was absent. PN displacement was performed if substrate, pace, activation and/or entrainment mapping demonstrated that the critical part of the circuit was adjacent to the PN and the documented VT remained inducible despite ablation at adjacent sites where no PN capture was evident.

**Maneuvers for PN displacement**

When PN displacement was performed with an inflated vascular balloon (NMT Medical, Boston, MA, USA, 18 mm x 20 mm) or an esophageal balloon (Hercules 3 step 18-20 mm esophageal
balloon; Cook Medical, Bloomington, IN, USA), the balloon was delivered through a steerable sheath (Agilis, St. Jude Medical). The deflated balloon was first advanced into the pericardial space and manipulated into position near the ablation catheter located at the site of intended ablation. The balloon was then inflated with the intention of displacing the PN away from the epicardium and repeat high-output pacing performed to ensure absence of PN capture. The sheath was used to provide stability and support that would allow the balloon to maintain its position thereby creating a physical space between the epicardium and the PN or displace the PN away from the region of interest for ablation. Multiple adjustments of the balloon were made, when necessary, which included advancement/retraction, repeated inflations and deflations in order reach the desired location and to maintain its position.

If multiple attempts at balloon placement were unsuccessful in PN displacement, or PN capture was still present, a non-irrigated 4mm catheter and sheath combination were used in an attempt toward PN displacement or vice versa. When the sheath/catheter combination was used, the catheter was directed to the epicardial site of PN capture. The catheter was then advanced to create a physical space between the epicardium and phrenic nerve, such that the nerve was “lifted” off the epicardial surface.

RFA was attempted endocardially at the site of earliest activation (for AT) or the critical region identified by mapping epicardially (for VT) after ensuring absence of PN capture. After ablation, repeat high output pacing was performed at each site to confirm absence of PN injury by tactile sensation of diaphragmatic stimulation and quantifying fluoroscopic diaphragmatic movement. Prior to each ablation at a new site, repeat PN pacing was performed to ensure absence of PN capture and diaphragmatic excursion checked on fluoroscopy. Diaphragmatic excursion during respiration was assessed at end of the procedure using fluoroscopy and
compared to that obtained pre-procedure.

**Follow up**

Patients were observed in hospital and examined the following day with assessment of diaphragm excursion on examination. A chest x-ray was obtained the next day if there was concern about possible limited diaphragm motion. Patients were then followed clinically typically at 6 weeks and 3 to 6 monthly intervals thereafter; repeat imaging was obtained as per the discretion of the referring clinician. For patients with AT, periodic monitoring (varying from 24 hour-30 day) was performed to document recurrence if symptoms were suspicious. In patients with VT, ICDs were interrogated for recurrence of ventricular arrhythmia. Follow up also included review of records of all hospital and outpatient clinic visits and discussion with referring cardiologists and primary care physicians.

**Statistical analysis**

The Statistical Package for the Social Sciences for Windows (IBM SPSS, release 22, Armonk, New York, USA) was used for analysis. Continuous variables were expressed as mean ± standard deviation (normally distributed) or median with ranges (if not normally distributed).

**Results**

Thirteen patients (mean age 49±16 years, 9 females) with atrial or ventricular arrhythmia origin in close proximity to the PN underwent epicardial PN displacement (Table 1). Patients had highly symptomatic arrhythmia (median of 24 months), failed multiple prior anti-arrhythmic drugs (median 2); all but 3 patients had failed prior catheter ablation attempts (Table). Procedural indication was atrial tachycardia (AT, 7 patients), superior vena cava (SVC)-triggered AF (1 patients) and epicardial VT (Table).

An epicardially placed steerable sheath/catheter combination (5 patients), a vascular
balloon (3 patients) or an esophageal balloon (5 patients) was ultimately successful in PN
displacement (Figure 1, Table).

**Atrial arrhythmias**

In all AT patients, PN capture with pacing was present at the site of earliest activation. All but 1
patient had failed one previous attempt at ablation with RF (6 patients) or both RF and
cryoablation (1); one patient had two failed RFA attempts. In 3 patients, RFA at sites adjacent to
the earliest activation without PN capture had failed. In one patient, multiple positional
maneuvers had also failed to prevent PN capture including a 30 and 45 degree wedge and
positioning the patient on their left side. In 2 patients, RFA was prematurely terminated due to
transient loss of PN capture during pacing in the SVC during ablation. In one patient with SVC-
triggered AF, SVC isolation was prevented by PN proximity (Table).

Following epicardial access, epicardial PN displacement was attempted with a balloon
only in 2/8 patients, steerable sheath/catheter combination only in 2/8 patients and multiple
modalities in 4/8 patients (Figure 1). PN displacement was ultimately successful in allowing
ablation at the earliest endocardial site using a balloon in 3 patients (vascular balloon 2,
gastrointestinal balloon 1), and combination of steerable sheath/catheter in 5 patients (Figure 1, 2).

Acutely successful ablation of the clinical AT was possible in all patients. One patient
suffered a complications occurred of pericardial bleeding (240 mL) starting immediately after
pericardial puncture, which was managed non-operatively. No patient developed PN injury
acutely. After a median follow up of 11 months (range 1-65 months), no patient developed
symptoms or signs suggestive of diaphragmatic palsy; 4 out of 8 patients had chest imaging at a
range of 1-17 days post procedure which showed no evidence of diaphragmatic dysfunction.
Survival free of clinical AT was achieved in all patients at a median follow up of 11 months (range 1-65 months).

In follow up, 2 patients developed another AT from the mid crista where PN capture was not evident which were successfully ablated. Two patients developed presumed inappropriate sinus tachycardia; no recurrence of the index AT was noted after intensive Holter monitoring in both patients and detailed electrophysiologic evaluation in 1 patient.

Particular difficulties with PN displacement are worthy of mention. This seemed to be largely related to the limited space between the right superior pulmonary vein and right atrium – SVC region that limited maneuverability in the pericardium near the right phrenic nerve. Access was attempted directly from the anterior pericardium, as well as by attempting to insert the catheter or balloon through the transverse sinus entered from the posterior aspect of the left atrium (Figure 2).\textsuperscript{27,28} Firstly, 4/8 patients (50%) required multiple modalities (e.g. balloon, steerable sheath/catheter combination) before epicardial PN displacement was ultimately successful. In one patient, multiple modalities were employed including instillation of pericardial fluid and use of a steerable sheath/catheter combination, followed by a use of a 30 x 3 mm vascular balloon which were both unsuccessful, eventually requiring a larger (18 x 20 mm) vascular balloon for displacement (Figure 1). Illustrative case examples are shown in Figure 3 and in Supplemental Material.

Secondly, in 3/6 patients (50%) attempted balloon placement was unsuccessful in allowing PN protection; a steerable sheath/catheter combination was ultimately successful in these patients.

Thirdly, 3/8 patients (38%) of patients required two separate pericardial punctures due to difficulties in PN displacement. In the first patient, the balloon length and tip stiffness caused
displacement of the sheath/balloon apparatus anteriorly, away from the epicardial PN site despite either switching from a posterior to anterior pericardial access; a sheath/catheter combination was ultimately successful. In the remaining two patients, the initial anterior access failed to provide consistent PN displacement. The first patient had failed PN displacement with the anteriorly delivered balloon, although posterior balloon delivery was ultimately successful, it would provide only a small area of consistent PN protection and balloon inflation resulted in displacement of the right atrial anatomy necessitating re-mapping of the AT. In the second patient, anterior balloon placement did not provide consistent PN displacement ultimately requiring a posteriorly delivered steerable sheath/catheter combination. Lastly, in 2 patients with AT, remapping of the AT was necessary due to distortion of right atrial anatomy once the balloon was inflated.

**Ventricular tachycardia**

Five patients with epicardial VT related to non-ischemic cardiomyopathy underwent epicardial PN displacement. Representative case examples are shown in Figure 4 and in Supplemental Material. Amongst the group of VT patients, there were a total of 12 inducible VTs (median 2, range 1-4) of which 7 VTs were “spontaneous” and 5 VTs were “undocumented”. All VTs were consistent with scar-mediated re-entry. Seven of 12 inducible VTs had evidence for critical parts of the re-entry circuit in close proximity to the left phrenic nerve established by the presence of late potentials with S-QRS delays >40 ms and ≥11/12 pace map match and/or entrainment mapping. Critical sites were located in the basal lateral (4 patients) and mid/apical lateral left ventricular epicardium (1 patient) directly underneath the left PN. In all patients, these sites had evidence of PN capture. Three patients had previous RFA attempts at adjacent epicardial sites where PN capture was not evident, however VT had recurred in all.
All patients underwent successful PN displacement using the vascular (1 patient) or the gastrointestinal balloon (5 patients). In 2 patients, absence of PN capture was difficult to achieve, requiring frequent repositioning (Figure 4); and was achievable only once the balloon was directly over the ablation catheter.

Successful ablation of the targeted (and spontaneous) VTs was possible in all patients. Acute non-inducibility of any VT was achieved in 4/5 patients; 1 patient had two undocumented VTs inducible post ablation. No patients developed PN injury either acutely. Complications occurred in 1 patient who develop a pleuro-pericardial fistula and moderate pericarditis; this resolved during treatment with colchicine. After a median follow up of 13 months (range 1-65 months), no patient develop symptoms or signs suggestive of diaphragmatic palsy; 4 out of 5 patients had chest imaging at a range of 1-39 days post procedure which showed no evidence of diaphragmatic dysfunction. Survival free of any VT was achieved in all but 1 patient at a median follow up of 13 months (range 1-65 months). One patient who had VT recurrence appeared to have recurrence of a different VT than that which was targeted during the PN displacement based on ICD interrogation.

Discussion

This study describes the procedural experience of 13 patients with atrial or ventricular arrhythmias originating within close proximity to the PN in whom epicardial PN displacement strategies were used in preventing PN injury. PN displacement was achieved with an epicardially placed vascular or gastrointestinal balloon (62% of patients) or an epicardially placed sheath/4mm catheter combination (38%). This allowed successful endocardial ablation targeted ATs and SVC isolation that were limited by close proximity to the right PN and successful epicardial ablation of targeted VTs in close proximity to the left PN. Importantly, no PN injury
occurred acutely and in follow up. Acute non-inducibility and freedom from the target arrhythmia in follow up was achieved in all patients.

Although epicardial PN displacement was ultimately successful in all patients, there were considerable technical and procedural challenges worthy of consideration. Firstly, significant maneuverability of the apparatus was necessary to establish and maintain consistent PN displacement (especially with the balloon). In 2/5 (40%) epicardial VT ablations, absence of PN capture during pacing from the ablation catheter could only be achieved when the balloon was directly over the ablation catheter. Second, in patients with atrial arrhythmias, frequent crossover between modalities was necessary (balloon then sheath/catheter or vice versa) with 50% of attempted balloon placements being unsuccessful in providing PN displacement subsequently requiring a sheath/catheter combination for success. Further, in patients with atrial arrhythmias, 38% of patients required repeat pericardial access to change the approach (e.g. anterior to posterior approach or vice versa) to allow adequate PN displacement. Third, remapping was sometimes necessary due to anatomic right atrial distortion created by balloon inflation in patients with atrial arrhythmias. The technical challenges appeared to be particularly pronounced in patients with AT requiring right PN displacement. Comparably, no crossover or repeated pericardial access was necessary in epicardial VT ablation. The data suggests that sheath/catheter combination is a reasonable technique to attempt for right PN displacement during AT ablation, whilst the steerable sheath/balloon is reasonable for left PN displacement during VT ablation. Lastly, complications were not infrequent, occurring in 2/13 patients (15%) related to pericardial access; furthermore, fluoroscopy times and radiation exposure were significant. These findings highlight that better tools for phrenic nerve protection are highly desirable.
Prior studies

Pacing to avoid ablation at sites of capture is the most commonly employed approach of PN protection however this strategy may not be successful if arrhythmia is of focal endocardial origin directly over the course of the PN (as in crista AT) or a critical component of a re-entrant epicardial VT circuit is directly underneath the course of the PN. Animal studies, isolated case reports and small series of patients undergoing PN displacement and catheter ablation after pericardial air insufflation, saline infusion, saline plus air instillation, or displacement with an epicardially placed sheath/catheter or a balloon have been reported. Di Biase et al, when comparing air, saline or both versus balloon placement in 8 patients found that the combination of air and saline prevented PN capture in 88% of patients, saline infusion never prevented PN capture, and the balloon was only successful in preventing PN capture in 37% of cases. No complications occurred in this cohort. As air is a poor conductor of electricity, concerns about inability to defibrillate the heart have been highlighted with pericardial air insufflation. Saline infusion causes tamponade physiology, and the operators must be vigilant for hemodynamic compromise. Whilst these reports and series have shown ultimately successful PN protection, the technical and procedural challenges and potential complications have not been appreciated. In this study, we highlight the limitations of current tools requiring frequent crossover, complexities in maneuverability and frequent need for apparatus repositioning, long procedural times and radiation exposure, technical challenges with mapping and the attendant risks of pericardial access (and sometimes, repeated access). All these factors must be considered in the risk-benefit analysis of this procedure. In addition, given the rarity of requirement for PN displacement (representing only 0.22% of all catheter ablation procedures at our center) PN displacement should be handled in centres highly experienced with epicardial
interventional procedures.

Limitations

As this was not a prospective study, no specific order of PN displacement strategies was followed and the results are likely influenced by accumulation of procedural experience over time. We assessed proximity to the PN by pacing. The optimal means of pacing is not clear and some advocate higher output pacing than was used in this study. We also do not know if PN capture at a site would always indicate that ablation would produce PN block. This may particularly be true along the thick crista terminalis. It is possible that PN capture happens when the catheter is lying along side the crista terminalis with the PN adjacent to the thinner atrial wall. However, we had not been successful in finding a site in the region where PN capture did not occur in these patients. The critical amount of energy needed to produce tissue conduction block whilst salvaging PN function is unknown. Experimental studies suggest that the PN is exquisitely sensitive to RF energy, with permanent PNI occurring with nerve temperatures as low as 45 degrees Celsius,\(^30\) indeed in one clinical study PNI occurred in 1.1% of patients with ablation at 10 Watts at sites of PN capture during SVC isolation.\(^15\)

We did not perform routine chest imaging to check for diagrammatic dysfunction in all patients; imaging was available in 8/13 patients performed upon the discretion of the referring physician. All patients had evidence of normal diaphragmatic excursion at the end of the procedure as assessed by fluoroscopy and none had clinical signs or symptoms of dysfunction in follow up. However it is highly unlikely that delayed PNI would have manifested.

The sample size of this study was small, but given the rarity of the need for PN displacement (0.22% of all ablation procedures), this series represents one of the largest series from a high-volume center. Multi-center registries may yield further insights into the utility and
limitations of different PN protection strategies.

**Conclusions**

Atrial and ventricular arrhythmias that originate in close proximity to the PN can be targeted successfully with PN displacement tools such as an epicardially placed steerable sheath/non-irrigated 4mm catheter combination, or a vascular or esophageal balloon, however considerable technical and procedural challenges must be appreciated. PN displacement appears particularly effective with use of an epicardially placed balloon placed through a steerable sheath. This study underscores the importance of better tools that allow safe and consistent PN protection.

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References:


**Table:** Baseline and procedural characteristics of patients undergoing phrenic nerve displacement.

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</tbody>
</table>

AADs - anti-arrhythmic drugs, LV - left ventricular, mGy - milligray, PN - phrenic nerve, SD - standard deviation, SMVT - sustained monomorphic ventricular tachycardia
Figure Legends:

Figure 1: (A) Flow diagram showing epicardial PN displacement in patients with atrial arrhythmias. Repeat intra-procedural attempts involving the balloon required switch from an anterior to a posterior pericardial access or vice versa. Note, in patients with ventricular arrhythmias, only the epicardial balloon was used which was successful in all cases (see text for details). (B) Method of PN displacement and their success according to the type of arrhythmia.

Figure 2: (A) Intimate anatomic relationship between the right phrenic nerve, right atrium/SVC junction and the pulmonary veins (left panel) and between the lateral epicardial left ventricle and the left phrenic nerve (right panel). Phrenic nerve displacement could be performed via the anterior approach (A, large arrow, left panel) or posteriorly via the transverse sinus from the posterior aspect of the left atrium (B, marked *). For epicardial VT ablation, the balloon is placed between the left phrenic nerve and the epicardium (A, dotted arrow, right panel). IVC- inferior vena cava, LPA- left pulmonary artery, LPVR- left pulmonary vein recess, PCR- post caval recess, RPVR- right pulmonary vein recess, RPA-right pulmonary artery, RA-right atrium, RB-right bronchus, RS- right superior pulmonary vein, RI-right inferior pulmonary vein, SCV/SVC- superior vena cava. (Panel A and B adapted from references27,28, with written permission from the publisher).

Figure 3: 23 year old female with debilitating atrial tachycardia with activation mapping (A) showing site of earliest endocardial activation (B) directly underneath the right phrenic nerve (black dots). An epicardially-placed steerable sheath/non-irrigated 4mm catheter (Cath+SS epi)
juxtaposed to the earliest endocardial site of activation (ABl endo) allowed PN displacement and successful ablation.

Abl- ablation catheter, Cath- catheter, CS- coronary sinus, Epi- epicardial, His- His bundle catheter, LAO-left anterior oblique, P1,2-P19,20- Pentarray catheter (Biosense Webster), RAA-right atrial appendage, RAO-right anterior oblique, SS- steerable sheath.

**Figure 4:** 34 year old female with non-ischemic cardiomyopathy and epicardial VT origin (A); substrate mapping showed areas of late potentials (black arrow on electrograms (B), within regions of low voltage scar in the mid lateral left ventricle (C, white arrow) whereas pace maps (D) matched the spontaneous VT but also resulted in PN capture. The balloon was required to be maneuvered into different locations multiple times (E-G) to allow consistent PN displacement. Absence of PN capture was achieved only once the balloon was directly over the ablation catheter.

ABl- ablation catheter, D1,2-D9,10-multipolar electrode catheter (DecaNav, Biosense Webster); epi-epicardial; ICD- implanted cardioverter-defibrillator; LV-left ventricle, SC- subcutaneous, SS-steerable sheath.
Atrial Arrhythmias 8 patients

First intraprocedural attempt

- Pericardial fluid 1 patient
  - Not successful 1

- Balloon 5 patients
  - Not successful 4
    - Sheath/catheter 2 patients
      - Success 2
    - Balloon 2 patients
      - Success 1

Second intraprocedural attempt

- Sheath/catheter 1 patient
  - Not successful 1

Third intraprocedural attempt

- Balloon 1 patient
  - Success 1

- Sheath/catheter 1 patient
  - Success 1
Epicardial Phrenic Nerve Displacement during Catheter Ablation of Atrial and Ventricular Arrhythmias: Procedural Experience and Outcomes

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**Supplemental Material**

**Supplemental Figure Legends**

**Supplemental Figure 1:** 60 female with persistent atrial fibrillation triggered from a SVC focus in whom SVC isolation was hindered by PN capture in its lateral aspect. An epicardially placed sheath/catheter combination (Cath + SS epi) allowed PN displacement to allow successful SVC isolation. Shown are right Abbreviations: Abl-ablation catheter, Cath- catheter, CS- coronary sinus, endo- endocardial, epi-epicardial, LAO-left anterior oblique, RAO-right anterior oblique, SS- steerable sheath, SVC- superior vena cava.

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**Supplemental Figure 2:** 35 year old male with non-ischemic cardiomyopathy who had epicardial VT (A). Substrate mapping showed a preponderance of late potentials (B) within the lateral epicardial LV low voltage scar (C) in close vicinity to the left PN (black dots), prohibiting ablation during the index procedure. Ablation at sites adjacent to late potentials without PN capture did not abolish VT, which recurred in follow up. Repeat attempt at epicardial ablation after PN displacement was successful (D) with abolishment of late potentials and non-inducibility of the targeted VTs originating form close proximity to the PN. Abbreviations: LV- left ventricle.
Supplemental Figure 1

Circular mapping catheter in SVC (endo)

Abl (endo)

Cath + SS (epi)

CS

RAO

LAO