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Longer Duration Versus Increasing Power During Radiofrequency Ablation Yields Different Ablation Lesion Characteristics

Ryan T. Borne, MD, William H. Sauer, MD, Matthew M. Zipse, MD, Lijun Zheng, MS, Wendy Tzou, MD, Duy T. Nguyen, MD

ABSTRACT

OBJECTIVES The goal of this study was to characterize differences in ablation lesions with varying radiofrequency ablation (RFA) power and time.

BACKGROUND Increasing power delivery or prolonging duration can improve the efficacy of RFA. However, the extent to which ablation lesion characteristics change, based on varying degrees of power and duration, is unknown.

METHODS An ex vivo model consisting of viable bovine myocardium in a circulating warmed saline bath was used. An open irrigated RFA catheter was positioned with 10 g of force in the perpendicular position, and RFA was delivered at powers of 20, 30, 40, and 50 W and for various time intervals, up to a total of 90 s, at each power. An in vivo porcine thigh preparation model was used to perform RFA at 50 W for 5 s and 20 W for 30 s. Lesion volumes were analyzed.

RESULTS Greater power delivery and longer radiofrequency time increased ablation lesion size. However, compared with a proportional change in radiofrequency duration, the same proportional increase in power produced a significantly larger lesion volume ($p < 0.01$). For in vivo models, 50 W/5 s ablation lesions yielded similar volumes but significantly less depth than 20 W/30 s ablation lesions. Peak temperatures were not significantly different at 2 and 4 mm with 50 W/5 s versus 20 W/30 s.

CONCLUSIONS Varying power and duration will confer different ablation lesion characteristics that can be tailored according to the substrate/anatomy that is being ablated. This phenomenon has important implications during catheter ablation. (J Am Coll Cardiol EP 2018;4:902–8) © 2018 by the American College of Cardiology Foundation.

Radiofrequency ablation (RFA) has become increasingly used and is considered first-line therapy for certain cardiac arrhythmias. Newer catheter development and design, including open irrigated, force-sensing catheters, have been shown to improve safety and outcomes (1–3). However, challenges remain in the delivery of durable ablation lesions, and complications arise related to collateral damage from ablation. The decision to deliver a larger, deeper lesion (i.e., mid-myocardial or epicardial substrates seen commonly with ventricular arrhythmias) or a superficial lesion (i.e., the posterior left atrial wall where risk of esophageal injury is present) needs to be considered with ablation to minimize collateral damage and to improve safety and efficacy.

Multiple strategies have been developed to improve the efficacy of RFA: changing the

From the Section of Cardiac Electrophysiology, Division of Cardiology, University of Colorado, Aurora, Colorado. This research was partly funded by a grant from Biosense Webster, Inc. Drs. Sauer and Nguyen receive significant research grants from Biosense Webster and CardioNXT and educational grants from Biosense Webster, Boston Scientific, and Medtronic. Drs. Sauer and Nguyen have a provisional patent on partially insulated focused catheter ablation. Drs. Nguyen and Sauer have nonpublic equity interests/stock options in CardioNXT. Dr. Tzou is a consultant to Biosense Webster, and Abbott; and has received speaker honoraria from Biosense Webster, Boston Scientific, and Medtronic. All other authors have reported that they have no relationships relevant to the contents of this paper to disclose.

All authors attest that they are in compliance with human studies committees and animal welfare regulations of the authors' institutions and Food and Drug Administration guidelines, including patient consent where appropriate. For more information, visit the *JACC: Clinical Electrophysiology* author instructions page.

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surrounding environment with the use of different irrigation solution (i.e., half normal saline), bipolar and multipolar ablation, and high-power/short-duration ablation strategies. However, the simplest change is by varying ablation power and/or duration. Although increasing power delivery and prolonging the duration of RFA are readily available strategies that can improve radiofrequency (RF) efficacy, the extent to which ablation lesion characteristics (e.g., size, shape, depth) change based on varying degrees of power and duration is unknown. The goal of the present study was to characterize differences in ablation lesions with varying RFA power and time.

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METHODS

The experimental protocols conformed to the Guide for the Care and Use of Laboratory Animals, and they have been approved by the Institutional Animal Care and Use Committees of the University of Colorado.

EX VIVO MODEL. An ex vivo model consisting of viable bovine myocardium, a submersible load cell, circulating bath, and an open irrigated ablation catheter was assembled. A load cell, used to standardize application of energy, was submersed in the bath and contained a section of bovine ventricular myocardium. An open irrigated catheter was positioned with 10 g of force perpendicular to the myocardium by using a deflectable sheath. This ex vivo model has been validated and well described (4–7). RFA was delivered at powers of 20, 30, 40, and 50 W and at various time intervals (15, 30, 60, and 90 s) for each power. Ablation lesion characteristics and volumes were analyzed. In addition, for ex vivo tissue temperature analyses, RFA was delivered at 50 W for 5 s and 20 W for 30 s with 10 g of force while tissue temperatures at various depths and lesion volumes were measured.

TISSUE TEMPERATURE ANALYSIS. T-type thermocouple wires were inserted horizontally into the myocardium at 2 mm and 4 mm depths and perpendicular to the ablation surface. Thermocouple analog inputs were converted to digital signals by using LabVIEW software version 7.0 (National Instruments, Austin, Texas). Temperature and temperature increases over time were recorded in a continuous fashion throughout the RF application at a rate of 5 Hz. Peak tissue temperature was defined as the maximum temperature reading during RF application. The area under the temperature curve was calculated as a temperature time integral for all lesions. RF applications that generated steam pops were excluded from the temperature curve analysis.

IN VIVO MODEL. An in vivo model was constructed. Yorkshire pigs were anesthetized, and porcine thighs were prepared bilaterally. Briefly, the skin and connective tissues were dissected to expose the underlying muscle. The skin was raised to form a cradle, and heparinized, warmed porcine blood was circulated at 350 ml/min. An ablation catheter was placed perpendicular to the muscle surface. Ablations were delivered at 50 W for 5 s and 20 W for 30 s with the same amount of force, as measured by a force-sensing, open irrigated tip RF catheter; ablation lesions were tagged by using the electroanatomic mapping system and averaged between 10 and 20 g of force. After the animals were euthanized, thigh preparations were resected, and the ablation lesion sizes were measured.

The power and duration parameters used in the in vivo models were determined after a limited pilot study to choose the optimal setting that would yield useful lesion volume measurements but not have excessive steam pops. Although 20 W is not frequently used for ventricular arrhythmias, it is often used during left atrial posterior wall ablation to mitigate risk of esophageal injury.

ABLATION LESION ANALYSIS. Single lesion volumes were acquired by visually analyzing tissue sections with a digital micrometer and were calculated by using the equation for an oblate ellipsoid based on the core lesion. For each lesion, maximum depth (A), maximum diameter (B), depth at maximum diameter (C), and lesion surface diameter (D) were measures.

$$LesionVolume = \left[0.75\pi\left(\frac{B}{2}\right)^2(A-C)\right] - \left[0.25\pi\left(\frac{D}{2}\right)^2(A-2C)\right]$$

A Nikon D7000 (Nikon Inc., Melville, New York) was used to obtain visual representations of the ablation lesions, and Adobe Photoshop Elements 12 (Adobe Systems Incorporated, San Jose, California) was used to process the images.

STATISTICAL ANALYSIS. Statistical analyses were performed by using IBM SPSS version 24.0 (IBM SPSS Statistics, IBM Corporation, Armonk, New York). The chi-square test was used for dichotomous

ABBREVIATIONS AND ACRONYMS

AF = atrial fibrillation
PVI = pulmonary vein isolation
RFA = radiofrequency ablation

TABLE 1 Ablation Lesion Characteristics and Parameters for Different Power and Duration in the Ex Vivo Model

	Volume (mm^3)	Average Maximum Depth (mm)	Maximum Diameter (mm)	Impedance Reduction (Ω)	Peak Temperature (°C)
20 W					
15 s	2.7 ± 1.9	0.4 ± 0.2	4.7 ± 0.5	14 ± 2	36 ± 1
30 s	8.3 ± 2.5	0.9 ± 0.2	4.9 ± 0.4	12 ± 2	36 ± 1
60 s	18.1 ± 10.3	1.5 ± 0.5	5.4 ± 0.8	18 ± 4	36 ± 1
90 s	35.5 ± 18.1	2.3 ± 0.6	6.4 ± 1.0	13 ± 10	36 ± 1
30 W					
15 s	10.9 ± 4.9	1.2 ± 0.3	4.9 ± 0.5	17 ± 4	37 ± 2
30 s	28.6 ± 17.7	2.0 ± 0.7	6.0 ± 1.1	16 ± 2	38 ± 1
60 s	85.2 ± 30.9	3.4 ± 0.6	8.4 ± 1.0	16 ± 3	38 ± 1
90 s	117.6 ± 42.4	4.0 ± 0.6	8.7 ± 0.8	16 ± 6	38 ± 1
40 W					
15 s	16.1 ± 9.3	1.4 ± 0.4	5.5 ± 1.1	16 ± 5	38 ± 1
30 s	56.9 ± 24.4	2.8 ± 0.5	7.5 ± 0.9	21 ± 9	38 ± 1
60 s	142.5 ± 31.8	4.5 ± 0.4	9.1 ± 0.8	31 ± 16	37 ± 1
90 s	215.8 ± 58.5	5.2 ± 0.5	10.4 ± 1.2	19 ± 9	39 ± 2
50 W					
15 s	30.9 ± 15.8	1.8 ± 0.5	6.7 ± 1.2	21 ± 5	39 ± 2
30 s	110.1 ± 33.3	3.8 ± 0.4	8.6 ± 1.1	19 ± 7	43 ± 2
60 s	249.4 ± 65.2	5.6 ± 0.5	10.7 ± 1.1	15 ± 8	40 ± 2
90 s	395.4 ± 104.0	6.6 ± 0.5	12.5 ± 1.3	31 ± 11	40 ± 2

Values are mean ± SD.

comparisons in lesion characteristics from various configurations, and the analysis of variance test was used to compare continuous variables. P values are from paired comparisons within each condition versus the control. Statistical significance was defined as a p value <0.05.

RESULTS

EX VIVO STUDIES. Table 1 describes ablation lesion characteristics in the ex vivo model at 15, 30, 60, and 90 s using 20, 30, 40, and 50 W. Both greater power delivery and longer RF time increased ablation lesion size (Figure 1). For example, a 30 s lesion with 20 W versus 50 W resulted in an ablation volume of 8.3 ± 2.5 mm^3 and 110.1 ± 33.3 mm^3, respectively, whereas a 30 W lesion for 15 s versus 90 s resulted in an ablation volume of 10.9 ± 4.9 mm^3 and 117.6 ± 42.4 mm^3. Figure 2 presents representative ablation lesions at 20 W, 40 W, and 50 W for various durations.

Compared with a proportional change in RF duration, the same proportional increases in power produced a significantly larger lesion volume. For example, doubling ablation duration at 20 W from 30 s to 60 s results in an increase in lesion volume from 8.3 to 18.1 mm^3, an increase of 2.2-fold. However, doubling power from 20 to 40 W for 30 s results in an increase in lesion volume from 8.3 to 56.9 mm^3, an increase of 6.7-fold. Higher powers for shorter duration created larger ablation lesions than lower powers for longer duration. A 40 W lesion for 30 s was larger than a 20 W lesion for 90 s (56.9 mm^3 vs. 35.5 mm^3, respectively). If force was held constant, lesion size would increase proportionally to power and only half as much for duration of ablation.

Impedance reductions and peak catheter tip temperatures are described in Table 1. Impedance reductions for 20 W/60 s was similar to those for 40 W/15 s (18 ± 4 Ω vs. 16 ± 5 Ω, respectively), and impedance reductions for 20 W/60 s were similar to 50 W/15 s (18 ± 4 Ω vs. 21 ± 5 Ω, respectively). Catheter tip peak temperatures for 40 W and 50 W at 15 s were higher than those for 20 W at all time intervals. Catheter tip peak temperature for 50 W lesions (39°C to 43°C) were higher than for all powers <50 W. There were no steam pops for any group or time.

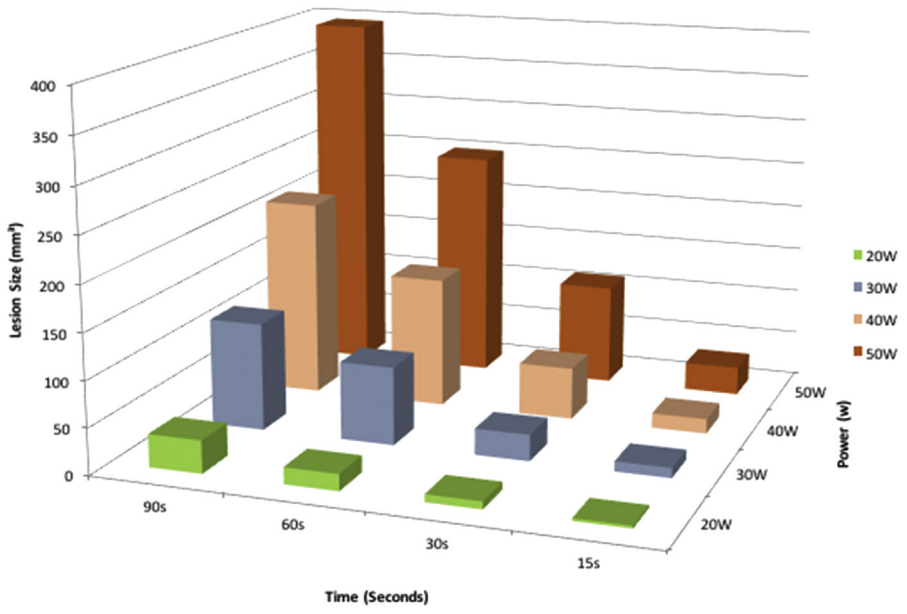
IN VIVO STUDIES. For in vivo studies, ablation lesion characteristics are described in Table 2. Neither lesion volume nor diameter was statistically different for 50 W/5 s and 20 W/30 s, although there was a trend toward smaller lesion volumes and larger lesion diameters for the high-power/short-duration group: lesion volumes of 35.3 ± 9.9 mm^3 vs. 44.2 ± 17.9 mm^3, respectively ($p = 0.07$) and lesion diameters of 6.8 ± 0.8 mm vs. 6.2 ± 1.5 mm ($p = 0.11$). Importantly, lesion depths were less for 50 W/5 s compared with 20 W/30 s lesions: 2 mm vs. 2.9 mm ($p < 0.01$).

EX VIVO TISSUE TEMPERATURES. Consistent with both in vivo and ex vivo ablation lesion findings, peak tissue temperatures were not statistically different for 50 W/5 s and 20 W/30 s at 2 mm (41.6 ± 2.3°C vs. 42.6 ± 2.5°C, respectively; $p = 0.20$) and 4 mm depths (40.2 ± 1.4°C vs. 40.6 ± 2°C; $p = 0.44$) (Figure 3). However, for 50 W/5 s, the slope of temperature rise was greater at 2 and 4 mm, 4.8°C/s vs. 1.3°C/s ($p < 0.01$) and 6.1°C/s vs. 1.3°C/s ($p < 0.01$), respectively, compared with 20 W/30 s. In addition, the temperature-time integral (area under the curve) was smaller for 50 W/5 s at both 2 mm and 4 mm depths, 2,129°C-s vs. 2,237°C-s ($p < 0.01$) and 2,111°C-s vs. 2,178°C-s ($p < 0.01$), compared with those for 20 W/30 s.

DISCUSSION

STUDY FINDINGS. In the present study, using both ex vivo and in vivo models of ablation, varying power and duration will confer different ablation lesion

FIGURE 1 Ablation Volumes for Varying Power (20 to 50 W) and Duration (15 to 90 s) in the Ex Vivo Model



characteristics. We found that, predictably, greater power delivery or longer RF time will increase ablation lesion size. However, compared with a proportional change in RF duration, the same proportional increase in power will produce a significantly larger lesion volume. If force were held constant, lesion size would increase proportionally to power and only half as much for duration of ablation. In addition, we found that high-power, short-duration RFA had similar lesion volumes but less lesion depth than low-power, long-duration lesions.

ABLATION LESION EFFICACY. Termination, non-inducibility, and survival free of arrhythmias are the goals of catheter ablation. However, this success

FIGURE 2 Representative Ablation Lesions With Varying Degrees of Power and Duration

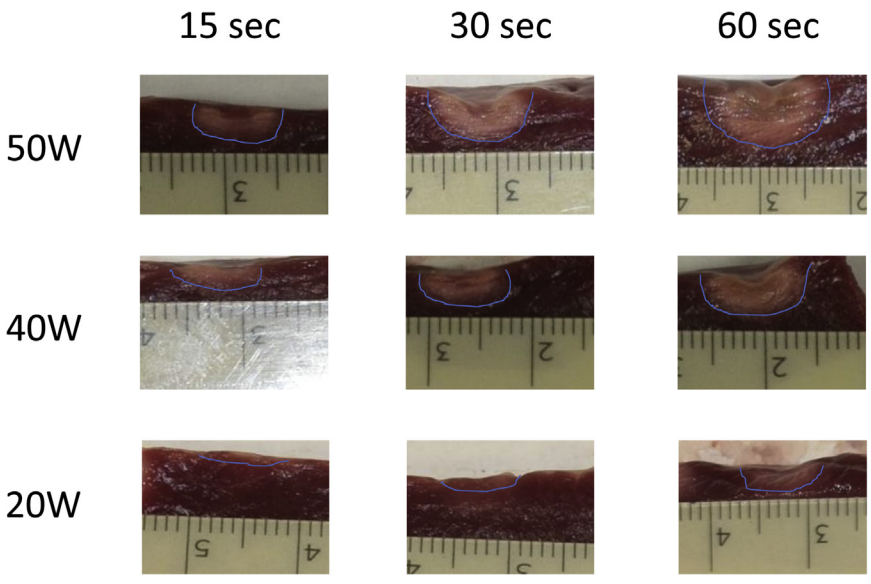


TABLE 2 Ablation Lesion Characteristics and Parameters for Low Power/Long Duration and High Power/Low Duration in the In Vivo Model

	50 W/5 s	20 W/30 s	p Value
Volume, mm^3	35.3 ± 9.9	44.2 ± 17.9	0.07
Average maximum depth, mm	2.0 ± 0.2	2.9 ± 0.6	<0.01
Maximum diameter, mm	6.8 ± 0.8	6.2 ± 1.5	0.11
Impedance reduction, Ω	20 ± 7	14 ± 7	0.01
Force, g	16 ± 1	16 ± 2	0.88

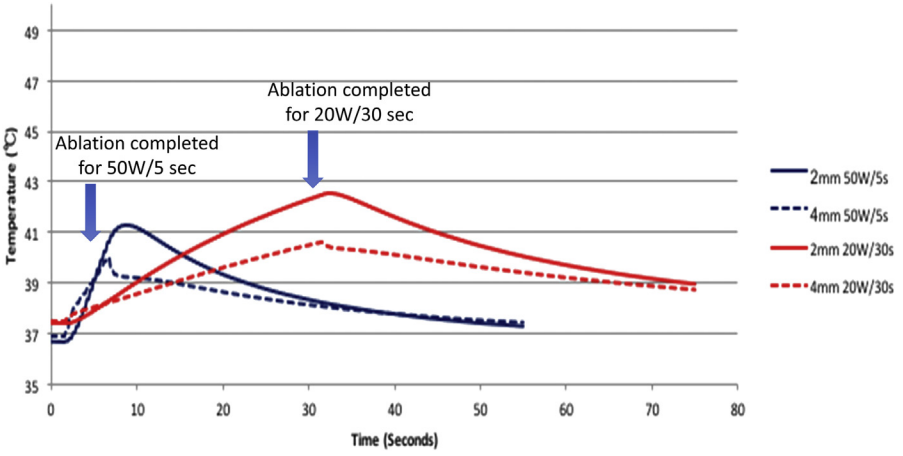
Values are mean ± SD.

depends on several factors, one of which is efficacy of tissue destruction. This study builds on the prior limited research in determining the efficacy of ablation with varying powers and duration. Lesion size is proportional to power, such that any method that will allow for greater power into the tissue will result in more tissue heating and greater depth of thermal injury. Likewise, longer duration will result in larger lesions. Tissue temperatures follow a monoexponential rise during RFA, with the half-time for lesion formation being 5 to 10 s (8). Therefore, lesion formation should be nearly complete by 45 to 60 s. Although the ex vivo data are consistent with these findings, lesion size continued to increase beyond 60 s. Further studies are therefore needed to determine optimal durations for ablation.

Bhaskaran et al. (9) evaluated the use of higher power, shorter duration lesions in an in vivo beating heart ovine model. Using a force-sensing, irrigated 3.5 mm ablation catheter, RFA was performed at 40 W for 30 s and 40 to 80 W for 5 s each. Lesion depth was >2 mm for all ablation delivery except for 40 W/5 s. The width and depth of 60 W/5 s were similar to those of 40 W/30 s. Steam pops occurred in the 40 W/30 s, 70 W/5 s, and 80 W/5 s groups. The results suggest that atrial transmural lesions will result from high-power/low-duration lesions but at the expense of higher risk of steam pops for power >60 W. Our in vivo results are also consistent with these findings in that lesion depth was >2 mm for both ablation strategies, but 50 W/5 s did not result in any steam pops.

A recent publication evaluated differences in lesions with high power/short duration and low power/long duration (10). A strategy of 90 W for 4 s was believed to yield the optimal conditions of lesion size and safety parameters and was compared with standard ablation lesions at 25 W for 20 s in a beating heart swine model. Lesion sets included superior vena cava isolation, pulmonary vein isolation (PVI), and linear ablation in the right atrium. The high-power/short-duration strategy yielded wider lesions that were of similar depth. However, compared with standard ablation, the lesion sets with high power/short duration yielded significant improvement in lesion-to-lesion consistency, reduced the frequency of linear gaps both visually and histologically, and were comparable with regard to safety profile. Although there was a single steam pop, there was no catheter char or perforation with the high-power/short-duration lesions. It is important to note that these findings are in atrial tissue and may not pertain to the ventricle (in particular to diseased tissue).

FIGURE 3 Temperature Curves for In Vivo Models of Low Power/Long Duration and High Power/Low Duration in the In Vivo Model



CLINICAL APPLICATION. Clinical outcomes comparing ablation with varying power and duration have also been limited. Among patients undergoing catheter ablation for atrial fibrillation (AF), the use of high-power lesions (50 W) and continuous "perpetual motion" was shown to be safe and effective (11,12). Yuyun et al. (13) performed a meta-analysis of power output during ablation for AF; only 5 studies examined some aspect of power and efficacy. Qualitatively, power <30 W was safe but had low efficacy; power of 30 to 45 W was safe and efficacious; and power >45 W was efficacious but had increased risks. Powers >45 W but for short duration were safe and efficacious. Kanj et al. (14) compared outcomes at different power outputs for patients undergoing PVI. During 6 months of follow-up, freedom from AF was observed in 78% (8 mm tip catheter group at 70 W), 82% (higher power irrigated catheter group at 50 W), and 68% (lower power irrigated catheter group at 35 W). Nilsson et al. (15) compared higher power and shorter application time (45 W/20 s) versus a conventional technique using a lower power output and longer application time (30 W/120 s). Although there were no significant differences in outcomes or complications between the 2 groups, the higher power group had significantly reduced total RF time.

Obviously, the use of increasing both power and duration need to be weighed against the risk of catheter tip char and/or steam pops. Although there were no steam pops or char formation in our ex vivo studies, this outcome may not accurately reflect the risk in clinical practice given that the tissue is not as viable and thus not as susceptible to tissue boiling and steam pops; also, with either strategy of increasing lesion size, there remains a concern for increasing the risk of complications. The high-power ablation used during PVI (up to 50 W) was associated with a significantly higher risk of steam pop (mean of 1.3 pops per patient) and 20% incidence of pericardial effusion (14). However, the high power (up to 45 W/20 s) used for PVI in another group resulted in no audible steam pops in any patient (15). Leshem et al. (10) found that the strategy of 90 W/4 s resulted in no catheter char and a single steam pop that did not lead to complications. Clearly, there is a narrow safety margin of high-power ablation that requires continuous monitoring of ablation parameters, and further studies are needed to assess the risk of complications in clinical practice.

There are 2 important implications of these findings. The first is that when ablating arrhythmias in which the substrate is deep, such as mid-myocardial ventricular tachycardia, papillary muscle ventricular tachycardia, or atrial arrhythmias arising from the left atrial appendage ridge, uptitration of power might be more efficacious than longer duration of lower power lesions. The second implication of these findings is the result of collateral damage. This concept is most important over the left atrial posterior wall, in which the thin-walled atrium is in close proximity to the esophagus (typically <5 mm), where the risk of esophageal injury (including atrio-esophageal fistula) exists (16). PVI requires ablation over the posterior wall, and thus effective ablation with shallow lesions are desired, in which case a strategy of high power/low duration might prove most effective and safe. Although this scenario has been observed in clinical studies, further studies are needed to directly assess the impact of a high-power/low-duration strategy during ablation of AF.

FUTURE INVESTIGATIONS. Although the ex vivo and in vivo models provide insight into ablation lesion characteristics associated with differences in power and duration of ablation, this insight does not necessarily equate to how best to perform ablation in clinical practice. Randomized trials should be performed with the specific outcomes being patient-centered clinical endpoints, in which the risks and benefits in differences of ablation strategies can be determined.

STUDY LIMITATIONS. First, the ex vivo and in vivo experimental models were performed on normal cardiac tissue and do not necessarily replicate the pathophysiologic substrates during clinical ablation. However, clinical pathologies frequently occur in which normal myocardium is ablated, and these studies provide insight into the basic understanding of RFA. In addition, the risk of steam pop in an ex vivo model, in which the tissue is not as viable and thus not as susceptible to tissue boiling, does not reflect those in a real-life setting. Second, an important variable, contact force, was held constant, and its contribution was not explored. This method is in contrast to ablation in a beating heart, when contact force is frequently not stable. Third, these studies only measure lesion volumes and do not explore potential collateral injury due to high powers, even if only for a shorter duration. Furthermore, lesion volumes were delineated by visual calculation of the core lesions, and histologic assessment was not performed. Fifth, ideally multiple power/duration combinations would be used in the in vivo studies;

however, given the limited number of animals, we were limited to choosing 2 combinations. Finally, although lesion size is a surrogate for effective ablation, it does not necessarily equate to improved clinical outcomes and safety.

CONCLUSIONS

Varying power and duration will confer different ablation lesion characteristics that can be tailored according to the substrate/anatomy that is being ablated. In our ex vivo model, power uptitration had a greater effect on creating larger lesion sizes, compared with the same proportional increase in RF duration. In our in vivo model, higher power, shorter duration RFA had similar lesion volumes but less lesion depth than lower power, longer duration RFA. This phenomenon has important implications during ablation procedures, such as PVI, or for refractory myocardial tissues, such as those responsible for certain ventricular arrhythmias. Further clinical data are needed to assess the efficacy and safety of differences in ablation strategies.

ADDRESS FOR CORRESPONDENCE: Dr. Duy T. Nguyen, Section of Cardiac Electrophysiology, University of Colorado, B-132, Leprino Building, 12401 East 17th Avenue, Aurora, Colorado 80045. E-mail: duy.t.nguyen@ucdenver.edu.

PERSPECTIVES

COMPETENCY IN MEDICAL KNOWLEDGE: Multiple ablation strategies are needed for different arrhythmic substrate. Deeper lesions are required for mid-myocardial substrates in ventricular arrhythmias, whereas shallower lesions may be safer for ablation over the left atrial posterior wall. Varying RFA power and duration will yield differences in ablation lesion characteristics. We found that increases in power produce a significantly larger lesion volume compared with the same proportional increase in duration. In addition, while high-power, short-duration lesions yield similar ablation volumes compared with low-power, long-duration lesions, the high-power/short-duration lesions are significantly more shallow than the alternative. These findings have important implications during catheter ablation.

TRANSLATIONAL OUTLOOK: This study examined the biophysical characteristics of increasing power and/or duration of ablation lesions in in vivo and ex vivo models. Although this study provides insight into ablation lesion characteristics associated with differing ablation strategies, human studies and randomized trials must be performed with the specific outcomes being patient-centered clinical endpoints, in which the risks and benefits of different ablation strategies can be determined.

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