

# Successful use of “cryo-mapping” to avoid phrenic nerve damage during ostial superior vena caval ablation despite nerve proximity

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## Abstract

**Background** The SVC may require ablation to treat atrial fibrillation. Phrenic nerve proximity identified with pacing maneuvers may preclude ablation.

**Methods** We tested a new method using “cryo-mapping” to ablate despite nerve proximity.

**Results** Of 833 patients undergoing ablation, 110 (12%) had arrhythmogenic substrate at the SVC/RA junction. Of these 110 patients, 66 (60%) had consistent diaphragmatic stimulation when pacing at 10 mA at the prospective site of ablation. Of these 66 patients, 7 had continued arrhythmogenicity despite attempts to modify this substrate. For these 7 patients, we paced 4 cm into the SVC where consistent phrenic nerve stimulation was obtained, and cryoablation at  $-30^{\circ}\text{C}$  was performed at sites requiring ablation. In 6 of 7 patients (86%), with continued diaphragmatic capture, cryoablation at  $-70/-80^{\circ}\text{C}$  was then performed. In 1 of 7 patients (14%), diaphragmatic stimulation ceased at  $-30^{\circ}\text{C}$ , and energy delivery stopped. In the 6 patients in whom cryoablation was completed, the arrhythmogenic substrate was successfully ablated without phrenic nerve injury.

**Conclusions** A novel “cryo-mapping” technique during phrenic nerve pacing can be used to successfully ablate arrhythmogenic substrate at the SVC/RA junction despite phrenic nerve proximity.

**Keywords** Atrial fibrillation · Cryoablation · RF ablation · Phrenic nerve · Complications · Superior vena cava

## 1 Background

Atrial fibrillation (AF) is the most common cardiac arrhythmia affecting over five million Americans [1]. Because pharmacotherapy is either ineffective or toxic in over 50% of patients requiring treatment, radiofrequency ablation is an increasingly used option. Although several methods for AF ablation exist, most techniques involve electrical isolation of the pulmonary veins [2]. Up to 30% of AF arises from non-pulmonary vein sites, and one-third of these extra pulmonary vein foci are found to arise from the musculature of the superior vena cava [3]. In order to treat this, *circumferential* ablation at the superior vena caval/right atrial (SVC/RA) junction is typically attempted, analogous to present pulmonary vein isolation approaches.

The right phrenic nerve typically courses between the superior vena cava posteriorly and the right upper pulmonary vein and then proceeds anterolaterally at variable distances to the SVC/RA junction. Because radiofrequency ablation at the SVC/RA junction may damage this nerve, pacing at high output (10 mA) at prospective sites of ablation at the SVC/RA junction is performed prior to energy delivery. If pacing at such output results in phrenic stimulation, RF ablation is not performed. Similarly, atrial tachycardia requiring ablation from the Crista Terminalis [4] or sites in the high right atrium may also arise close to the phrenic nerve.

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Cryoablation is an alternate form of energy delivery to ablate arrhythmogenic substrates [5–7]. A unique feature of cryoablation is that cooling to a temperature of  $-30^{\circ}\text{C}$  can result in *reversible* loss of electrical conduction. This unique reversible nature of cryo-energy delivery at temperatures higher ( $-30^{\circ}\text{C}$ ) than that required for permanent ablation ( $-70^{\circ}/-80^{\circ}\text{C}$ ) has been termed “cryo-mapping” [8].

We wished to determine how frequently the SVC/RA junction required ablation but was considered inappropriate because of pacing determined phrenic proximity. We further assessed the feasibility and efficacy of a new technique utilizing the principle of cryo-mapping during phrenic nerve pacing in these situations.

## 2 Methods

We searched the Electrophysiology Laboratory database at the Mayo Clinic, Rochester Minnesota, looking for patients who underwent AF ablation between January 2001 and June 2007. This retrospective study was undertaken after approval of the institutional review board of Mayo Clinic Foundation. The ablation procedure was performed with the patients intubated and mechanically ventilated under general anesthesia using isoflurane, desflurane, propofol, midazolam, and fentanyl for analgesia. Care was taken that at the time of ablation, the patient’s muscle and nerve responses were intact.

### 2.1 Ablation procedure

Radiofrequency ablation for AF was performed with wide area circumferential isolation around the pulmonary veins

**Fig. 1** Intracardiac electrograms demonstrating arrhythmogenic potentials in the superior vena cava and ectopy arising from the vein. A 20-pole multielectrode catheter (IS 19,20 [proximal]–IS 1,2 [distal]) is placed from the right atrium (proximal) into the superior vena cava (distal). The first complex seen in the tracing shows the venous potentials as near-field electrograms, particularly on poles IS 1,2–IS 9,10. In the following beat (arrow), the activation now proceeds out of the vein with the near-field electrogram now preceding the far-field right atrial electrograms (see text for details). CS 1,2–CS 19,20: coronary sinus distal-proximal, ABL d–ABL p: ablation catheter placed in low right atrium, HBE 1–HBE 4: His bundle recording catheter



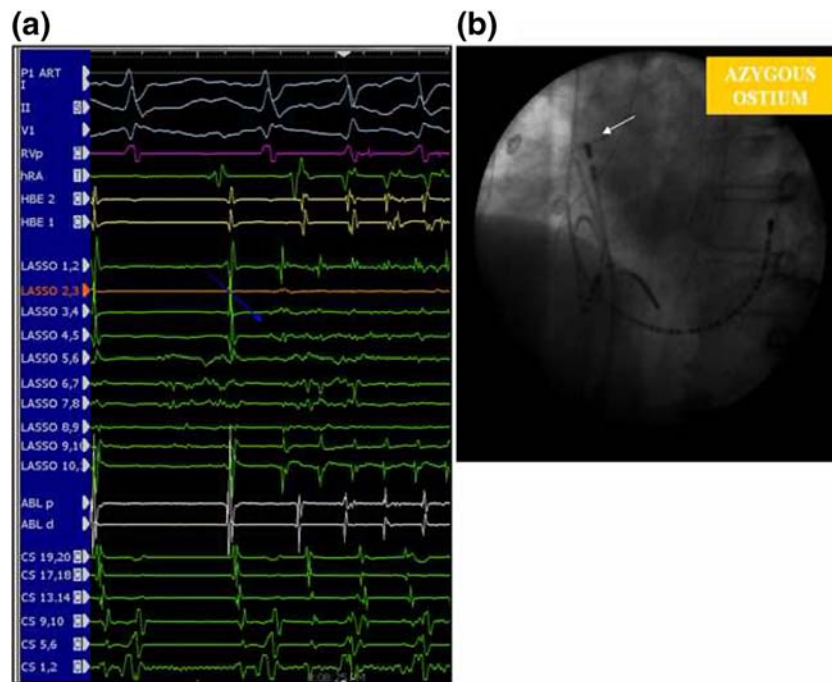
and mapping and ablation of induced persistent atrial flutters as has been described elsewhere [3, 9, 10]. In addition, intracardiac ultrasound using a linear phased-array catheter was used to identify the venoatrial junction including the SVC/RA junction [11]. Recordings were made using the Prucka™ recording system with filter settings 30–500 Hz. Pacing was performed in the standard fashion via the mapping/ablation catheter placed at or near the SVC/RA junction.

When radiofrequency ablation was performed at the SVC/RA junction, either an 8 French 5-mm distal electrode EPT™ (Boston Scientific, Natick MA) or a 6 French 4-mm tip EPT™ (Boston Scientific, Natick MA) or an 8 French 4-mm tip Carto (Johnson & Johnson, New Brunswick NJ) ablation catheter was used.

### 2.2 SVC/RA junction arrhythmogenicity determination

Ablation at the SVC/RA junction was attempted if either:

- A circumferential mapping catheter placed in the SVC identified near-field superior vena caval potentials separated from the far-field right atrial electrograms by an isoelectric period of  $>30$  ms [12] (Fig. 1), *or*
- Ectopy, initiating either atrial fibrillation or atrial flutter, arising spontaneously from the musculature of the SVC was identified (Fig. 2), *or*
- A focal automatic atrial tachycardia was found arising at the SVC/RA junction, *and* in addition,
- Pacing maneuvers [12, 13] definitively excluded the right upper pulmonary vein, azygos vein, or fragmented atrial electrograms as the source for the SVC potential.



**Fig. 2** Initiation of atrial fibrillation from the superior vena cava. Panel (a) shows an initiation of atrial fibrillation. The earliest electrograms are noted for the initiating beats on the circumferential mapping catheter placed close to the ostium of the SVC (LASSO 1,2–10,1). Activation is seen to occur later when conduction from the SVC is present to the right atrium (hRA, His bundle region [HBE], and

coronary sinus [CS]). Panel (b) shows a left anterior oblique fluoroscopic image with the circumferential mapping catheter placed in the SVC and the ablation catheter placed about a centimeter below the opening of the azygos vein (arrow). The SVC was considered arrhythmogenic and requiring further ablation if continued recurrences of atrial fibrillation clearly originating from this vein was documented

### 2.3 Identification of phrenic nerve proximity

Once ablation at the SVC/RA junction was deemed necessary, at each prospective ablation site, bipolar pacing with a distal electrode as the cathode at 10 mA output was undertaken. Radiofrequency ablation energy at 30 watts, 50°C (temperature controlled) was delivered if no phrenic stimulation was seen. If phrenic nerve stimulation was evident when pacing from the distal electrode, then radiofrequency energy was not delivered at that site.

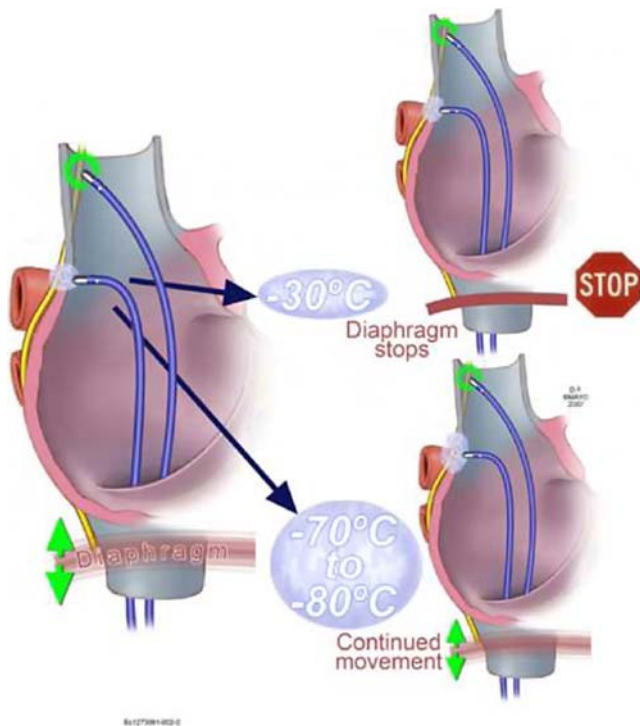
### 2.4 Identifying patients where further ablation at the SVC/RA junction is considered essential despite phrenic nerve proximity

Patients were considered to require further ablation at the SVC/RA junction even after phrenic nerve proximity identified if one or more of the following was still seen:

1. Continued recurrent atrial fibrillation with the site of earliest activation in the musculature of the SVC (Fig 2).
2. Focal atrial tachycardia arising at a site of pacing determined phrenic nerve proximity.

### 2.5 “Cryo-mapping” procedure

Once further ablation was considered essential, a pacing catheter (EP Technologies™ 4 mm/5 mm tipped electrode) was advanced into the SVC 3–4 cm cephalad to the SVC/RA junction (Figs. 3 and 4). Pacing from this catheter was performed at 20 mA output and consistent phrenic nerve stimulation with palpable and fluoroscopic movement of the right hemidiaphragm with pacing documented for at least 30 consecutive paced beats and 3 complete respiratory cycles. The patients were either under general anesthesia or deeply sedated *without* using a muscle relaxant for this period of the procedure. At the time of constant pacing with consistent phrenic stimulation, a cryo-catheter (Cryo Cath Technologies™) 4-mm tip was advanced to the site of continued RA/SVC conduction or the earliest site of activation of a focal tachycardia at or near the SVC/RA junction. Cryo-energy was delivered with a target temperature of  $-30^{\circ}\text{C}$ . If after a period of 30 seconds at this temperature consistent and continued right phrenic nerve stimulation and right hemidiaphragmatic pacing induced movement was noted, then further cooling to  $-70/-80^{\circ}\text{C}$  was undertaken. If diaphragmatic pacing was no longer seen with stimulation from the pacing catheter, then cryo-energy was turned off.



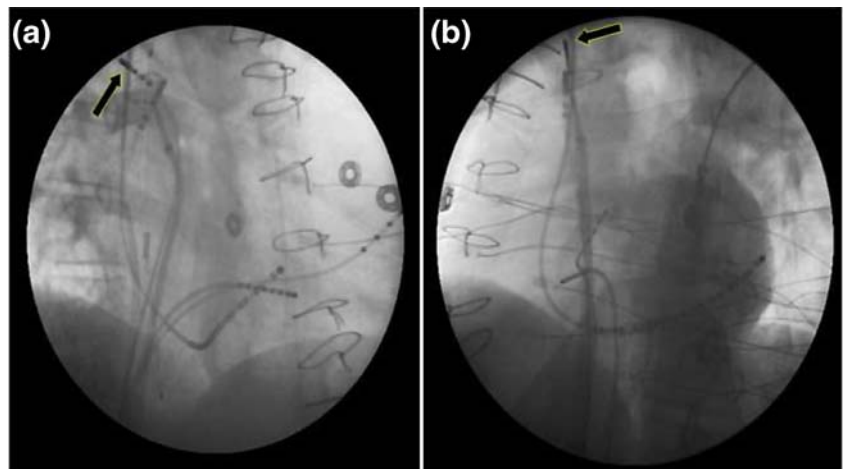
**Fig. 3** Diagrammatic representation of the cryo-mapping technique for ablation near the phrenic nerve. The pacing catheter is deeper in the SVC, and consistent diaphragmatic stimulation with pacing is first obtained. Cryo-energy to a temperature of  $-30^{\circ}\text{C}$  is applied at the site requiring ablation near previously determined phrenic nerve proximity. Top panel: If diaphragmatic movement with pacing ceases, then cryo-energy is turned off. Right bottom panel: If diaphragmatic movement continues unabated, then further cryo-energy delivered to a target temperature of approximately  $-75^{\circ}\text{C}$  until entrance block into the SVC is obtained

#### 2.6 Endpoints for cryoablation

Cryo-energy was continued at the selected sites until one of the following occurred:

1. Entrance block into the superior vena cava during sinus rhythm or right atrial pacing (Fig. 5).

**Fig. 4** Fluoroscopy of catheter position during SVC cryoablation while pacing the phrenic nerve. Panel (a) the RAO projection and panel (b) the LAO projection is shown. Note that the pacing catheter arrow is located above (cephalad) to the site of ablation. Shown also is the circumferential mapping catheter (LASSO™) and cryoablation catheter placed at the SVC-RA junction. A “wide” range fluoroscopic image is obtained so that pacing locations and the diaphragm can be viewed in the same image with realtime fluoroscopy



2. Exit block during atrial tachycardia or atrial fibrillation arising from the SVC musculature (Fig. 6).
3. Termination of focal automatic atrial tachycardia at or near the SVC/RA junction.

#### 2.7 Follow-up

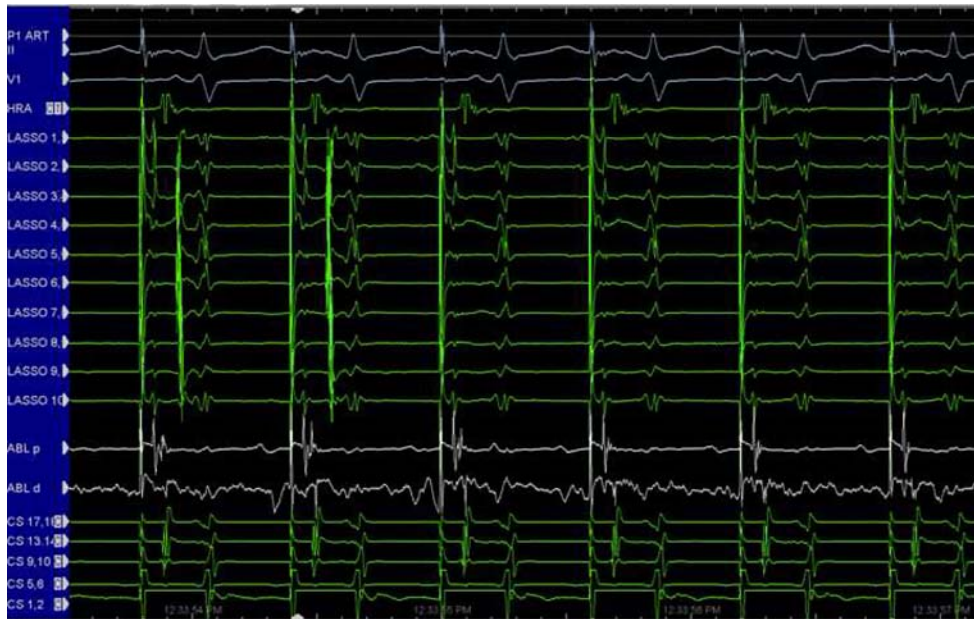
Cinefluoroscopy was performed at the end of the procedure in all patients during mechanical ventilation, spontaneous respiration following extubation, and when patients could cooperate with “sniffing” (forced inspiration against a closed glottis). Patients had follow-up at three months and one year for clinical recurrence of arrhythmia and symptoms suggestive of phrenic nerve damage. All patients had an inspiratory and expiratory chest x-ray done the morning after the procedure.

### 3 Statistical analysis

Continuous variables with symmetric distributions are presented as mean  $\pm$  standard deviation. Discrete variables are presented as frequency and percentage. Group comparison (comparing recurrence rates between patients with radiofrequency vs. cryoablation) was performed using the Fisher’s exact test.

### 4 Results

Between January 2001 and June 2007, 833 patients underwent radiofrequency ablation for drug refractory, paroxysmal or permanent atrial fibrillation. Of these patients, 110 (12% [age  $54 \pm 11$  years, 83% men and 17% women]) had partial or circumferential radiofrequency ablation at or near the SVC/RA junction. The reason for addressing the superior vena cava as an arrhythmogenic substrate was the presence of



**Fig. 5** Intracardiac electrograms obtained during cryoablation at the SVC-RA junction while pacing the phrenic nerve resulting in entrance block. (LASSO—circumferential mapping catheter placed at SVC-RA junction; CS—coronary sinus catheter (1,2 distal-17,18 proximal; ABL—ablation catheter at SVC junction.) In the first two beats obtained during coronary sinus pacing, an initial far-field electrogram (RA) follows the pacing spike. Then, a near-field SVC potential is

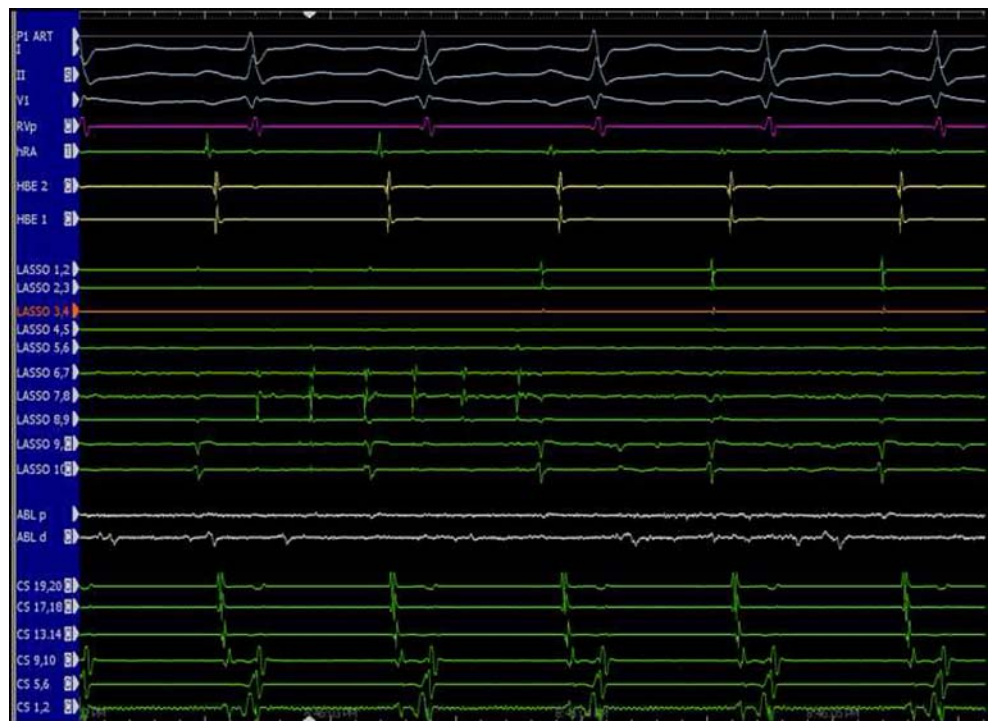
seen followed by a far-field ventricular electrogram. In the third beat on the tracing, an abrupt change in this electrogram sequence with disappearance of the near-field SVC potential is noted, signifying entrance block into the vein. Persistent synchronized movement of the diaphragm resulting from the phrenic nerve pacing that was continuously performed was consistently observed during and after ablation

arrhythmogenic potentials with isoelectric period between the far-field right atrial electrogram and the SVC potential of > 30 ms in 47 patients (43%), SVC ectopy in 33 (30%), atrial tachycardia arising from the SVC in 9 (8.1%), and atrial

fibrillation arising from the SVC in 40 (36.4%). 19 of 40 patients with AF from the SVC also had ectopy from the vein.

Of these 110 patients, 66 (60%) had phrenic nerve proximity as ascertained by pacing at 10 mA output at

**Fig. 6** Intracardiac electrograms following successful ablation at the SVC-RA junction. (LASSO—circumferential mapping catheter placed in the SVC; CS—coronary sinus multielectrode catheter; ABL—ablation catheter at SVC-RA junction; HBE—atrium near His bundle region; Hra—lateral right atrial recording catheter.) Continued rapid paroxysmal tachyarrhythmia with irregular electrograms continued to be noted on the circumferential mapping catheter within the SVC but with continued sinus rhythm following cryoablation at the SVC-RA junction. This exit block was observed for up to one hour following ablation including with the use of isoproterenol at 2 mcg/min



prospective sites of radiofrequency energy delivery. In 59 of these 66 patients (83.3%), the SVC/RA junction was ablated at sectors where phrenic nerve proximity was not present based on the above pacing maneuver. Typically, 50–75% of the circumference was ablated. In these patients, entrance block into the superior vena cava was not established as a result of this ablation, and we considered the SVC to be modified but not isolated. If there was no clear evidence of continued atrial fibrillation originating in the SVC and conducting to the atrium, no further ablation was performed. Of the 66 above mentioned patients, 7 (10.6%) had persistent atrial fibrillation arising from the SVC or had a focal atrial tachycardia at the site of pacing-determined phrenic nerve proximity and mandated further ablation. The cryo-mapping procedure, as described above, was performed in these 7 patients. Freezing to  $-30^{\circ}\text{C}$  resulted in loss of diaphragmatic capture when pacing the phrenic nerve in 1 of 7 patients, and in this patient, further electro-anatomic mapping guided modification of the SVC/RA junction was performed. In this patient, entrance block into the superior vena cava was not achieved. However, previously observed isoproterenol-induced recurrent initiation of atrial fibrillation from the SVC was no longer seen after modification. In 6 of 7 (86%) patients, diaphragmatic stimulation was consistently seen during phrenic nerve pacing. In these patients, further cryo-energy was delivered to a temperature of  $-75/-80^{\circ}\text{C}$ . Entrance block into the superior vena cava (Fig. 5) along with either exit block (Fig. 6) or cessation of recurrent atrial fibrillation was noted in 5 of the 6 patients (83.3%), and successful ablation of a focal atrial tachycardia was performed in the remaining patient. None of the 7 patients undergoing the cryo-mapping protocol and subsequent ablation had evidence of phrenic nerve injury either at the end of the procedure or on subsequent follow-up. Atrial fibrillation recurred in 2 out of 7 patients during  $9 \pm 8$  months of follow-up (range 3–36 months). One of the two patients with recurrence was the only patient with partial cryoablation ( $-30^{\circ}\text{C}$ ). There was no difference in recurrence rate between patients who had radiofrequency ablation and those who had cryoablation (31/103 [30%] vs 2/7 [29%],  $p=0.99$  NS). Phrenic nerve injury was documented in 1 out of 103 patients (0.9%) who underwent radiofrequency modification of the SVC/RA junction.

## 5 Discussion

Because of poor efficacy and toxicity associated with pharmacotherapy for atrial fibrillation, radiofrequency ablation procedures have been increasingly utilized [6]. The cornerstone for AF ablation procedures is to achieve electrical isolation of the pulmonary veins, and doing so results in significant success. Additional targets for ablation

are often required, and these include extra pulmonary triggers (superior vena cava, vein of Marshall, coronary sinus) [3, 12, 13] and multiple macroreentrant atrial flutters.

### 5.1 Role of the superior vena cava

The superior vena cava is the most common extra pulmonary trigger site for atrial fibrillation [14, 15]. Analogous to pulmonary vein arrhythmogenicity, triggers may arise from the vena caval musculature, [16] and ablation is typically performed at the SVC/RA junction to electrically isolate the SVC muscle from the right atrium. This isolation is confirmed at ablation with entrance block (loss of activation proceeding from the RA into the SVC) and exit block, atrial tachycardia, or triggers for AF unable to exit from the SVC into the RA (Fig. 6). In this study, arrhythmogenicity of the superior vena cava was identified when a superior vena caval potential, atrial tachycardia, or triggers for atrial fibrillation arising from this musculature or recurrence of AF following pulmonary venous isolation mapped to the SVC. In addition, pacing from the right atrium, right upper vein, left atrium, and within the SVC (peri-vein and intra vein pacing) was performed to clearly document the SVC (rather than the pulmonary vein) origin of these potentials [12, 13]. The SVC potential (near-field) succeeded the far-field right atrial signal during atrial pacing or sinus rhythm, but with the triggers identified, the near-field vein potential preceded the far-field atrial signals recorded on the circumferential mapping catheter, a finding diagnostic of SVC origin for the arrhythmia.

### 5.2 The phrenic nerve

The right phrenic nerve has important anatomic relations with the superior vena cava and right atrium [14]. Typically, the nerve courses from head to foot first posterior to the SVC where it is anterior to the right upper pulmonary vein and then posterolateral at the level of the SVC/RA junction continuing caudally lateral to the right atrium. Although this is the typical relationship, the course of this nerve can be variable, thus necessitating online identification of its location prior to delivering radiofrequency energy [17–19]. The technique we utilized to identify phrenic nerve proximity is one that is commonly employed, that is, pacing at 10 mA output from a catheter placed endocardially at the putative site for ablation. Capturing the phrenic nerve when pacing in a non-paralyzed patient likely suggests that the nerve is near the ablation site and radiofrequency energy delivery may injure the nerve. There are several limitations with this approach. At times during ablation energy delivery, the catheter moves and the lesion may be larger than the “range” of the pacing catheter (at 10 mA output) to stimulate the phrenic nerve. Vascular

supply to the phrenic nerve arises from the pericardial phrenic arteries, and injury to these vessels may also affect the nerve even though the ablation site is not particularly close to the nerve [20]. Typically, if pacing at the site of planned ablation is associated with diaphragmatic stimulation, then ablation energy is not delivered. In our study, when this circumstance was encountered, ablation at the SVC/RA junction, except at the sector where the phrenic nerve site was identified, was performed. In 44 of the 110 patients that we attempted SVC ablation for and had no evidence of pacing diagnosed phrenic nerve proximity, complete circumferential ablation with resulting electrical isolation of the SVC was obtained. In 59 of the 66 patients where phrenic nerve proximity was found, segmental ablation (50–75% of the circumference) avoiding the sector of phrenic nerve proximity was performed. Conduction into the vein was modified, but entrance block (electrical isolation) was not obtained in these patients. In our study, there was no difference in outcomes between complete isolation, modification with RF, or the use of our novel cryo-mapping technique (see below). It should be noted, however, that the cryo-mapping technique was utilized in patients who continued to demonstrate arrhythmogenicity (atrial tachycardia or a-fib) clearly arising from the SVC.

### 5.3 “Cryo-mapping”

In 7 patients, despite modification of the SVC/RA junction, either a focal atrial tachycardia (1/7) or recurrent atrial fibrillation arising from the SVC continued to be seen. When recurrent atrial fibrillation arising from the SVC despite partial RF ablation was seen, we proceeded with our novel technique of cryo-mapping.

Cryoablation has been used to treat various cardiac arrhythmias both endovascularly and epicardially at open chest surgical procedures [5, 7, 21–26]. One important difference between cryo-energy delivery and radiofrequency or other energy delivery is that cooling myocardial tissue to a temperature less (not as negative) than that required for ablation may be associated with transient effects on cardiac conduction. This principle (cryo-mapping) is utilized when ablating septal accessory pathways near the AV conduction system. Whether similar reversible effects occur with nerve conduction are not known but were tested in this study. In 6 of the 7 patients targeted for this procedure, there was no effect on the phrenic nerve (continued diaphragmatic capture from pacing at a site cephalad to cryo-energy delivery). In one patient, however, there was an abrupt cessation of diaphragmatic stimulation which had been consistently present until cryo-energy was delivered. On immediately stopping cryo-energy delivery, phrenic nerve stimulation from the pacing catheter resumed diaphragmatic stimulation. It is important that the energy that is being delivered is

*between* the pacing site and the diaphragm (Fig. 3). This is because with neurapraxia or even with complete phrenic nerve damage, pacing at a site *between* the injured site and the diaphragm will continue to stimulate the diaphragm [20]. Although the series is small, cryo-mapping does appear to reversibly affect phrenic nerve function.

All the patients who had continued cryoablation to  $-70^{\circ}$ – $-80^{\circ}\text{C}$  were found to have entrance block into the SVC and/or exit block of atrial fibrillation foci/tachycardia from the SVC, and no patient was found to have phrenic nerve injury at the end of the procedure or at follow-up.

### 5.4 Implications

The technique of cryo-mapping applied to avoid phrenic nerve damage during ablation may permit amelioration of arrhythmogenic substrate in the SVC when previously thought unsafe to do so. Care must be taken to maintain constant capture of the diaphragm, pacing from a site cephalad to the ablation site. This technique can also be used to avoid damage to the phrenic nerve during linear right atrial ablation (scar-related atrial flutter) or when ablating near the left atrial appendage, epicardial left ventricle, or within the posterolateral coronary venous system (left phrenic nerve sites—pacing site at most cephalad site with the phrenic capture). Ablation at or near the right upper pulmonary vein/left atrial junction particularly with balloon ablation techniques [18, 20, 27–30] may also result in phrenic nerve damage. Therefore, utilizing the principle of continued, sustained phrenic nerve pacing from a cephalad site with or without cryo-mapping at sites of planned energy (laser, ultrasound, radiofrequency, etc.) can also be considered but would require further validation.

### 5.5 Limitations

We did not have a control group in our study. Whenever continued recurrent atrial fibrillation was seen arising from the SVC in patients with phrenic nerve proximity (7 patients), cryo-mapping approach was performed. We did not demonstrate in our study improved efficacy either with complete isolation of the SVC or specifically with the use of our novel cryo-mapping technique. Our study design, however, was such that we attempted the cryo-mapping procedure only in patients who had continued initiation of atrial fibrillation or atrial tachycardia clearly arising from the musculature of the superior vena cava. Ideally, this specific group of patients (continued arrhythmogenicity) should have been randomized to further ablation vs. no further therapy to understand the incremental value of this technique. In this study, we primarily wanted to demonstrate the feasibility and safety of this new technique to offer an option when ablationists decide to pursue further

ablation despite modification at the SVC/RA junction. From an electrophysiological standpoint, atrial tachycardia or continued recurrent atrial fibrillation clearly mapped to the superior vena cava likely required ablation, and it was this premise that prompted the use of the cryo-mapping procedure. However, whether such arrhythmias seen in the EP laboratory translate to symptomatic clinical arrhythmias is not known. The methods we used to assess phrenic nerve function were simple and commonly employed (sniff test, cinefluoroscopy, history and examination). These tests would not have identified subtle changes in phrenic nerve function or diaphragmatic paresis.

## 6 Conclusion

Cryo-mapping at the SVC/RA junction where phrenic nerve proximity was identified can be effective in ablating arrhythmogenic substrate related to the SVC. Care must be taken to consistently pace the phrenic nerve from a site cephalad to the ablation site. Further study is required to assess whether cryo-energy ( $-30^{\circ}\text{C}$ ) related phrenic nerve dysfunction is always transient.

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