The Effective Contact Force to Minimize Edema Relative to Chronic Lesion Formation During Radiofrequency Ablation in Ventricular Wall

Kennosuke Yamashita,1,2 MD, Elyar Ghafoori,1,3 MS, Josh Silvernagel,1,3 MS, John Ashton,4 PhD, Derek J. Dosdall,2,3,5 PhD, Robert MacLeod,2,3 PhD and Ravi Ranjan,1,2,3 MD

Summary
Radiofrequency (RF) ablation results in creation of acute edema which can lead to temporary disruption of electrical propagation.

The goal of this study was to find the effective contact force (CF) to minimize edema formation in comparison to the lesion size.

Ventricular RF lesions (n = 49) were created by a CF-sensing catheter in a canine model (n = 10) with varying force for 30 seconds. Animals underwent T2-weighted (T2w) and late gadolinium enhancement MRI (LGE-MRI) immediately after ablation and at 12 weeks. Acute LGE lesion volume, acute edema, and chronic LGE lesion volume were measured. Acute edema/acute LGE lesion volume ratio was used to divide the lesions into two groups.

Mean edema/lesion volume ratio was 5.0 ± 2.8. The lesions were divided into greater edema group (n = 8) and smaller edema group (n = 41) based on a cutoff edema/lesion volume ratio. When comparing the two groups, the CF and force time integral (FTI) were significantly lower in the greater edema group. There was no difference in catheter power setting, tip temperature change, impedance drop, and bipolar electrogram voltage change. Acute LGE volume and chronic lesion depth were significantly smaller in the greater edema group. Moreover, receiver-operator characteristic curve for the smaller edema lesion group showed that the most discriminant cutoff values for CF and FTI were 12.4 g and 584 gs, respectively.

To minimize edema size while still forming permanent lesions, ablation should be performed with FTI > 584 gs or CF > 12.4 g.

Key words: Acute edema, Magnetic resonance imaging

Radiofrequency (RF) catheter ablation has become an important modality to treat most cardiac arrhythmias. With real-time monitoring of tip-to-tissue contact force (CF) there has been a significant improvement in clinical outcomes along with a decrease in complications. In spite of best efforts, arrhythmia recurrence rates following catheter ablation are still high enough for additional procedures to be needed to improve outcomes. Acute ablation-related edema is thought to be one of the main causes of reversible electrical conduction block and arrhythmia recurrence. We have recently reported that RF ablation is associated with creation of extensive acute edema that resolves over the span of about a week and that RF ablation results in greater edema as compared to Cryo ablation. Late gadolinium enhancement magnetic resonance imaging (LGE-MRI) has been used to estimate myocardial lesion maturation after catheter ablation and T2 weighted (T2w) MRI has been used to estimate edema formation. The goal of this study was to determine the effective ablation setting to minimize edema formation in comparison to the chronic lesion size.

Methods
This study was performed in a canine model (n = 10). The study protocol was approved by the Institutional Animal Care and Use Committee at the University of Utah. Dogs were initially anesthetized using propofol and intubated for ventilation, and general anesthesia was maintained with 1% to 3% isoflurane. Bifemoral vein access...
was obtained percutaneously and a 5 Fr sheath was inserted in a femoral artery for continuous arterial blood pressure monitoring. Through the left femoral vein, an intra-cardiac echocardiogram (ICE) catheter (Siemens Healthcare, Erlangen, Germany) was inserted into the right atrium. An 8.5 Fr SL0 sheath was inserted into the right femoral vein and left atrial access was achieved with a trans-septal BRK-1 needle (St. Jude Medical, Minnetonka, USA) under ICE and fluoroscopic guidance. A fast-anatomical map of the biventricular chambers was created using CARTO3 (Biosense Webster, Diamond Bar, USA) and lesions were marked on the endocardial surface. A total of four to six ablation lesions was placed in ventricles using the SmartTouch™ CF-sensing catheter (Biosense Webster, Diamond Bar, USA) and marked in the CARTO3 mapping system. Ablation parameters included varying the CF in a power-controlled mode at 25 W, 30 W, or 40 W for 30 seconds. We also recorded the catheter position during the ablation to look at catheter movement and measured catheter stability. After the initial ablation procedure, the animal underwent a MRI (0 day: Acute phase) and then was extubated and recovered. Each animal underwent a repeat MRI at 12 weeks (Chronic phase). Following 12-week MRI, the animals were euthanized and the hearts were excised for pathological lesion assessment.

**Lesion characterization in gross pathology:** The hearts were fixed in 10% formalin solution and then sliced into 2-mm sections. The lesions were matched with the corresponding locations marked in the electro-anatomical map of the CARTO system for the correct ablation parameters. Lesions that were distinct and without overlap were included in the analysis. Digital images of both sides of each slice were obtained. The area of the transmural lesion (average of the calculated area on both sides of the slice) was multiplied by the slice thickness to get the lesion volume for each slice. For slices that had lesions only on one edge of the slice, the depth of the lesion and area of the lesion on the surface were used to calculate the lesion in that slice assuming a conical shape for the lesion. The volume across all the slices for each lesion was summed to get the total lesion volume. For calculating the depth of the lesion, incisions were made through each lesion to measure the maximal depth.

**MR imaging:** Following the ablation procedure, the animal remained intubated and anesthetized and was transferred to a 3T MRI scanner (Siemens Healthcare, Erlangen, Germany). We obtained both T2w images for edema quantification as well as LGE-MRI for lesion quantification. The corresponding T2w and LGE images were identified. The volume of enhancement for T2w and LGE-MRI were calculated using Seg3D image processing software (SCI Institute, University of Utah, USA). The area of enhancement was quantified for each slice and summed up over all the slices covering that lesion. Figure 1 shows an example of quantification for edema volume (T2w) and LGE enhanced volume in the acute phase. Ablated lesions were defined using a pixel intensity threshold algorithm as described in previous reports. Normal and ablated tissues were distinguished based on a bimodal distribution of pixel intensities and ablated lesions were defined at three standard deviations above the normal mean tissue pixel intensity in LGE-MR imaging. The acute lesion in LGE-MRI is characterized with a hypo-intense region in the middle, encircled with a ring of enhancement. After segmentation of the ring-like enhanced area based on the quantitative threshold, the hypo-intense area in the middle was added to it and included in the acute lesion volume. Edema was defined similarly at two standard deviations above the normal wall mean tissue pixel intensity in T2w MR imaging. For non-contrast T2w images we used respiratory navigated, ECG triggered, DIR prepared 2D TSE pulse sequence with TE = 81 ms, TR = 3 cardiac cycles, echo train length = 21, fat suppression using SPAIR, in-plane resolution of 1.25 × 1.25 mm, slice thickness of 4 mm. LGE-MRI was acquired 20 minutes after infusion of Gd-BOPTA (0.15 mmol/kg, Bracco Diagnostic Inc., Princeton, NJ). For LGE-MRI, we used respiratory navigated, ECG triggered, inversion recovery prepared 3D GRE with resolution = 1.25 × 1.25 mm, slice thickness of 2.5 mm, TR/TE = 3.1/1.4 ms, flip angle = 14°, TI = 230-330 ms.

**Statistical analysis:** Statistical analyses were performed with JMP 13 software (SAS Institute Inc., Cary, NC, USA). Categorical data were expressed as frequencies and were compared using chi-square or Fisher’s exact tests. Continuous data were presented as mean ± standard deviation and were compared by Student’s t-test. Acute edema volume/acute LGE volume was calculated and the mean + 1 SD was used as cutoff value to divide into greater edema lesions and smaller edema lesions. Comparison between LGE-MRI data and the pathology data was done with univariate linear regression analysis. To dichotomize the force time integral, the receiver-operator characteristic (ROC) curve was built to determine the best cutoff value by maximizing the Youden index and then the area under curve was calculated. A probability (P)-value < 0.05 was accepted as indicating statistical significance.

**Results**

Forty-nine ventricular lesions in 10 canine models (weight 28.9 ± 5.3 kg) were assessed in this study. An example of overlapping lesions that was excluded from the analysis as they could not be segmented separately is shown in Figure 2. Mean edema/lesion volume ratio was calculated as 5.0 ± 2.8 in all lesions. The lesions were divided into greater edema group (n = 8) and smaller edema group (n = 41) based on a cutoff edema/lesion volume ratio of 7.8 (mean + 1 SD). Figure 3 shows examples of lesion maturation in MRI in acute phase in both groups immediately after ablation and chronic phase and gross pathology. While acute lesion volumes in LGE-MRI were more than twice as large as chronic ones, chronic lesion volumes measured by LGE-MRI and pathology were comparable. Also, no edema was detected by T2w imaging in chronic phase. Table I contains the catheter information, edema, and LGE-MRI volume in the acute and chronic phase and the gross pathology volume data for both the groups. Mean force and minimum force were significantly higher in the smaller edema group. Also, force time integral (FTI) was significantly larger in the smaller edema group. Acute edema volume was compara-
Figure 1. Examples of LGE-MRI and edema (T2w) volume quantification. A: Example of enhancement in LGE-MRI shown in gray scale (left) and volume quantification by Seg3D software (right). Ablation lesion enhancement was defined as three standard deviations above the normal mean tissue pixel intensity and is shaded in red. B: Example of edema based on T2w MRI showing enhancement in gray scale (left) and edema volume quantification by Seg3D (right). Edema was defined as two standard deviations above the normal wall mean tissue pixel intensity and is shaded in blue. LGE, late gadolinium enhancement; and MRI, magnetic resonance imaging.

Figure 2. Examples of overlapping lesions (white arrow) in LGE (A) and T2w MRI (B) that were excluded from the analysis.

ble between the two groups but the acute LGE volume and chronic LGE volume in greater edema group was significantly smaller. Additional to the MRI volumes, chronic lesion volume and lesion depth in gross pathology were also significantly different in both the groups. On the other hand, no significant difference was observed in
power, change of catheter tip temperature, impedance, and bipolar electrogram. The maximum catheter tip movement corrected for respiratory movement was 0.87 mm in greater edema group and 0.84 mm in smaller edema group, and these results were not significantly different. Moreover, we have analyzed all included lesions at four different locations (Table II). Mean CF and FTI were higher in LV apex and LV free wall than in LV septal and RV septal. Change of catheter tip temperature in RV septal was higher than others. However, no significant difference was found in the acute lesion volume, chronic lesion depth, and edema/lesion ratio. Figure 4 shows the correlation between acute edema volume and acute LGE-MRI volume with the acute edema being 2.7 times larger than the area of enhancement in acute LGE-MRI. Acute edema volume/LGE-MRI volume ratio shows inverse relationship with CF (Figure 4B). Figure 5 shows the correlation between chronic LGE-MRI lesion depth and volume with that measured in gross pathology, with both the measurements having a strong correlation ($r^2 = 0.86$, $P < 0.0001$ and $r^2 = 0.75$, $P < 0.0001$). Since the FTI was significantly different between the two groups, we next calculated the most discriminant cutoff value for the FTI as 584 gs (sensitivity = 1.00, specificity = 0.66) by maximizing the Youden index as shown in Figure 6.
In this study, we analyzed RF ablation lesion formation with acute edema quantification while monitoring the CF and other ablation parameters. We have previously reported that acute edema is significantly larger for RF lesion as compared to Cryo ablation. In that study, no power data was shown for Cryo ablation as CF has little relevance for Cryo lesions. On the other hand, higher CF is related to larger lesion size in RF ablation but there have been no data to date on how to make a durable scar while minimizing the acute edema relative to the lesion size. The main results obtained from this study are as follows: The primary predictor of ventricular lesions with relatively larger edema was the relatively smaller CF and FTI. The mean stable catheter-to-tissue CF as well as the minimum CF was the biggest differentiator between smaller edema and greater edema lesions. Other catheter parameters such as power used, impedance drop, catheter movement, and decrease in local bipolar signal amplitude were not statistically different between the two groups.

Creating durable lesions is crucial to having good outcomes following ablation procedures. Numerous reports have shown that not all areas targeted for ablation result in chronic scar and that lack of effective lesion creation affects clinical outcomes. Preclinical studies have shown correlation between CF and lesion size. Edema has always been known to be associated with RF ablation but only in recent studies has the creation of extensive edema as seen in acute MRI been quantified. FTI indicates force time integral; and LGE, late gadolinium enhancement.

### Discussion

In this study, we looked at the various ablation parameters and compared their relationship to creating chronic lesions minimizing the associated acute edema relative to the chronic lesion size. We found that for powers ranging from 25 W to 40 W the biggest predictor of creating durable lesions without overwhelming edema was the greater CF and FTI. For lesions associated with the greater edema group, the mean force was 12.9 g (with a minimum mean force of 4.0 g) as compared to 27.2 g (with a minimum of 12.4 g) for the smaller edema group. So, at low CF there is extensive relative edema creation without significant chronic lesion creation. One of the main reasons is that

### Table I. Comparison of Lesion Characteristics

|               | Greater edema group | Smaller edema group | P value |
|---------------|---------------------|---------------------|---------|
| n             | 8                   | 41                  |         |
| Catheter      |                     |                     |         |
| Power, W      | 28.7 ± 4.9          | 30.3 ± 6.5          | 0.51    |
| Mean Force, g | 12.9 ± 4.9          | 27.2 ± 12.8         | 0.003   |
| Minimum Force, g | 4.1 ± 4.2        | 12.4 ± 4.9          | 0.03    |
| FTI, gs       | 390.2 ± 150.0       | 802.8 ± 364.7       | 0.003   |
| ΔTip temperature, °C | 2.5 ± 2.3        | 2.0 ± 3.4           | 0.68    |
| ΔImpedance, ohm | −20.0 ± 13.4     | −25.2 ± 14.2        | 0.34    |
| ΔBipolar electrogram, mV | −6.6 ± 5.1     | −4.5 ± 3.4          | 0.15    |
| Max catheter movement, mm | 0.87 ± 0.33    | 0.84 ± 0.46         | 0.88    |
| MRI           |                     |                     |         |
| Acute LGE volume, mm³ | 121.2 ± 42.4  | 401.4 ± 158.1       | < 0.0001|
| Acute edema volume, mm³ | 1189.7 ± 320.8 | 1541.8 ± 700.1     | 0.17    |
| Chronic LGE volume, mm³ | 75.3 ± 18.6     | 141.2 ± 67.9        | 0.0095  |
| Chronic edema volume, mm³ | 0             | 27.6 ± 1.9          | 0.85    |
| Time gap between LGE imaging and gadolinium injection | 27.8 ± 1.6 | 27.6 ± 1.9 | 0.85 |
| Pathology     |                     |                     |         |
| Lesion volume, mm³ | 56.6 ± 21.7      | 118.6 ± 55.2        | 0.008   |
| Lesion depth, mm | 3.1 ± 2.8       | 6.8 ± 2.3           | < 0.001 |

FTI indicates force time integral; and LGE, late gadolinium enhancement.

### Table II. Comparison of Lesion Characteristics at Each Location

|               | LV apex | LV free wall | LV septal | RV septal | P value |
|---------------|---------|--------------|-----------|-----------|---------|
| Power, W      | 28.8 ± 5.2 | 32.8 ± 6.9  | 31.0 ± 6.6 | 28.8 ± 5.5 | 0.28    |
| Mean Force, g | 25.3 ± 13.3 | 31.3 ± 14.2 | 19.6 ± 9.6 | 19.8 ± 10.2 | 0.04    |
| Minimum Force, g | 10.0 ± 12.5 | 14.5 ± 9.4  | 8.4 ± 7.2  | 9.5 ± 4.6  | 0.23    |
| FTI, gs       | 763.3 ± 399.7 | 908.9 ± 397.2 | 585.3 ± 286.5 | 593.5 ± 294.9 | 0.05    |
| ΔTip temperature, °C | 0.9 ± 3.1   | 1.5 ± 3.1   | 0.5 ± 2.4  | 4.8 ± 2.6  | 0.002   |
| ΔImpedance, ohm | 25.0 ± 14.6  | 27.3 ± 14.9 | 24.8 ± 17.2 | 19.5 ± 9.6 | 0.51    |
| ΔBipolar electrogram, mV | 3.8 ± 2.7   | 4.0 ± 2.1   | 4.2 ± 2.5  | 7.1 ± 5.8  | 0.08    |
| Wall thickness | 11.3 ± 2.0  | 12.5 ± 1.9  | 12.2 ± 1.8 | 12.4 ± 2.1 | 0.15    |
| Acute LGE volume, mm³ | 340.1 ± 151.7 | 422.6 ± 180.5 | 350.8 ± 180.9 | 276.3 ± 174.2 | 0.16    |
| Edema/Lesion ratio | 5.0 ± 0.6     | 4.6 ± 3     | 5.7 ± 3    | 5.2 ± 3.4  | 0.79    |
| Lesion depth in histology, mm | 5.3 ± 2.7   | 6.5 ± 1.8   | 5.6 ± 3.5  | 5.5 ± 2.8  | 0.29    |

LV indicates left ventricular; RV, right ventricular; FTI, force time integral; and LGE, late gadolinium enhancement.
lower tip-to-tissue CF and FTI values are not enough to create large durable scar lesions. As a result, the acute edema volume/acute LGE lesion volume ratio in the greater edema group becomes relatively larger. We also looked at catheter stability while creating these lesions. The average catheter movement in these studies was minimal at less than a millimeter in both groups, so catheter movement was unlikely to play a role. We have also found that we could not use local bipolar electrogram attenuation as a means of differentiating between lesions with relatively greater or smaller edema as the amplitude of electrogram amplitude attenuation was similar in both the groups. Similarly, changes in catheter tip temperature change, or impedance change was not useful in differentiating between the two groups. However, edema/lesion ratio was not affected by catheter power directly. Higher power application has been shown to result in making bigger and deeper lesions but high power alone does not seem to help in avoiding making insufficient lesions with large edema.

When translating this new information to clinical practice, it is important to be mindful of the chamber being ablated. Even in the greater edema group we found le-

Figure 4. A: Correlation between acute T2w and LGE-MRI volume at day 0. B: Correlation between acute T2w/LGE-MRI volume ratio and contact force. LGE, late gadolinium enhancement; and MRI, magnetic resonance imaging

Figure 5. Correlation between chronic lesion depth (A) and chronic lesion volume (B) as seen in LGE-MRI versus gross pathology. LGE, late gadolinium enhancement; and MRI, magnetic resonance imaging

Figure 6. ROC curve for the force time integral for predicting smaller edema formation. ROC indicates receiver-operator characteristic.
sion depths of 3.1 mm.

The walls of the atria are much thinner; thus, it is possible that additional force applied to the atria may not lead to an improvement in the edema/lesion volume ratios. Even at low CF, relatively large edema creation will extend laterally but still result in transmural lesions in the atria. On the other hand, if one is targeting areas in the ventricle, a higher CF like in the smaller edema group, with a mean of 27.0 g, will yield larger chronic lesions with an average depth of 6.8 mm while minimizing relative size of the edema. In our study, the best FTI cutoff value for avoiding larger edema formation was 584 gs. In the TOCCATA-16 and EFFICAS studies,10 20 g force was used as target CF and 400 gs as minimum FTI. In our study, the FTI and the minimum CF were significantly different between the groups, indicating that the low catheter tip-to-tissue CF was associated with the creation of insufficient lesion formation.

The use of MRI for evaluating myocardial substrate as well as lesion quality assessment is becoming more routine.6-9,11,16-18 In this study, we confirmed that that acute LGE-MRI overestimates chronic lesion size by almost a factor of three and that the chronic LGE-MRI is an excellent predictor of pathology-determined lesion size both in terms of depth and volume.

In summary, we have shown that very low CF (< 10 g) at clinically used power settings (25-40 W) results in large edema with smaller chronic lesions. This new finding will be useful in the clinical setting when carrying out ablation, especially in the ventricle.

Limitations: The study was designed to look at the ventricular lesion size and edema size after RF ablation. As a result, we need to be careful when applying this to atrial lesion formation. Given the difficulty in measuring accurate edema due to the thin atrial wall, this might be the closest we can get to directly imaging the edema. Also, given the thin atrial wall, edema will be lateral to the lesion itself as most lesions will be transmural so the edema volume will be much smaller although not of any less significance as we can still get temporary conduction block lateral to the ablation lesion.

Conclusions

Chronic lesion size was significantly smaller in the greater edema group. Moreover, both CF and FTI were also significantly smaller. Ventricular radiofrequency ablation procedure should be performed with FTI ≥ 584 gs or minimum CF ≥ 12.4 g to avoid creating small lesions with relatively large edema.

Disclosure

Conflicts of interest: None.

References

1. Calkins H, Kuck KH, Cappato R, et al. HRS/EHRA/ECAS Expert Consensus Statement on Catheter and Surgical Ablation of Atrial Fibrillation: Recommendations for Patient Selection, Procedural Techniques, Patient Management and Follow-Up, Definitions, Endpoints, and Research Trial Design: a Report of the Heart Rhythm Society (HRS) Task Force on Catheter and Surgical Ablation of Atrial Fibrillation. Developed in Partnership with the European Heart Rhythm Association (EHRA), a Registered Branch of the European Society of Cardiology (ESC) and the European Cardiac Arrhythmia Society (ECAS); and in Collaboration with the American College of Cardiology (ACC), American Heart Association (AHA): Pacific; the Asia; 2012 Heart Rhythm Society (APHRS), the Society of Thoracic Surgeons (STS), the Governing Bodies of the American College of Cardiology Foundation, the American Heart Association, the European Cardiac Arrhythmia Society, the European Heart Rhythm Association, the Society of Thoracic Surgeons: Pacific; the Asia Heart Rhythm Society, and the Heart Rhythm Society. Heart Rhythm 2012; 9: 632-96.
2. Aliot EM, Stevenson WG, Almendral-Garrote JM, et al. EHRA/ HRS Expert Consensus on Catheter ablation of ventricular Arrhythmias: developed in a partnership with the European Heart Rhythm Association (EHRA), a Registered Branch of the European Society of Cardiology (ESC), and the Heart Rhythm Society (HRS); in collaboration with the American College of Cardiology (ACC) and the American Heart Association (AHA). Heart Rhythm 2009; 6: 886-933.
3. Reddy VY, Dukkipati SR, Neuzil P, et al. Randomized, controlled trial of the safety and effectiveness of a contact force-sensing irrigated catheter for ablation of paroxysmal atrial fibrillation: results of the TactiCath contact force ablation catheter study for atrial fibrillation (TOCCASTAR) study. Circulation 2015; 132: 907-15.
4. Tung R, Vaseghi M, Frankel DS, et al. Freedom from recurrent ventricular tachycardia after catheter ablation is associated with improved survival in patients with structural heart disease: An International VT Ablation Center Collaborative Group study. Heart Rhythm 2015; 12: 1997-2007.
5. Ouyang F, Antz M, Ernst S, et al. Recovered pulmonary vein conduction as a dominant factor for recurrent atrial tachyarhythmias after complete circular isolation of the pulmonary veins: lessons from double Lasso technique. Circulation 2005; 111: 127-35.
6. Parmar BR, Jarrett TR, Burgon NS, et al. Comparison of left atrial area marked ablated in electroanatomical maps with scar in MRI. J Cardiovasc Electrophysiol 2014; 25: 457-63.
7. Ranjan R, Kato R, Zviman MM, et al. Gaps in the ablation line as a potential cause of recovery from electrical isolation and their visualization using MRI. Circ Arrhythm Electrophysiol 2011; 4: 279-86.
8. Ghafoori E, Kholmovski EG, Thomas S, et al. Characterization of gadolinium contrast enhancement of radiofrequency ablation lesions in predicting edema and chronic lesion size. Circ Arrhythm Electrophysiol 2017; 10.
9. Yamashita K, Kholmovski E, Ghafoori E, et al. Characterization of edema after cryo and radiofrequency ablation based on Serial MR Imaging. J Cardiovasc Electrophysiol 2019; 30: 255-62.
10. Ikeda A, Nakagawa H, Lambert H, et al. Relationship between catheter contact force and radiofrequency lesion size and incidence of steam pop in the beating canine heart: electrogram amplitude, impedance, and electrode temperature are poor predictors of electrode-tissue contact force and lesion size. Circ Arrhythm Electrophysiol 2014; 7: 1174-80.
11. Parmar BR, Jarrett TR, Kholmovski EG, et al. Poor scar formation after ablation is associated with atrial fibrillation recurrence. J Interv Card Electrophysiol 2015; 44: 247-56.
12. Krahn RP, Singh SM, Ramanan V, et al. Cardiovascular magnetic resonance guided ablation and intra-procedural visualization of evolving radiofrequency lesions in the left ventricle. J Cardiovasc Magn Reson 2018; 20: 20.
13. Yokoyama K, Nakagawa H, Seres KA, et al. Canine model of esophageal injury and atrial-esophageal fistula after applications of forward-firing high-intensity focused ultrasound and side-
firing unfocused ultrasound in the left atrium and inside the pulmonary vein. Circ Arrhythm Electrophysiol 2009; 2: 41-9.

14. Reddy VY, Shah D, Kautzner J, et al. The relationship between contact force and clinical outcome during radiofrequency catheter ablation of atrial fibrillation in the TOCCATA study. Heart Rhythm 2012; 9: 1789-95.

15. Kautzner J, Neuzil P, Lambert H, et al. Efficas II: Optimization of catheter contact force improves outcome of pulmonary vein isolation for paroxysmal atrial fibrillation. Europace 2015; 17: 1229-35.

16. Ranjan R, Kholmovski EG, Blauer J, et al. Identification and acute targeting of gaps in atrial ablation lesion sets using a real-time magnetic resonance imaging system. Circ Arrhythm Electrophysiol 2012; 5: 1130-5.

17. McGann C, Akoum N, Patel A, et al. Atrial fibrillation ablation outcome is predicted by left atrial remodeling on MRI. Circ Arrhythm Electrophysiol 2014; 7: 23-30.

18. Kholmovski EG, Silvernagel J, Angel N, et al. Acute noncontrast T1-weighted MRI predicts chronic radiofrequency ablation lesions. J Cardiovasc Electrophysiol 2018; 29: 1556-62.