Atrioventricular Node Slow-Pathway Ablation Reduces Atrial Fibrillation Inducibility: A Neuronal Mechanism

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Background—Radiofrequency ablation (RFA) for atrioventricular nodal reentrant tachycardia appears to reduce atrial tachycardia, which might relate to parasympathetic denervation at cardiac ganglionated plexuses.

Methods and Results— Compared to 7 control canines without RFA, in 14 canines, RFA at the bottom of Koch’s triangle attenuated vagal stimulation–induced effective refractory periods prolongation in atrioventricular nodal and discontinuous atrioventricular conduction curves but had no effect on the sinoatrial node. RFA attenuated vagal stimulation–induced atrial effective refractory periods shortening and vulnerability window of atrial fibrillation widening in the inferior right atrium and proximal coronary sinus but not in the high right atrium and distal coronary sinus. Moreover, RFA anatomically impaired the epicardial ganglionated plexuses at the inferior vena cava inferior left atrial junction. This method was also investigated in 42 patients who had undergone ablation of atrioventricular nodal reentrant tachycardia, or 12 with an accessory pathway (AP) at the posterior septum (AP-PS), and 34 patients who had an AP at the free wall as control. In patients with atrioventricular nodal reentrant tachycardia and AP-PS, RFA at the bottom of Koch’s triangle prolonged atrial effective refractory periods and reduced vulnerability windows of atrial fibrillation widening at the inferior right atrium, distal coronary sinus and proximal coronary sinus but not the high right atrium. In patients with AP-free wall, RFA had no significant atrial effects.

Conclusions—RFA at the bottom of Koch’s triangle attenuated local autonomic innervation in the atrioventricular node and atria, decreased vagal stimulation–induced discontinuous atrioventricular nodal conduction, and reduced atrial fibrillation inducibility due to impaired ganglionated plexuses. In patients with atrioventricular nodal reentrant tachycardia or AP-PS, RFA prolonged atrial effective refractory periods, and narrowed vulnerability windows of atrial fibrillation. (J Am Heart Assoc. 2016;5:e003083 doi: 10.1161/JAHA.115.003083)

Key Words: atrial fibrillation • atrioventricular node • ganglion plexus • slow-pathway • vagal stimulation

In patients with atrioventricular nodal reentrant tachycardia (AVNRT), the effects of radiofrequency ablation (RFA) on the sinus node, atrioventricular nodal (AVN), and atrial electrophysiological properties are unclear. Previous studies had suggested the contribution of neuronal denervation caused by RFA.1–7 However, experimental evidence of parasympathetic denervation is lacking.

In the vagal pathways, the fat pad at the junction of the inferior vena cava and inferior left atrium contains the right inferior ganglionated plexus (GP_{IVC-ICA}), from which convergence points of vagal stimulation (VS) project into the AVN region.8–10 Researchers have suggested that the GP_{IVC-ICA} might be the “gateway” or integration center for extrinsic innervation to the AVN.8,11 Anatomically, the GP_{IVC-ICA} lies adjacent to the endocardially located coronary sinus ostium.12 Studies have shown that ablation in this area inhibits vagal activity in the AVN, as well as in the atria.3,4,13 Moreover, ablation of the “slow pathway” in patients with AVNRT decreases vulnerability to pacing-induced atrial fibrillation (AF),3,14 suggesting that local parasympathetic denervation is a possible mechanism. Therefore, we hypothesized that ablation at the bottom of Koch’s triangle targeting the slow pathway may result in vagal denervation due to GP_{IVC-ICA} neuronal damage. We performed a canine study to determine whether such ablation alters vagal innervation in the atria and
atrioventricular conduction due to impaired neurons within the GPivc-ICA. Furthermore, we investigated whether such denervation in canines is relevant to RFA targeting the slow pathway of Koch’s triangle in patients with supraventricular tachycardia (SVT).

Methods

Part I: Canine Study

Animal model preparations

The Institutional Animal Care and Use Committee of Dalian Medical University approved the experimental protocol in advance. Twenty-one mongrel dogs (10-15 kg each) in 2 groups of ablation (14 dogs) and control (7 dogs) were anesthetized with sodium pentobarbital (150 mg/kg intravenously). The dogs were ventilated with a constant volume-cycled respirator through a cuffed endotracheal tube, and blood oxygen saturation was maintained above 95%. The temperature and illumination of the operating room were kept stable throughout the experiment. Six-lead ECGs and intracardiac electrograms were recorded (Prucka 7000; GE Healthcare, Milwaukee, WI). The cut-off frequencies were 30–300 Hz for the bipolar intracardiac electrograms at a sampling frequency of 1 kHz.

Vagal stimulation

Propranolol was administered, initially as a 2-mg/kg bolus and subsequently in a maintenance dosage of 2 mg/kg per hour to inhibit sympathetic activity. Both cervical vagal trunks were exposed, and the cranial ends of the vagal nerves were ligated. Two pairs of electrodes were embedded in the caudal end of the vagosympathetic nerve track for stimulation. A rectangular pulse was delivered through a constant voltage stimulator at 20 Hz with a pulse width of 2 ms by a programmable stimulator (RST-2, Huanan Medical, Hunan, China). The VS threshold was defined as the voltage level that could decrease the heart rate (HR) by 30% or result in 2:1 atroventricular block. Half of the threshold voltage was used to test the effect of VS on the AVN effective refractory period (ERP). The threshold voltage × 2 was used to test the atrial ERP (AERP).

Catheter positioning

A decapolar catheter was used to record the signals in the proximal (CSp) and distal (CSD) portions of the coronary sinus. A deflectable duodecapolar Halo catheter was positioned in the right atrium to monitor the high right atrium (HRA) and inferior (IRA) right atrium, and a quadripolar catheter was placed in the His-bundle region. In addition, a 4-mm nonirrigated tip ablation catheter was deployed at the bottom of Koch’s triangle for mapping and ablation. A quadrapolar catheter was advanced into right ventricular apex for temporary pacing. All catheters were manufactured by Cordis, Biosense Webster, Inc. (Diamond Bar, CA) and were positioned with fluoroscopic guidance (Innova 2000; GE Healthcare) (Figure 1A).

Electrophysiologic studies

An atrial pacing protocol involving a single extrastimulus was performed with a programmable multichannel stimulator (Model DF-5A; Dongfang Electric Co., Chengdu, China). The pacing amplitude was set at twice the diastolic threshold. The atrial ERP was defined as the longest coupling interval of the extrastimulus that failed to capture the local atria. The AVN ERP was defined as the longest atrial coupling interval (A1–A2) observed on the His-bundle electrograms when A did not conduct to the His bundle. To determine the atrial ERP, we performed an extrastimulus with coupling intervals of 200 ms that were progressively shortened by 10 ms with a basic drive cycle length of 250 ms at all sites. AF was defined as more than 2 s of atrial activity appearing as an irregular cycle length on the intracardiac ECG and fibrillatory waves on the surface ECG. The vulnerability window (VW) for development of AF was defined as any coupling interval range of the extrastimulus at which fibrillation was induced. The control group underwent only the baseline electrophysiology study.

Radiofrequency ablation at the bottom of Koch’s triangle in canines

Radiofrequency energy was delivered at the bottom of Koch’s triangle with a 4-mm nonirrigated-tip ablation catheter (Cordis; Biosense Webster Inc.) connected to Stockert (Biosense Webster Inc.). Ablation was performed by moving the tip in a point-by-point manner from the coronary sinus ostium toward the His bundle until the His signal was detected. The tip was then moved back 2 mm for ablation (Figure 1B). For each ablation, energy was applied and then stopped automatically when the abrupt impedance rose to 30 Ω above the baseline level. The highest energy given was 60 W, with a temperature threshold of 55°C and a duration of 60 s.

High-frequency stimulation

In dogs that underwent ablation at the Bottom of Koch’s Triangle, the function of the GPivc-ICA within Koch’s triangle was assessed by delivering high-frequency stimulation (20 Hz, 10–150 V, 1–10-ms pulse width; S-88 stimulator; Grass Instruments Division, AstroNova, Inc., West Warwick, RI) to each site for 5 s. The immediate response was defined as a >50% increase in R-R intervals and a >30% increase in...
hypotension (compared to that observed without high-frequency stimulation) during stimulation.18

Histopathologic results

After the in vivo experiments were completed, all animals were humanely euthanized, and their hearts were removed for histologic examination. Tissue samples from Koch’s triangle were excised according to the anatomic and ablation markers, fixed with 4% paraformaldehyde, embedded in paraffin wax, and cut into 10-μm-thick cross-sections. Slides were stained for microscopic examination with hematoxylin and eosin, anticholine acetyltransferase (Abcam, Cambridge, MA), and antityrosine hydroxylase (EMD Millipore, Darmstadt, Germany). The number of visible nuclei was factored for the square area of the GP visible in each field with ImageJ software (National Institutes of Health, Bethesda, MD).

Part II: Clinical Study

Ablation in patients with SVT

Between 2011 and 2013, 590 patients underwent ablation of AVNRT, an accessory pathway (AP) at the posterior septum (AP-PS), or an AP at the free wall (AP-FW) at the First Affiliate Hospital of Dalian Medical University. A total of 88 patients qualified for the current study, including 42 patients with AVNRT, 12 AP-PS, and 34 AP-FW. The patients with AP-FW served as a control group, because the ablations for AP-FW were not within the Koch’s triangle. Exclusion criteria included AF; use of amiodarone; left ventricular ejection fraction <50%; congenital, ischemic, or valvular heart disease; stroke; diabetes mellitus; overweight status (body mass index >30); and renal impairment.

The study protocol was preapproved by the university’s Research Development and Human Ethics Committee. Before enrolling in the study, all patients gave written informed consent. All antiarrhythmic medications were suspended for at least 5 half-lives before the procedure. In all cases, lidocaine was administered for local anesthesia at the catheter access site.

Induction of AF

The inducibility of AF was determined as in the canine study described above. The VW of AF was determined before and after ablation. Briefly, AF inducibility was evaluated by performing a programmed single extrastimulus at twice the threshold value, followed by burst atrial pacing for 5 s at twice the threshold value. Induction was repeated at least 3 times at each site. AF was defined as >2 s of atrial activity, as revealed by an irregular cycle length on the intracardiac ECG and fibrillatory waves on the surface ECG.

Figure 1. Effects of radiofrequency ablation (RFA) at the bottom of Koch’s triangle on the heart rate (HR) and effective refractory periods (ERPs) of the atrioventricular node (AVN) in dogs. A, Catheter position; (B) Koch’s triangle and RFA sites; (C) HR; (D) AVN ERPs. ABL indicates RFA sites; CSd, distal coronary sinus; CSp, proximal coronary sinus; CT, crista terminalis; FO, fossa ovalis; Halo, Halo catheter; HIS, His bundles; HRA, high right atrium; IRA, inferior right atrium; IVC, inferior vena cava; LAO, left anterior oblique; RAO, right anterior oblique; RV, right ventricle; VS, vagal stimulation. (∗P<0.05; **P<0.01). DOI: 10.1161/JAHA.115.003083
Statistical Analysis
Data were reported as the mean value±SD. A repeated measurement of ANOVA and ANCOVA model followed by a postestimation was used to compare 3 groups of baseline, 4 sites, and pre- and postablation on AERP and VW. Paired t tests were conducted between preablation and postablation values. A first-order exponential model was used to fit the curves of A-H intervals versus the A-A pacing intervals from individual dogs. A P value of ≤0.05 was considered significant. All tests were performed with SPSS software, Version 16.0 (IBM SPSS Statistics, Chicago, IL).

Results
Part I: Animal Study
RFA at the bottom of Koch’s triangle attenuated VS-induced prolongation of AVN ERPs
Figure 1A and 1B show the location of the catheters and ablation sites, and Table 1 presents the parameters used for ablation and VS. There was no significant difference between the ablation and control groups in regard to the VS threshold. The ERPs of the sinoatrial and atrioventricular nodes, as well as of 4 atrial sites, were tested with and without VS, preablation and postablation. The HRs and the ERPs of the AVN with VS were compared pre- and postablation at the bottom of Koch’s triangle. As shown in Figure 1C, RFA had no significant effect on VS-induced reduction of the HR (107±6.1 bpm preablation versus 111±6.2 bpm postablation; P>0.21). The differences in HR responses to VS were significant preablation (152±6 versus 46±6 bpm; P<0.01) and postablation (158±5 versus 47±3 bpm; P<0.01), but VS-induced reductions in HR were comparable pre- and postablation (106.7±6.0 versus 110.9±6.2 bpm; P=0.08).

Table 1. Canine Study: Parameters for Ablation and VS

| Parameters                        | Ablation (n=14) | Control (n=7) |
|----------------------------------|----------------|--------------|
| Ablation wattage, W              | 30.5±2.15      | —            |
| Ablation time, s                 | 169.3±10.69    | —            |
| Ablation lesions (points)        | 5.2±0.5        | —            |
| Ablation temperature, °C         | 53.5±2.07      | —            |
| VS voltage, V                    | 7.8±0.35       | 7.8±0.5      |
| VS voltage at AVN ERP testing, V*| 1.3±0.07       | 1.3±0.09     |
| Procedure duration, hr           | 4.8±0.25       | 1.9±0.34     |
| Animal weight, kg                | 12.7±0.42      | 13.2±0.63    |

AVN ERP indicates atrioventricular nodal effective refractory periods; VS, vagal stimulation.

* 11 dogs were tested for AVN ERP, because 3 dogs showed AV block with VS.

Vagal stimulation significantly prolonged the AVN ERP preablation (from 159±16 to 176±17 ms; P=0.05), but it produced no significant effects postablation (from 160±13 to 164±17 ms; P=0.38) when tested at atrial pacing cycle lengths (A-A) of 250 ms with a half threshold voltage of VS. Therefore, RFA attenuated VS-induced prolongation of the AVN ERP (postablation: 4.44±4.74 ms versus preablation: 16.67±5.53 ms; P<0.05) (Figure 1D). The AVN ERPs without VS were comparable to each other (P=0.85).

RFA at the bottom of Koch’s triangle attenuated VS-induced shifts of A-H conduction–time curves
The AVN conduction time, tested as the A-H interval, was prolonged when atrial pacing cycle lengths A-A (or drive cycle lengths) were shortened from 300 to 150 ms in decrements of 10 ms in the IRA. To determine the effects of VS on the AVN conduction time, A-H conduction-time curves were compared to the A-A pacing interval pre- and postablation. As shown in Figure 2A, obtained from a representative dog, VS shifted the A-H curves toward the right, where the shift could be blocked by RFA.

During VS, the AVN conduction curves were discontinuous, or exhibited “jumping phenomena,” manifested as a sudden increase in A-H and a decrement in A-A coupling intervals. The discontinuities were defined as the maximal prolongation of A-H intervals (ΔA–H_max) during reduction of the A-A interval in 10-ms decrements. As shown in Figure 2B, VS increased the ΔA–H_max significantly, from 13±2 to 33±4 ms (P<0.01). After RFA, however, the ΔA–H_max response to VS was attenuated from 14±2 to 13±2 ms (P=0.58).

In the first-order exponential model, the time-constants (τ) of the curves were used to assess the A-H conduction intervals. As shown in Figure 2C, the τ values with VS were decreased from 88.46±7.36 to 52.03±6.99 ms (paired P<0.01; n=7). Postablation, the τ values were comparable with VS (75.7±8.23 ms) and without VS (83.79±9.56 ms) (paired P=0.06). Moreover, the changes in τ values between baseline and VS were significantly decreased postablation (12.24±3.27 ms) (paired P <0.05) compared to preablation (36.43±9.01 ms) (Figure 2D).

RFA at the bottom of Koch’s triangle partially attenuated VS-induced atrial ERP shortening
Before RFA, VS significantly shortened the atrial ERPs at all sites compared to the ERPs at baseline (Figure 3). Additionally, VS-induced shortening of atrial ERPs was comparable among the 4 sites (ANOVA; P=0.11). However, after RFA, VS-shortened atrial ERPs were diverse (ANOVA; P=0.01). Shortened atrial ERPs were comparable preablation and postablation at sites in the HRA (ΔERP: 72±19 versus 67±22 ms; P=0.45) but were decreased at sites in the Csd (ΔERP: 59±7
versus 29±7 ms; P<0.05). However, VS-induced shortening of the ERP was attenuated at sites of CSp (ΔERP: 48±7 versus 6±4 ms; P<0.01) and IRA (ΔERP: 66±5 versus 11±3 ms; P<0.01).

**RFA at the bottom of Koch’s triangle reduced the VS-induced VWS of AF**

Before and after ablation, AF was barely induced at all sites without VS, where the VWS trended to 0. Therefore, the VWS during VS were compared only for preablation versus postablation. The results showed that RFA significantly narrowed the VWS at sites in the IRA and CSp (IRA: 49±36 versus 1±3 ms; P<0.05; CSp: 45±34 versus 10±12 ms; P<0.05); however, there were no changes at sites in the HRA (63±25 versus 63±31 ms; P=0.99) and CSd (57±28 versus 35±37 ms; P=0.07) (Figure 4). At all sites, the preablation and control VWS were comparable.

**Neuronal mechanism of ablation at Koch’s triangle**

The function of GPs was evaluated by high-frequency stimulation before and after ablation. At least 1 area of response was identified within Koch’s triangle before ablation. There was no response after successful ablation. Typical response and nonresponse pressure tracings are shown in Figure 5A and 5B, respectively.

At Koch’s triangle, the atrial tissues with ablation markers were collected and sliced for histologic examination. The neuronal ganglia and fibers were found on the epicardial side, located transmurally across the atrial wall from the ablation points (Figure 5). In samples from the control group, the GP was clearly seen to connect with neuronal fibers and to be surrounded by adipose tissue (Figure 5C). Both cholinergic and adrenergic neurons were detected with antibodies for choline acetyltransferase (Figure 5D) and antityrosine hydroxylase staining (Figure 5E), respectively. In addition, the neurons were severely impaired in the tissues from the RFA group (Figure 5F). The fraction of nuclear numbers in a cross-sectional area of the GPs was compared in the ablation versus control groups. In the ablation group, the fraction of the normal nuclear number in the cross-sectional area of the GPs was significantly reduced (33±8% versus 15±7%; P<0.01).

**Part II: Clinical Study**

**Study population**

Eight-eight patients (40 men and 48 women, aged 47.9±14.3 years) who had undergone RFA for SVT at our
institution were enrolled in the study. The patients were divided into 3 groups, depending on the site of ablation: AVNRT (n=42), AP-FW (n=34), and AP-PS (n=12). The SVT had lasted for a mean period of 11.1±7.6 years, and was heterogeneous among 3 groups (P<0.05). The AP-FW patients have the longest duration, and AVNRT have the shortest.

Figure 3. Vagal-stimulation (VS)–induced atrial effective refractory periods (ERPs) preablation and postablation at the bottom of Koch’s triangle in dogs. A, Inferior right atrium (IRA); (B) high right atrium (HRA); (C) proximal coronary sinus (CSp); (D) distal coronary sinus (CSd). PreABL indicates preablation; PostABL, postablation (**P<0.01).

Figure 4. Vagal-stimulation (VS)–induced changes in the vulnerability windows (VWs) of atrial fibrillation preablation (PreABL) and postablation (PostABL) at the bottom of Koch’s triangle in dogs. A, Inferior right atrium (IRA); (B) high right atrium (HRA); (C) proximal coronary sinus (CSp); (D) distal coronary sinus (CSd) (**P<0.01).
There was no significant intergroup difference in heart chamber size or diastolic function (Table 1). Table 2 shows the group’s basic characteristics.

Effects of slow-pathway ablation on the sinus node and AVN in SVT patients

In accordance with SVT procedural guidelines, accessory pathways were mapped, and the following RFA protocol was used to treat AP-PS and AP-FW. The end point of ablation was elimination of the slow pathway, as indicated by the presence of junctional rhythm and absence of induced junctional reentry. The median number of RFA applications was 3 (range, 1–8). The averaged ablation wattage and time were less for AVNRT than for AP-PS (P<0.01) and AP-FW (P<0.01) (Figure 6A and 6B). After RFA, sinus rate increased in the AVNRT group (paired P<0.05) and tended to increase in the AP-PS group (P=0.08), but the AP-FW group had no significant changes in sinus rate (P=0.37) (Figure 6C). The antegrade AVN ERPs were prolonged in patients with AVNRT (P<0.05) and AP-FW (P<0.05), but changes in the ERPs were similar in both groups (P=0.69). However, the antegrade AVN ERP showed a trend toward shortening in patients with AP-PS (P=0.09) (Figure 6D).

Effects of slow-pathway ablation on atrial ERPs and VWs of AF in SVT patients

Atrial ERPs at 4 sites were tested in the 3 groups, at the preablation and postablation (Figure 7A through 7D). RFA showed diverse effects among groups and sites (P<0.01). RFA in AVRNT and AP-PS patients significantly affected the atrial ERP at sites of CSd, CSp, and IRA (P<0.05). However, RFA had no significant effect on all sites in AP-FW patients. Also, RFA had no significant effects at sites of HRA for all 3 groups of patients (P=0.88). For effects on VW, RFA showed diverse effects among groups and sites (P<0.01). Similarly, RFA showed diverse effects among groups and sites (P<0.01). RFA significantly narrowed the VWs of AF in the AVNRT and AP-PS patients at sites of CSd, CSp, and IRA (P<0.05), but produced
no significant effects at all sites in the AP-FW patients. Moreover, there were no significant changes at sites in the HRA in any of the 3 groups (Figure 7E through 7H). Furthermore, a regression analysis indicated that the duration of SVT history has no significant contribution to the diversity of atrial and atrioventricular node ERP and VW to AF.

Discussion

Main Findings

In the present study, we demonstrated in canines that RFA at the bottom of Koch’s triangle, where the GPV-ICA is located epicardially, attenuated the following VS-induced changes: (1) prolongation of the AVN ERP, (2) shifts of the AVN conduction curves, (3) shortening of the atrial ERP, and (4) widening of the VW of AF. Furthermore, in patients with AVNRT and AP-PS, ablation of the slow pathway within Koch’s triangle prolonged the atrial ERPs and reduced AF inducibility. However, ablation had no significant effects on the atrial ERPs in AP-FW patients, in whom the ablation sites were not located close to Koch’s triangle.

Role of VS in Dual AVN Physiology

In the mid-1950s, Moe et al\(^1\) described dual AVN physiology of the canine heart. Not until 1973, however, did Denes et al\(^2\) describe reentry of the AVN based on the theory of

| Characteristic | AVNRT (n=42) | AP-FW (n=33) | AP-PS (n=12) | P Value |
|----------------|--------------|--------------|--------------|---------|
| Male (%)       | 17 (40%)     | 17 (52%)     | 6 (50%)      | 0.616   |
| Age, y         | 50.3±13.9    | 45.3±14.5    | 47.0±15.2    | 0.307   |
| Duration of tachycardia, mo | 8.8±7.1      | 13.8±8.0*    | 11.1±6.1    | 0.016   |
| Echocardiography |              |              |              |         |
| LVEDd, mm      | 45.1±3.1     | 44.6±3.2     | 44.3±3.7     | 0.651   |
| LVESd, mm      | 27.5±2.1     | 26.7±2.4     | 26.8±2.6     | 0.272   |
| LA, mm         | 34.6±1.6     | 33.8±2.4     | 34.3±1.6     | 0.218   |
| LVEF, %        | 62.9±4.9     | 64.2±4.7     | 64.2±3.7     | 0.459   |

AP-FW indicates atrioventricular reentrant tachycardia at the free wall; AP-PS, atrioventricular reentrant tachycardia at the posterior wall; AVNRT, atrioventricular nodal reentrant tachycardia; LA, left atrial dimension; LVEDd, left ventricular end-diastolic dimension; LVESd, left ventricular end-systolic dimension. *P vs AVNRT.

Figure 6. Effects of radiofrequency ablation of the slow pathway on the heart rate (HR) and effective refractory periods of the atrioventricular node (AVN ERPs) in patients with supraventricular tachycardia. A, Average ablation wattage; (B) average ablation times; (C) heart rate; (D) AVN ERPs. AP-FW, accessory pathways at the free wall; AP-PS, accessory pathways at the posterior wall; AVNRT, atrioventricular nodal reentrant tachycardia; PreABL, preablation; PostABL, postablation (\(\ast P<0.05; \ast \ast P<0.01\)).
functional longitudinal dissociation of dual AVN physiology, which is the mechanism that underlies AVNRT.\textsuperscript{21,22} Nevertheless, the precise anatomic site and nature of the pathways remain unknown. Chiou CW et al\textsuperscript{23} reported that responses to VS were different in the slow versus fast pathways: VS significantly prolonged the ERP of antegrade conduction in the fast pathway but had no effect on retrograde or antegrade conduction in the slow pathway. In the typical slow–fast form of AVNRT, VS might be involved in formation of the AVNRT circuit in the pattern of antegrade conduction in the slow pathway.

**Figure 7.** Effects of radiofrequency ablation of the slow pathway on atrial effective refractory periods (ERPs) and vulnerability windows (VWs) in patients with supraventricular tachycardia. A and E, inferior right atrium (IRA); B and F, high right atrium (HRA); C and G, proximal coronary sinus (CSp); D and H, distal coronary sinus (CSd). AP-FW indicates accessory pathways at the free wall; AP-PS, accessory pathways at the posterior wall; AVNRT, atrioventricular nodal reentrant tachycardia; PreABL, before radiofrequency ablation at the bottom of Koch's triangle; PostABL, after radiofrequency ablation at the bottom of Koch's triangle. *$P<0.05$, **$P<0.01$ vs. PreABL.

DOI: 10.1161/JAHA.115.003083
pathway, as well as retrograde conduction in the fast pathway. Also, Mazgalev et al.\textsuperscript{24–26} used VS to induce AVNRT in isolated rabbit hearts, thus providing evidence of VS modulation in dual AVN physiology. In the present study, VS amplified the difference in conduction between the slow and fast pathways, thereby manifesting as discontinuous AVN conduction curves.

**Hyperactive VS Triggers SVT**

Ablation of the slow pathway has become an efficient, well-established treatment for AVNRT.\textsuperscript{27} However, evidence of anatomic reentry or circulating pathways is lacking and the mechanism of AVNRT remains controversial. In our study, after ablation of the slow pathway, discontinuous atrioventricular conduction was detectible in certain cases, but SVT could not be induced. In contrast, some AVNRT patients exhibited a smooth AVN conduction curve.\textsuperscript{28} This suggests that dual AVN physiology is not an exclusive mechanism of AVNRT.\textsuperscript{28} Therefore, like others, we have demonstrated the important contributions of vagal activities in triggering SVT. Ablation at the bottom of Koch’s triangle attenuated the vagal-related heterogeneity in atrioventricular conduction, thereby reducing the potential for reentry, as confirmed by impairment of the GP and blockade of vagal activity after ablation.

**Ablation of the Slow Pathway May Prevent AF Induction**

Little information exists about the specific distribution of the vagal pathways to the atrial myocardium. In this study, RFA was delivered to the endocardial tissues at the bottom of Koch’s triangle, which mimicked the epicardial fat pad at the GIvc-LA.\textsuperscript{29} Histologic results confirmed that RFA impaired the nerve fibers and neurons located in the epicardial fat pad. Ablation attenuated the ERP shortening response to VS near the region of ablation but not in any remote areas; this indicated that ablation at the bottom of Koch’s triangle resulted in remarkable denervation of the atrial vagus nerves. Previous studies showed that innervation of the GIvc-LA is the integration center for extrinsic vagal pathways. Autonomic branches from both the right and left vagus nerves pass through the GIvc-LA to the AVN.\textsuperscript{30,31} Ablation of the GIvc-LA both attenuated VS-induced VW widening and increased AF inducibility.\textsuperscript{30}

**Clinical Implications**

Ablation of the intrinsic cardiac autonomic nervous system, particularly targeting of the GP, has been shown to increase the success of AF ablation. Indeed, it has been suggested that RFA for AVNRT results in parasympathetic denervation with inadvertent tachycardia. However, it is not clear whether such denervation affects the atria. In the present study, we showed that RFA of the slow pathway at the bottom of Koch’s triangle impaired the epicardial GIvc-LA in canine atria and resulted in vagal denervation in the atria and AVN. In patients with AVNRT, slow-pathway ablation has been well documented as having a high success rate, but the anatomic mechanism for the reentrant or circulating pathway is unknown. In our dogs, VS induced discontinuities or similar “jumping phenomena” in AVN conduction curves, thereby indicating the role of vagal activity in AVNRT formation. This role was supported by the observation of increased vagal activity in patients with AVNRT.\textsuperscript{23} Moreover, in the present study, slow-pathway ablation in patients with AVNRT and AP-PS altered the atrial ERP and AF inducibility.

**Limitations**

Lack of information concerning the incidence of—and vulnerability to—AF in these patients limited our ability to determine whether or not ablation contributed to AF. Follow-up studies of these patients are ongoing regarding the incidence of AF and other arrhythmias. Also, as a retrospective study, the present study may not be representative of the general population and may be prone to selection bias due to lacking of power analysis and sample size. However, the present study indicates that the area of Koch’s triangle might need more attention. Future prospective studies are warranted to optimize the strategies for AF.

The location of the GIvc-LA was not identified with high-frequency stimulation before ablation. The endocardial ablation of the GIvc-LA might have been confounded with tissue ablation. Although the canine histologic findings indicated that GP structure was impaired after ablation, the location of the GIvc-LA may have differed from subject to subject. Only ERPs were tested and compared in this study, so it may not precisely reflect the atrial effects of RFA, such as local conduction in the atria and AVN. Further study is warranted to investigate underlying mechanisms by using a mapping system to perform ex vivo mapping with direct ablation of the GIvc-LA epicardially.

**Conclusions**

In canines, RFA at the bottom of Koch’s triangle impaired the GIvc-ICA and attenuated local autonomic innervation in the AVN and atrial tissue, which might contribute to VS-induced discontinuous AVN conduction and atrial ERP shortening. Moreover, in SVT patients, RFA of the slow pathway within Koch’s triangle prolonged local atrial ERPs and decreased AF inducibility. These findings suggested that in certain types of AF, such as vagal AF, the effect of slow-pathway ablation on

DOI: 10.1161/JAHA.115.003083
AF might be related to the denervation of local autonomic nerves.

Sources of Funding
This work was supported by external grants to Yin from Liaoning Province (201201009, L2011154, 2015020259, 201501853) and from the Chinese Ministry of Health (w201003). It was also supported by internal grants from Dalian Medical University.

Disclosures
None.

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