



High-power, low-flow, short-ablation duration—the key to avoid collateral injury?

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Abstract

Background A common approach to ablating along the posterior wall of the left atrium in atrial fibrillation ablation is to use low power with longer duration for durable lesions and reducing thermal injury. We hypothesize that similar lesions can be safely obtained at high power with low open-irrigation flow and low duration.

Methods Twenty-two porcine ventricles were placed in a tissue bath with circulating 0.45% NaCl at a maintained temperature of 37 °C. Bipolar radiofrequency ablation (RFA) with a 4-mm-tip irrigated, force-sensing catheter was performed with various combinations of irrigation, power, and duration at 20g of contact force. Fiber optic temperature probes were placed at depths of 3 mm and 5 mm. Temperature was measured during and 30 s after each ablation.

Results Two hundred sixty-eight lesions were made. At a fixed power and flow rate, lesion surface diameter, maximum lesion width, and lesion depth all increased with longer ablation duration. At fixed duration and irrigation flow rate, increased power led to increased lesion dimensions. At a lower flow rate (2 ml/min), surface lesion diameter and maximum width were significantly larger compared to a higher flow rate (17 ml/min), but lesion depth was not significantly different. The maximum temperature and the rate of temperature rise at a depth of 5 mm with different power settings and ablation durations were lower as compared to a depth of 3 mm at both flow rates (2 ml/min and 17 ml/min).

Conclusions Effective lesions can be performed with high-power and short-ablation durations, thereby reducing RFA procedure time. Higher power, shorter duration lesions result in adequate temperature for myocardial lesion formation at 3 mm, but do not result in excessive temperature at 5 mm depth, potentially reducing the risk of collateral injury. Compared to higher irrigation flow rate, larger surface lesions and comparable maximum lesion width are achieved with lower irrigation flow rate, thus resulting in better lesion contiguity.

Keywords Radiofrequency catheter ablation · Atrial fibrillation · Complications · Thermodynamics

1 Introduction

Radiofrequency catheter ablation (RFA) is an accepted treatment for atrial fibrillation (AF) with low overall complication rates [1–3]. Even so, thermal injury from radiofrequency ablation may cause unintended collateral damage to contiguous

structures including the esophagus. This can result in esophageal ulcerations or, rarely, atrioesophageal fistulas (AEF) and possible death [4–8]. Many techniques aimed at reducing unintended thermal injury to the esophagus, such as using lower RF power with longer ablation duration when ablating the posterior wall of the left atrium, or monitoring esophageal temperatures with ablation termination if excessive esophageal heating is detected, have been proposed to mitigate this risk but have had no proven benefit [9–12]. Even the introduction of force-sensing catheters which was promoted as a means of limiting excessive catheter tip force to thin-walled regions of the atria may have actually been associated with an increased rate of thermal injury [13–15].

Investigators have studied the utility of high-power and short-duration (50–80 W for 5 s) ablation achieving similar lesion depth and fewer complications compared to conventional lower-power, longer-duration settings (20–30 W for 30 s),

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suggesting that limiting ablation power may not be the best strategy at minimizing thermal injury [16]. Latency of thermal conduction may result in rapid heating of superficial tissues with limited heating of deeper layers if duration of energy delivery is brief. Also, reducing rate of catheter irrigation would be anticipated to favor superficial lesion formation because of reduced surface convective cooling. We hypothesized that RFA with high power, low open-irrigation flow, and short duration would achieve tissue heating deep enough to assure transmural ablation of thin-walled atrium but have less deep heating when compared to ablation with lower-power, high open-irrigation flow, and long-duration conditions.

2 Methods

2.1 In vitro preparation

Twenty-two freshly killed porcine hearts were obtained, and the ventricles were harvested for ablation. The left ventricle was sutured to an indifferent electrode, mounted onto a tissue holder, and placed in a plexiglass tank with circulating 0.45% normal saline maintained at a constant temperature of 37 °C via a digital heating immersion circulator (model 1122S, VWR, Radnor, PA). Superfusate flow velocity was set at 9 L/min with a maintained temperature of 37 °C. The Beaumont Research Institute approved this study, and no external funding was received.

Ablation protocol Radiofrequency ablation was performed with a 4-mm-tip open-irrigated contact force-sensing catheter (ThermoCool SmartTouch, Biosense Webster, South Diamond Bar, CA). The catheter was positioned perpendicular to the left ventricular tissue and adjusted by the operator maintaining a constant desired contact force of 20g throughout energy delivery. Two fluoroptic thermometry probes were inserted directly beside the ablation electrode into the left ventricular tissue at depths of 3 mm and 5 mm and maintained at these depths throughout energy delivery by placing a custom made adhesive barrier around the probes. Continuous temperature data was collected (Luxtron model 3000, Lumasense Technologies, Inc., Santa Clara, CA; measurement range, 0–125 °C; accuracy, ± 0.2 °C) throughout and for an additional 30 s after each ablation. Power settings for the ablation were set at 20 W, 30 W, 40 W, and 50 W. Ablation durations were set at 5, 10, 20, 30, and 40 s. Open-irrigation flow using 0.45% normal saline through the ablation catheter was set at 2 ml/min and 17 ml/min for each power and duration setting. For each combination of power, flow, and irrigation, five attempts were performed. Steam pops were directly visualized and recorded with immediate termination of energy delivery.

Data collection The lesions were measured for its maximum lesion diameter on the endocardial surface. Lesions were then

bisected in two perpendicular planes to measure depth and maximal internal width. Lesions with observed steam pops were excluded from the analysis.

Statistical analysis Data were recorded and stored in an electronic database. Continuous values were expressed as means \pm standard deviations. Depth, maximum width, and surface width were all examined separately with repeated measure multivariable analyses adjusting for the power, irrigation flow, and time of ablation. A *p* value of < 0.05 was considered significant. SAS for Windows® 9.3 (Cary, NC) was used for all analyses. The differences between the maximum temperature at 3 mm, and the 5-mm depths were examined with Wilcoxon rank sum tests without adjusting for power, irrigation, or duration.

3 Results

A total of 268 lesions were produced in 22 porcine heart preparations. At a fixed power and flow rate, lesion surface width, maximum lesion width, and lesion depth all increased with increasing ablation duration ($p < 0.0001$). Similarly, at fixed duration and irrigation flow rates, increased power resulted in larger lesions ($p < 0.0001$) (Table 1, Fig. 1). The multivariable analysis revealed that at an irrigation rate of 2 ml/min, surface width, and maximum lesion width were significantly larger compared to 17 ml/min ($p < 0.0069$), whereas lesion depth was not.

Ablation could not be completed at any of the following settings due to occurrence of steam pops: irrigation flow rate of 2 ml/min, power 40 W or 50 W, and ablation duration greater than 10 s; irrigation flow rate of 17 ml/min, power 40 W, and ablation duration greater than 30 s; and irrigation flow rate of 17 ml/min, power 50 W, and ablation duration greater than 10 s.

Maximum temperature measurements at tissue depths of 3 mm and 5 mm are displayed in Fig. 2. The multivariable analysis revealed that at each depth (3 mm and 5 mm), there was no statistical difference in maximum temperatures achieved with either 2 ml/min or 17 ml/min irrigation flow rates. At all irrigation flow rates, powers, and ablation durations, temperatures were higher when closer to the RF source (3 mm vs. 5 mm). Higher maximum temperatures were achieved with higher power at any fixed irrigation flow rate and ablation duration. However, the temperature differential between the 3-mm and 5-mm depths was greatest with the low irrigation flow rate (Figs. 3 and 4a and b). The rate of temperature increase was also greater at 3 mm compared to 5 mm. With longer duration of ablation, temperatures at the 5-mm measuring depth were higher for a longer period of time when compared to those of short duration ablations.

Table 1 Lesion dimensions (*N* = 9 in each cell unless otherwise noted)

Duration of ablation		5 s		10 s		20 s		30 s		40 s	
		2 ml/min	17 ml/min	2 ml/min	17 ml/min	2 ml/min	17 ml/min	2 ml/min	17 ml/min	2 ml/min	17 ml/min
20 W	Surface width (mm)	4.4 ± 1.0	3.8 ± 0.7	5.7 ± 0.9	4.8 ± 0.9	6.4 ± 0.8	5.8 ± 1.1	7.6 ± 0.6	6.2 ± 0.8	7.5 ± 1.0	6.8 ± 0.9
	Maximum width (mm)	5.1 ± 1.4	4.2 ± 1.6	6.7 ± 1.6	5.6 ± 1.2	7.4 ± 1.2	6.8 ± 1.6	9.3 ± 1.1	8.2 ± 1.7	8.5 ± 3.0	8.7 ± 2.7
	Depth (mm)	1.44 ± 0.9	1.7 ± 1.1	2.6 ± 2.4	1.9 ± 1.3	2.7 ± 1.3	3.4 ± 1.4	4.1 ± 1.5	4.6 ± 1.0	5.5 ± 1.7	5.3 ± 1.2
30 W	Surface width (mm)	5.6 ± 1.4	5.3 ± 0.6	6.9 ± 1.0	6.6 ± 1.0	7.7 ± 1.0	7.2 ± 0.9	8.2 ± 0.7	7.7 ± 0.8	8.6 ± 0.6	7.9 ± 0.9
	Maximum width (mm)	5.7 ± 1.4	5.9 ± 0.7	7.9 ± 1.7	6.9 ± 1.5	9.7 ± 2.3	9.1 ± 2.2	10.6 ± 1.4	9.6 ± 1.3	11.1 ± 1.1	10.5 ± 1.6
	Depth (mm)	2.1 ± 1.1	1.7 ± 0.9	3.0 ± 1.0	2.8 ± 1.2	4.8 ± 1.2	4.3 ± 1.4	5.4 ± 1.3	5.1 ± 1.2	5.8 ± 0.9	5.6 ± 0.6
40 W	Surface width (mm)	6.1 ± 1.8	5.6 ± 0.6	<i>N</i> = 8	<i>N</i> = 8	*	<i>N</i> = 4	*	<i>N</i> = 5	*	*
	Maximum width (mm)	6.6 ± 1.9	6.4 ± 1.4	8.0 ± 1.5	6.7 ± 1.3	*	7.8 ± 1.0	*	7.8 ± 1.3	*	*
	Depth (mm)	2.4 ± 1.6	2.6 ± 1.0	8.7 ± 1.8	7.8 ± 1.6	*	10.4 ± 1.7	*	9.4 ± 2.5	*	*
50 W	Surface width (mm)	6.7 ± 1.2	6.3 ± 0.8	4.1 ± 1.4	3.7 ± 1.4	*	4.8 ± 1.3	*	5.1 ± 1.7	*	*
	Maximum width (mm)	7.2 ± 1.7	7.3 ± 1.5	8.3 ± 0.8	7.9 ± 1.2	*	*	*	*	*	*
	Depth (mm)	2.9 ± 1.5	3.0 ± 1.7	9.1 ± 1.0	7.9 ± 1.7	*	*	*	*	*	*
				5.0 ± 2.1	4.9 ± 2.9						

4 Discussion

This in vitro study on porcine left ventricular myocardium demonstrated that higher power ablations for short durations at 20g of contact force with low irrigation flow rates created more superficial lesions with less heating of deeper tissue layers than were observed with traditional ablation parameters (lower power, longer duration, higher irrigation flow rates).

The lesion measurements and measured temperature profiles indicated that the higher power, shorter duration, and low irrigation flow rate conditions would be anticipated to reliably create transmural lesions of the posterior left atrial wall in patients with AF, but may lessen injurious heating of deeper structures such as the esophagus.

The determination for temperature probe placement and contact force was based on several studies. Average left atrial

Fig. 1 Lesion characteristics

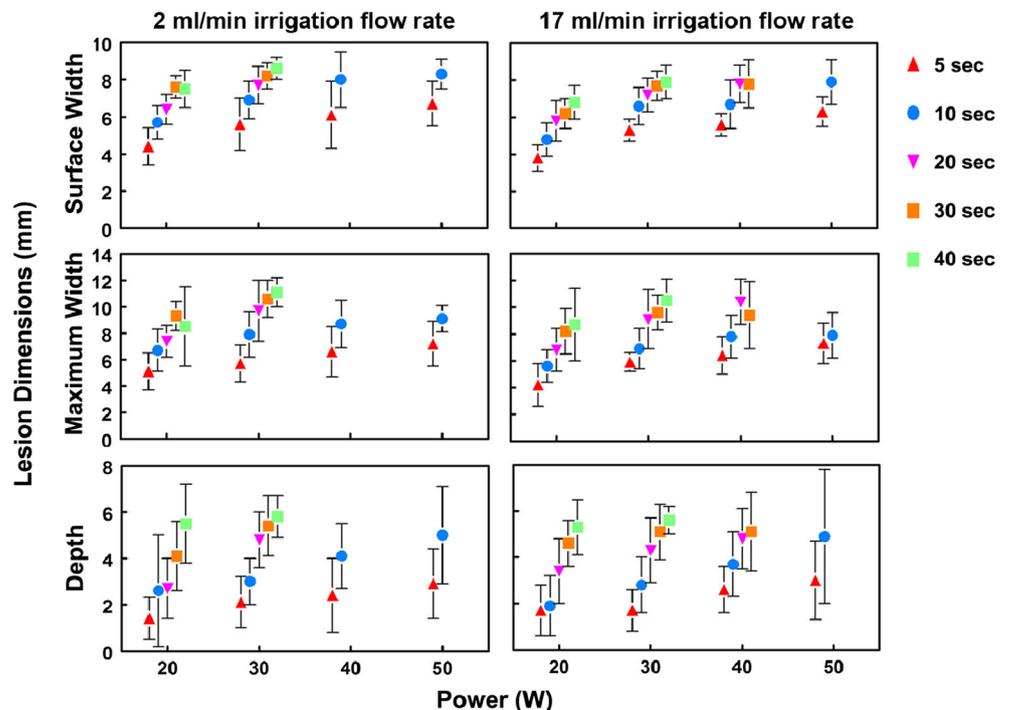
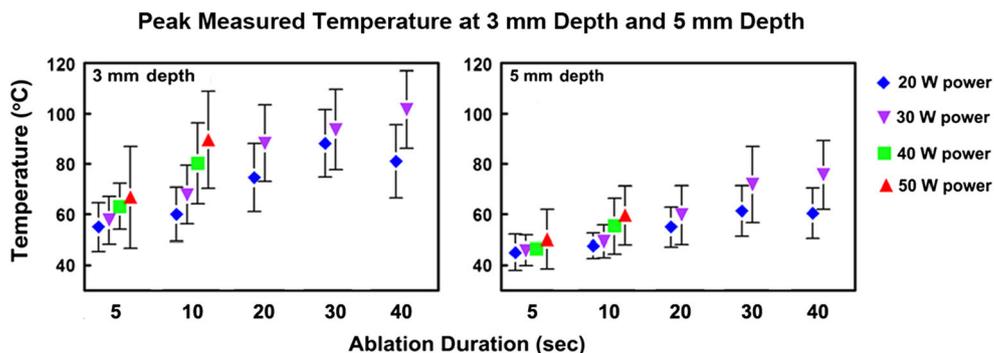


Fig. 2 Maximum temperature measurement* at 2 ml/min (left) and 17 ml/min (right) flow rates. *No statistical difference in temperature measurements between 2 ml/min and 17 ml/min at each depth



wall thickness reported on human autopsy series is 2–3 mm, thereby helping to determine our temperature probe placement at 3 mm to demonstrate transmuralty of lesions while the temperature probe placement at 5 mm would be to demonstrate collateral damage [17]. There is no consensus on the optimal amount of catheter contact force required during radiofrequency ablation on atrial tissue [18–20]. The reported range varies from 10g to greater than 20g [21–23]. In the TOCATA study, comparing the clinical efficacy of using contact force-sensing catheter in AF ablation showed higher 1-year success rate when contact force was maintained above 20g [24]. Therefore, we chose 20g of contact force.

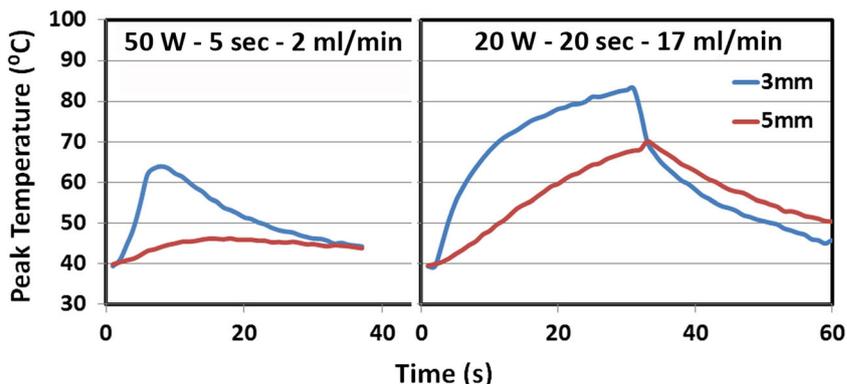
The selection of power, irrigation flow, and ablation durations was based on previous studies that supported the combinations of these parameters. It has been demonstrated that radiofrequency application with higher power is feasible with irrigation of the ablation electrode [25, 26]. Delivering higher power to the tissue while avoiding thrombus formation at the electrode was shown to create deeper lesions [27]. The impact of different catheter irrigation flow rates on the development of lesion dimension on sheep’s thigh muscle was studied, and it was reported that the surface lesion diameter was significantly smaller following radiofrequency applications irrigated with a flow rate of 20 ml/min compared to the lower flow rates of 5 ml/min and 10 ml/min at fixed power and duration. There was no thrombus formation at these different flow rates [25]. Because lesion size is proportional to power density but increases in a negative mono-exponential fashion with

increasing ablation duration, it is anticipated that increasing radiofrequency ablation power should be more effective in creating larger lesion volumes than extending radiofrequency ablation duration time [28]. It has also been shown that lesion dimensions are similar at low power, long duration compared to those at high power, short duration.

The present study results validate the above hypotheses and findings in that the lesion size increased with increasing power and duration for a fixed irrigation rate. Lesions dimensions were similar at high power, short duration compared to low power, long duration at a fixed irrigation rate. Larger surface lesion widths and maximum lesion widths were achieved with low irrigation compared to ablation with similar power and ablation duration parameters but higher irrigation rates. This would suggest that formation of large contiguous superficial lesions would be enhanced by employing lower irrigation flow rates.

Tissue temperature monitoring at 3 mm and 5 mm from the electrode-tissue interface during radiofrequency ablation at different power and duration revealed important findings. The peak temperatures at 3 mm and 5 mm were greater with higher power. During long-ablation duration, temperature readings at 3 mm greatly exceeded 50 °C, even when low-power settings were tested, indicating that a therapeutic ablation could be achieved with these parameters during ablation of the posterior left atrium in the clinical setting. However, with high temperatures at 3-mm depth, conductive heating to surrounding structures could

Fig. 3 Temperature measurements over time



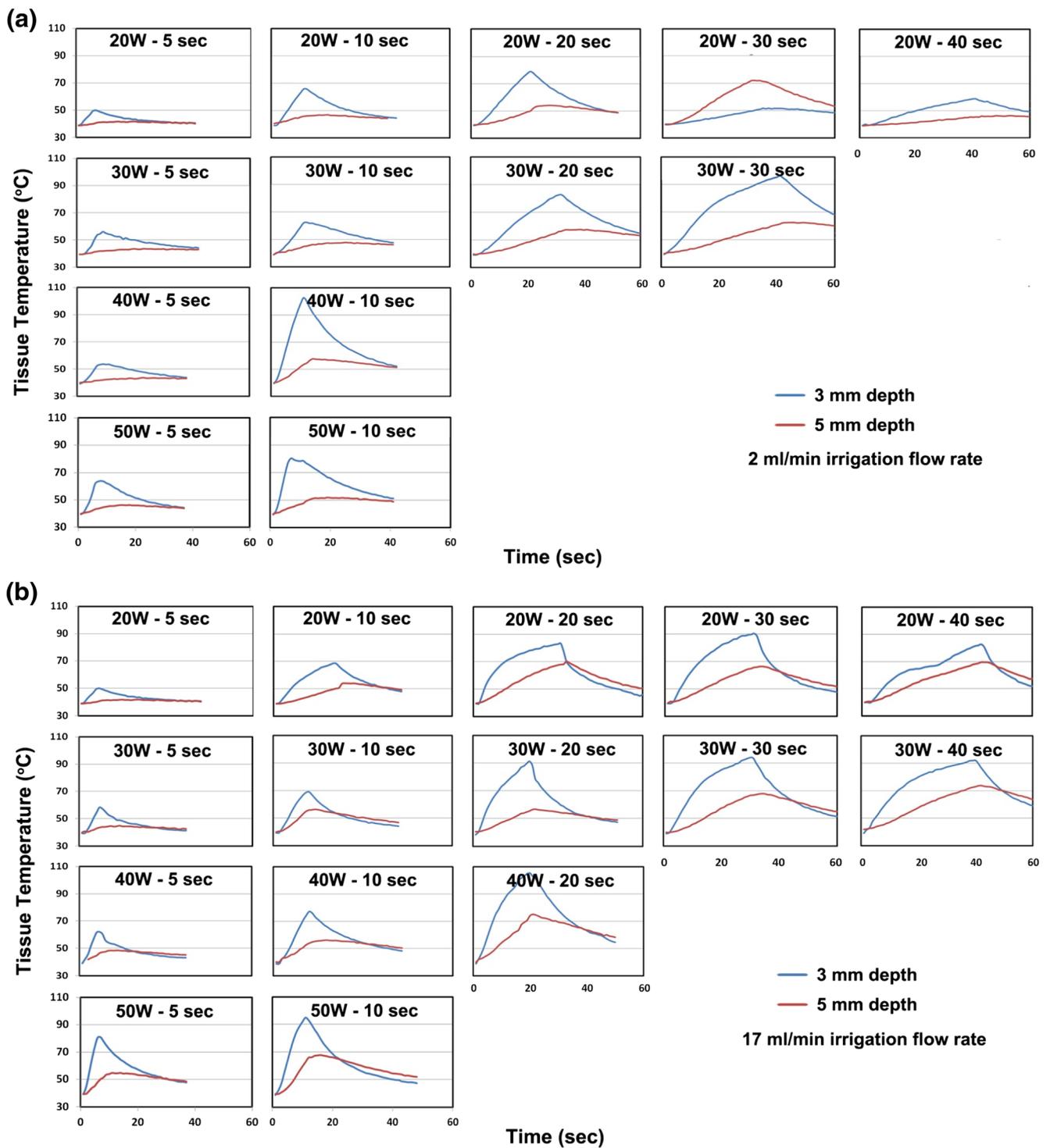


Fig. 4 **a** Temperature measurements over time at 2 ml/min irrigation flow rate. **b** Temperature measurements over time at 17 ml/min irrigation flow rate

result in damage to collateral structures that would be of greater extent if longer ablation durations were employed. Maximum temperatures achieved at 5 mm were lower than the maximum temperatures achieved at 3 mm for any fixed power, duration, and irrigation flow setting. But we found that maximum temperatures at 5-mm depth with high

power, short duration (50 W for 5 s) were lower than 50 °C (the temperature of irreversible injury). This finding lends support to the hypothesis that high-power, short-duration RF ablation may be safer in preventing collateral damage to structures such as the esophagus than conventional ablation parameters.

The greatest difference in temperature differentials occurred between the 3-mm and 5-mm depth at low flow rates. This may be due to the lack of endocardial sparing during low flow as opposed to high flow rates. It has been postulated that endocardial sparing during lesion formation occurs because the high flow rates produce surface cooling that reduce surface endocardial lesion dimension [9]. We hypothesize that low flow rates would result in maximal lesion formation that is less deep than that of high flow rates, such that tissue at the 5-mm depth would be relatively spared compared to that at 3 mm.

Although we performed low-flow irrigation through a ThermoCool SmartTouch catheter designed for high-flow irrigation which raises the concern of comparability to a low-flow designed ablation catheter, a recent study showed maximum lesion diameter and depth were similar among high-flow capable catheters that were set to low-flow irrigation (ThermoCool SmartTouch vs. ThermoCool SmartTouch-SF vs. FlexAbility) [29]. Lesion formation is determined by CF, impedance change, power, duration, and temperature measurements [30]. Several factors can influence temperature measurements such as blood flow or externally irrigated catheters due to cooling of the tissue surface [31]. Since lesion formation was similar among different catheters, we can presume that whether a high or low-flow catheter was used in our study, it would not change our results.

Our study demonstrated consistent steam pops at or above 40-W power longer than 10 s. Several studies have shown an increased frequency of steam pops with higher power [19]. A recent study by Winkle et al. reported no steam pops with 50-W power for an average ablation time of 11.2 s and a contact force of 10–20g. However, the author reports the RFA generator utilized 2 s to achieve a full power of 50 W [32], thus 9.2 s would be comparable to our study, in which we did not have any steam pops.

The utility and safety of higher power RFA have been extensively studied [33, 34]. A systemic review examined the impact of power output on efficacy and safety outcomes associated with radiofrequency ablation for AF. This study found that power output >45 W at shorter duration (15–20 s) is safe and efficacious [35]. Investigators propose that radiofrequency ablation at 50 W while continuously moving the catheter yields higher individual procedure cure rates for persistent AF with shorter procedure and fluoroscopic times but increase in complications. Similar results have been reported by others [36]. Our study corroborated the finding that high power (50 W) and short duration (5 s) were efficacious at 20g contact force with 2 ml/min irrigation flow, with the creation of wide lesions and adequate depth. However, any power at or above 40 W at either 2 ml/min or 17 ml/min for longer than 10 s consistently resulted in steam pops.

5 Study limitations

Although this experiment was performed under a controlled environment, the normal human internal physiology is difficult to simulate. Therefore, variations in lesion size and dimension are expected in vivo. For example, circulating blood in vivo contains coagulation factors that could trigger thrombus formation at ablation sites, thus limiting heat conduction and lesion dimension. Also, we did not terminate energy delivery for impedance rise nor did we exclude lesions with an impedance rise that did not result in a steam pop. This study was performed in a porcine myocardium preparation instead of the endocardium of a beating heart to control tip-electrode contact force and to allow measurement of temperatures at various tissue depths beneath the electrode. The flat surface of the preparation allowed for accurate determination of lesion size and geometry. In contrast, delivering radiofrequency current to the endocardium of a beating heart often results in an irregular lesion shape and greater variation in lesion size than those found in this study. Our five trials per combination of power, duration, and irrigation flow were also not powered to show a statistical difference in temperature profile. Lastly, the ventricular myocardium differs anatomically and histologically from the atrial myocardium in regard to trabeculation and wall thickness. A higher power may lead to deeper penetration of energy along a thin-walled atrium. Although some studies have demonstrated efficacy and safety ablating with high power and low duration, with our study corroborating the same, further human studies are required to directly assess the impact of high power, low flow, and low duration in AF ablation.

6 Conclusion

Our study documented the following findings: (1) lesion width and depth increased when ablation duration, power, or irrigation flow was altered while the other settings were fixed, all with a constant contact force; (2) low irrigation flow resulted in wider lesions as compared to high irrigation flow at any fixed power and ablation duration; (3) lesions dimensions are similar at high power, short duration compared to low power, long duration at a fixed irrigation rate; and (4) temperature curves at high power, short duration, and low irrigation flow were adequate to achieve ≥ 50 °C at adequate depths without causing excessive heating of deeper tissue, thereby potentially preventing collateral damage during AF RFA. Further studies evaluating high power, low flow, and short duration in vivo with characterization of collateral organ damage are needed to ensure the safety of this setting.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

Ethical approval The Beaumont Research Institute approved this study.

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