

Impact of electrode tip shape on catheter performance in cardiac radiofrequency ablation



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BACKGROUND The role of catheter tip shape on the safety and efficacy of radiofrequency (RF) ablation has been overlooked, although differences have been observed in clinical and research fields.

OBJECTIVE The purpose of this study was to analyze the role of electrode tip shape in RF ablation using a computational model.

METHODS We simulated 108 RF ablations through a realistic 3-dimensional computational model considering 2 clinically used, open-irrigated catheters (spherical and cylindrical tip), varying contact force (CF), blood flow, and irrigation. Lesions are defined by the 50°C isotherm contour and evaluated by means of width, depth, depth at maximum width, and volume. Ablations are deemed as safe, critical (tissue temperature >90°C), and pop (tissue temperature >100°C).

RESULTS Tissue–electrode contact is less for the spherical tip at low CF but the relationship is inverted at high CF. At low CF, the cylindrical tip generates deeper and wider lesions and a 4-fold larger volume. With increasing CF, the lesions generated by the spherical

tip become comparable to those generated by the cylindrical tip. The 2 tips feature different safety profiles: CF and power are the main determinants of pops for the spherical tip; power is the main factor for the cylindrical tip; and CF has a marginal effect. The cylindrical tip is more prone to pop generation at higher powers. Saline irrigation and blood flow effect do not depend on tip shape.

CONCLUSION Tip shape determines the performance of ablation catheters and has a major impact on their safety profile. The cylindrical tip shows more predictable behavior in a wide range of CF values.

KEYWORDS Cardiac ablation; Computational modeling and simulation; Electrode tip; Lesion science; Open irrigation; Radiofrequency; Steam pop

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Introduction

Radiofrequency (RF) catheter ablation is extensively used for the treatment of tachyarrhythmias. Several improvements in the technology have been implemented over the years to maximize lesion size while minimizing complications. Despite an optimal equilibrium with the current available technology, complications still occur and are not always predictable.

It is well known that contact force (CF), power, and ablation time are the main determinants of lesion characteristics and safety.¹ However, some groups have observed differ-

ences in terms of pop formation when comparing various currently available, open-irrigated RF ablation catheters, suggesting that catheter tip shape also may play a significant role.^{2–4} However, classic research approaches have not been able to elucidate which characteristics of tip shape may have an impact on the safety and efficacy of lesion formation and how they can be used to optimize ablation.

The study and development of RF ablation has been based mainly on *in vivo* and *in vitro* experiments, which have important limitations that are difficult to circumvent, mostly related to the large number and variability of factors interrelated in lesion formation.

The recent development of computational models for RF ablation is a powerful tool to evaluate interacting factors in lesion formation in an independent manner.^{5,6} This approach allows study of specific catheter designs⁷ and assessment of new protocols, such as high-power/short-duration applications.⁸

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KEY FINDINGS

- Electrode tip shape plays a crucial role in terms of the safety and efficacy of radiofrequency ablation.
- The cylindrical tip has a more predictable behavior in a wide range of contact force values but seems to be more prone to steam pop generation.
- Each catheter design needs different specific settings to achieve similar ablation efficiency while avoiding complications.

The purpose of this study was to analyze the role of catheter tip shape in RF ablation using our validated advanced computational model,⁹ which accounts for the elastic deformation of the electrode–cardiac tissue interface, thus allowing a full evaluation of different scenarios. Recent experimental studies have highlighted the correlation between catheter contact area and lesion size.¹⁰ Because the catheter contact area depends on tissue deformation, which, in turns, depends on both CF and tip shape, our model represents a natural candidate to study, in an independent manner, the different tip shapes and their role in RF ablation. The results will provide a better understanding of the pathophysiology of RF ablation and pop occurrence and possibly identification of hazardous ablation protocols.

Methods

Computational model

Our computational model of RF is based on an *in vitro* experimental setup reported by Guerra et al.² In brief, the model simulates a porcine heart considering fixed conditions, which allows for standard comparison of different ablation settings. The mathematical model, detailed in the Supplementary Material, is built within a 3-dimensional computational framework,¹⁰ which considers tissue elasticity, blood flow, and its interaction with the irrigated saline and the thermoelectric interaction between the electrode and the target ablation area.

Simulations were performed using our self-developed software in FEniCS-HPC (www.fenics-hpc.org) on BCAM in-house HPC cluster (18 nodes/624 cores with 4-TB RAM).

No patient data or animals were used in this study. The computer model was validated in a previous study by Petras et al.⁹

Electrode tip shape

We considered 2 different electrode tip shapes, based on commercially available and clinically used, open-irrigated catheters: one with a hemispherical tip and one with a cylindrical tip. Both electrodes have diameter of 2.33 mm (7F) and length of 3.5 mm, and feature 6 irrigation pores (0.5-mm diameter) (Figure 1).

Tissue characteristics

We studied virtual porcine cardiac tissue of 20-mm thickness.¹¹ The biophysical and mechanical parameters are summarized in the Supplementary Material.

Lesion assessment

Considering irreversible tissue damage at 50°C,¹² lesions were identified by the 50°C isotherm contour. The measured dimensions were depth (D), lesion volume (V), width (W), and depth of maximum width (DW), considering the zero at the undeformed endocardial surface (Figure 1).

Ablation settings

For both electrode tips, we simulated 30 seconds of ablation for several protocols in terms of power (20–50 W) and CF (5g–20g). All simulated ablations are performed perpendicular to the endocardium, resulting in progressive deformation of the tissue. The ablation protocols use a power-control mode without temperature limit.

Two blood flow protocols commonly used in *in vitro* experiments were considered²: high blood flow (0.5 m/s), representing heart areas of high flow such as the cavotricuspid isthmus, ventricle, or outflow tracts; and low blood flow (0.1 m/s), representing flow in areas such as below a valve leaflet, the pulmonary veins, or the atrium. Two saline irrigation rates were simulated that typically are used in RF: low rate (17 mL/min) and high rate (30 mL/min).

Complication assessment

We considered a steam pop to occur when the tissue temperature reached 100°C.¹² Whenever a pop occurred, the simulation was terminated, and the time to pop was recorded. Due to slight fluctuations of the temperature at which steam pop occurs,¹³ we defined a *critical area*, which corresponds to simulated lesions in which the tissue temperature reaches between 90°C and 100°C. Although reaching a boiling temperature does not automatically result in a pop, given the seriousness of this complication, we equated the risk of pop with the occurrence of it. Each virtual lesion was classified as *pop*, *critical*, or *safe*, based on the maximum tissue temperature (T_{\max}) reached. For each electrode tip shape, a color-coded risk map of the protocol was drawn based on CF and power. The ablation protocols that led to $T_{\max} < 90^\circ\text{C}$ after 30 seconds were classified as *safe* and represented in green; for T_{\max} between 90°C and 100°C, the ablation protocol was deemed *critical*, represented as yellow; and for $T_{\max} = 100^\circ\text{C}$, the protocol was deemed *pop*, represented in red.

We registered the *time to critical temperature* as a surrogate of the safe ablation interval time, defined as the time from the beginning of an ablation to $T_{\max} > 90^\circ\text{C}$.

Study design

The study was performed in 3 parts. (1) In the first set of experiments, we studied the safety of both catheter shapes at different ablation protocols in terms of power (20–50 W) and CF (5g–20g). For this set, we maintained constant blood

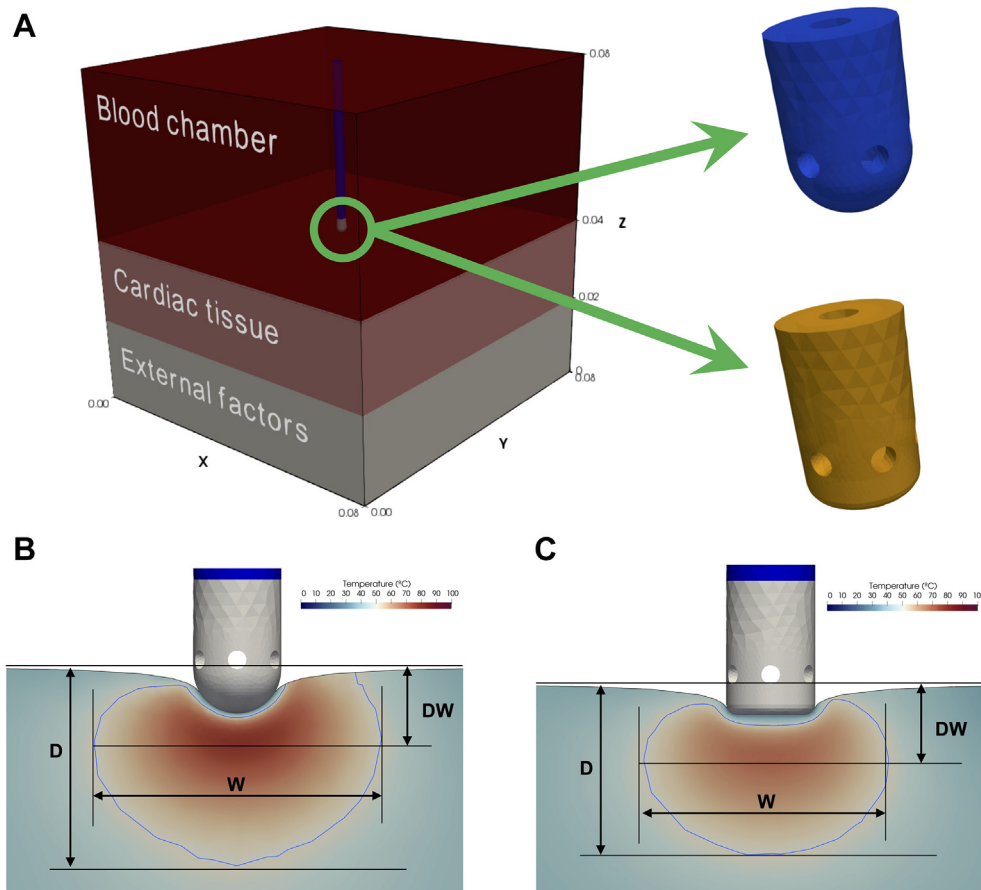


Figure 1 A: The computational model and the 2 electrode tip shapes studied. B, C: Simulated lesions with each catheter. The area of irreversible tissue lesion is delimited by the blue line, which represents the 50°C isotherm. Lesion measurements are depth (D), width (W), and depth of maximum width (DW)

flow (0.5 m/s) and low saline irrigation rate (17 mL/min), which are the values used in the *in vitro* experiments against which the computational model was validated. (2) The second set of experiments aimed to compare the impact of CF in terms of lesion size for both catheter tip shapes. For that purpose, we chose a routine clinical protocol of 30 W for 30 seconds and 4 different CF levels (from 5g to 20g). Blood flow and irrigation rate were kept at 0.5 m/s and 17 mL/min, respectively. (3) Finally, we analyzed the impact of blood flow and saline irrigation level on safety and efficacy. For each catheter, we focused on the highest power not producing a pop identified from the previous experiments at a standard CF of 10g.

Results

A total of 108 RF catheter ablation lesions were simulated, combining tip shape, CF, RF power, saline irrigation rate, and blood flow.

Impact of catheter tip shape on safety

The 2 catheter tip shapes show very different risk profiles (Figure 2). For ablations with the spherical tip, a combination of CF and power is needed to lead to pop. A low-power delivery (up to 25 W) would lead to safe lesions at any CF,

whereas very low CF offers a wide safety margin at any power tested (up to 50 W). An increase in 1 of the 2 parameters over the other shows a progressive reduction in safety.

For the cylindrical tip, power proves to be the main factor contributing to tissue overheating. Whereas power <30 W seems to be generally safe at any CF, at 35 W the risk of pop rises suddenly even at low CF. In contrast, variations of CF seem to have a marginal effect on the risk of pop.

The *time to critical temperature* (ie, safe ablation interval time) is shown in Figure 3. This interval is larger at lower power, lower CF, and with the spherical tip rather than with cylindrical one. Stepwise increases in CF lead to an exponential decline of this time for the spherical tip, whereas the decline of the curve is smoother for the cylindrical tip.

Impact of CF for each tip shape

We compared 4 different CFs in a standard clinical scenario (30 W, 30 seconds), and the results are summarized in Table 1 and Figure 4. We observed that at low CF, the cylindrical tip generates deeper and wider lesions (and a 4-fold larger volume) than the spherical tip. With increasing CF, the lesions generated by the spherical tip become progressively closer to those generated by the cylindrical tip. Moreover, increasing CF from 5g to 15g results in a 6-fold larger lesion for the spherical tip but a mere 50% increment for the

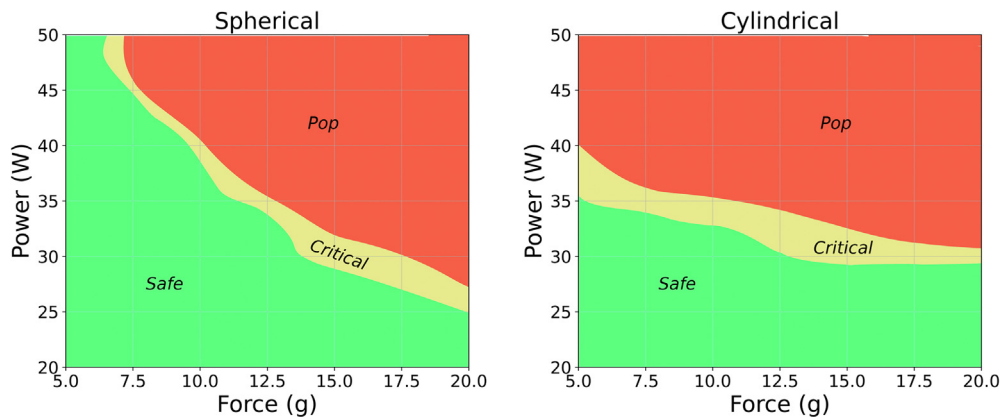


Figure 2 Contact force–power steam pop risk maps for each electrode tip shape. Blood flow and irrigation rate were kept at 0.5 m/s and 17 mL/min, respectively. Ablation time was 30 seconds. Safe protocols are represented in green, critical in yellow, and pop in red.

cylindrical tip. A similar pattern can be observed for T_{max} . For the spherical tip T_{max} is 61°C at 5g and produces a pop (after 21.5 seconds) at 20g, whereas for the cylindrical tip T_{max} only rises from 80°C at 5g to 94°C at 20g. Hence, lesion size and complications are determined mostly by the power for the cylindrical tip and by the combination of power and CF for the spherical tip.

Impact of blood flow and saline irrigation

For this evaluation, we chose, at a conventional CF of 10g, the largest power not producing a pop for each tip shape: 35 W for the cylindrical tip and 40 W for the spherical tip. Table 2 summarizes the lesion dimensions and tissue temperatures with varying blood flows and saline irrigation rates. No steam pop is observed, although all simulated protocols are deemed critical for both tip shapes. The overall variation of T_{max} is below 2°C.

Discussion

To the best of our knowledge, this is the first study to use an advanced and realistic computational model to explore in a controlled and independent manner the impact of catheter tip shape on the safety and the efficacy of RF ablation. The main findings are as follows. (1) The tip shape determines the contact surface with the tissue and how it changes based on CF. (2) CF is more critical for the spherical tip than for the cylindrical tip with regard to safety and efficacy. (3) The

safety profiles of the 2 tip shapes are very different. (4) Independent of tip shape, power and CF are the 2 major determinants of pop formation, whereas catheter irrigation and blood flow have a minor impact.

Model validation

Our computational model was previously validated for a spherical tip against *ad hoc*, *in vitro* experimental results.⁹ For the cylindrical tip, despite lacking a twin experimental model for validation, the simulated lesion sizes were in good agreement with the *ex vivo* experimental results recently reported by Masnok and Watanabe,¹⁰ who used a 6-hole cylindrical electrode. Moreover, our results align with the nonoccurrence of steam pops reported therein for 30-W/30-second ablations in the range of CF (up to 20g) we studied (Figure 2).

Tip shape and contact surface

Heat transfer to tissue depends directly on the contact surface between the metallic region of the catheter tip and the cardiac wall.¹ Although a recent experimental study stressed the importance of the contact surface between electrode and tissue using 5 different angles of the catheter and a wide range of CF values,¹⁰ the role of the catheter tip shape has been overlooked. Our simulations clearly show how that catheter tip shape is a major determinant of the amount of surface tip area that comes into contact with the tissue. As shown

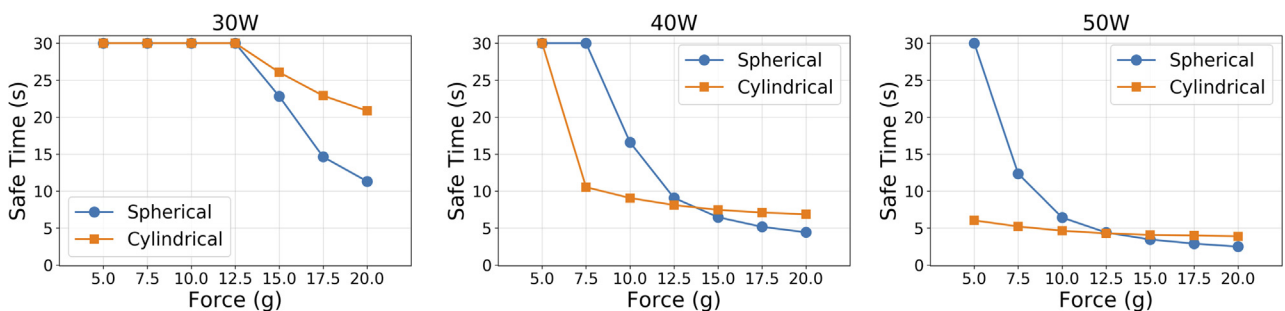


Figure 3 Time to critical temperature for the 2 electrode tip shapes at different power/contact force combinations.

Table 1 Lesion characteristics for the 2 tip shapes at different CFs

CF	Tip	D (mm)	W (mm)	DW (mm)	V (mm ³)	T _{max} (°C)
5g	Spherical	3.29	4.84	0.77	32.7	60.8
	Cylindrical	4.74	7.4	1.31	124.8	80.2
10g	Spherical	4.69	6.84	1.49	106.4	77.6
	Cylindrical	5.22	7.87	1.62	161.2	86.5
15g	Spherical	5.60	8.27	1.28	182.3	92.6
	Cylindrical	5.60	8.43	1.71	193.4	91.2
20g	Spherical	5.55*	8.35*	0.98*	182.3*	100.0*
	Cylindrical	5.92	8.85	1.42	220.2	94.0

Ablation protocol is 30 W, 30 seconds. Blood flow is kept at 0.5 m/s and irrigation rate at 17 mL/min.

CF = contact force; D = depth; DW = depth of maximum width; T_{max} = maximum tissue temperature; V = volume; W = width.

*Protocol popped at 21.4 seconds. Values measured at time of pop.

in Figure 4 (center panel), for the spherical tip, the tissue surface area that is in contact with the catheter tip has a major dependence on CF. In the absence of CF, only a small area of a spherical tip will be in contact with the tissue. In contrast, for the cylindrical tip, the whole base is in contact with the tissue, leading to greater power delivery. As CF increases, so does the contact surface for both catheters. However,

this occurs much faster for the spherical tip than for the cylindrical tip, whose contact surface shows only slight variations at a wide range of CFs. Hence, at low CF the percentage in contact is much lower for the spherical tip than the cylindrical tip (7% vs 13%); at moderate CF the percentage difference rapidly reduces; and at CF 20g the relationship is inverted (18% vs 17%). As a result, lesions generated at low CF are larger with the cylindrical tip than with the spherical tip. Increasing the CF would require a reduction in power to remain in the safe zone, especially for the spherical tip.

Impact of CF

Our analysis clearly shows the critical role of CF in lesion formation and complications for spherical tips, whereas large variations of CF have only a minor impact on cylindrical tips.

In line with our results, *ex vivo* and *in vivo* experimental studies based on RF lesions using a spherical catheter tip have shown that the increase in lesion size depends more on CF than on power: lesions obtained with 30 W/20g were greater in depth and width than those obtained with 40 W/10g.¹⁴ A recent study compared the lesions obtained by matching a predefined value on the lesion size indicator provided by the navigation system of 2 commercially

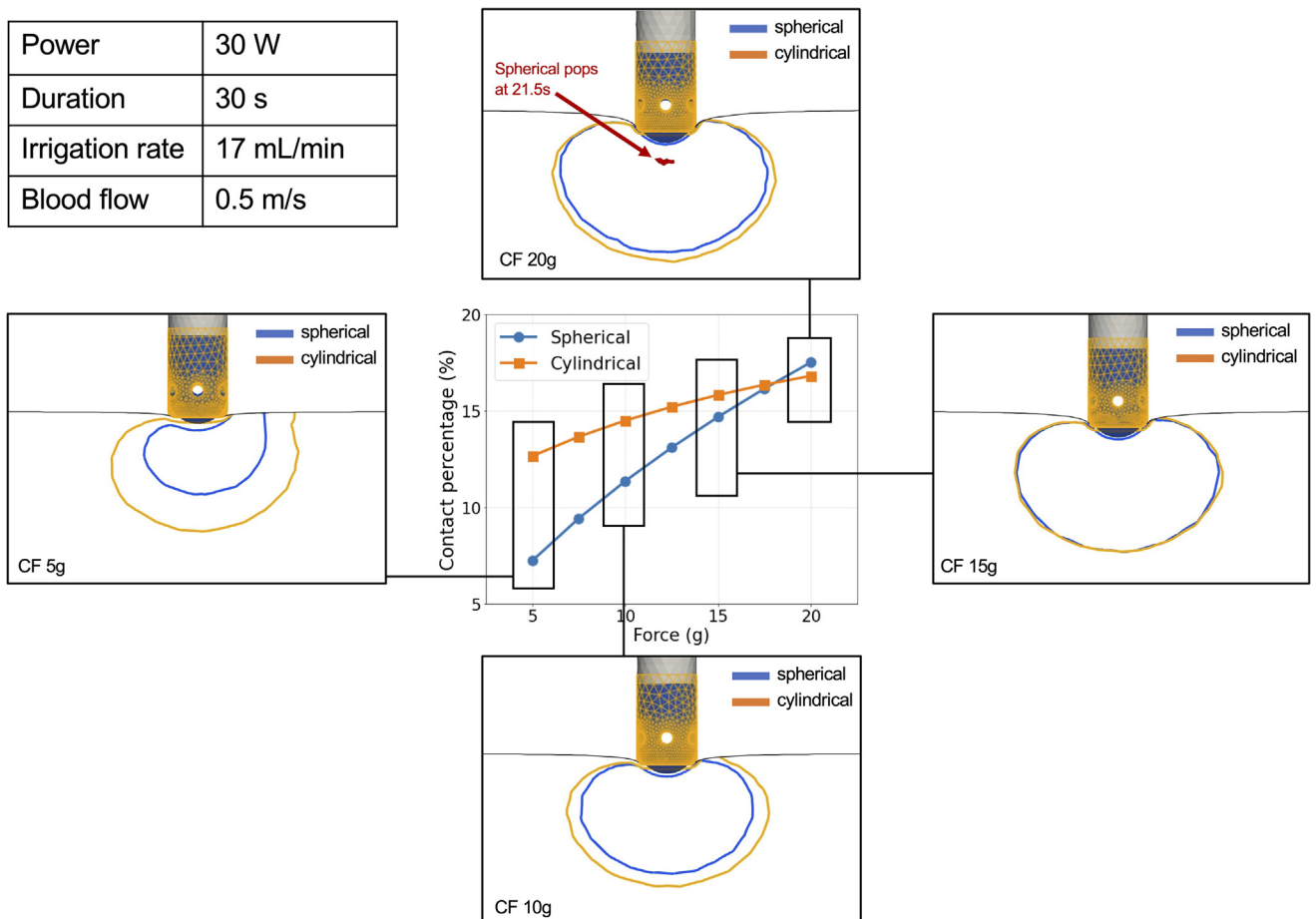


Figure 4 Contact surface percentage with the tissue according to contact force (CF) for each catheter tip shape (spherical in blue, cylindrical in orange) and comparison of the corresponding lesions generated with a 30-W/30-second ablation protocol. Blood flow and irrigation rate were kept at 0.5 m/s and 17 mL/min, respectively. In all plots, blood flows from left to right.

Table 2 Lesion characteristics for the 2 tip shapes applying different blood flows and saline irrigation rates

	Electrode tip protocol							
	Spherical (40 W, 10g)				Cylindrical (35 W, 10g)			
	HBF (0.5)		LBF (0.1)		HBF (0.5)		LBF (0.1)	
Blood flow (m/s)								
Saline irrigation rate (mL/min)	30	17	30	17	30	17	30	17
D (mm)	5.48	5.49	5.53	5.50	5.64	5.64	5.68	5.66
W(mm)	8.21	8.29	8.48	8.32	8.66	8.72	8.77	8.79
DW (mm)	2.33	2.34	2.28	2.35	2.24	2.23	2.18	2.36
V(mm ³)	176.6	185.3	200.3	186.7	207.7	213.8	222.8	217.9
T _{max} (°C)	96.2	96.2	98.0	97.1	98.2	98.0	99.9	99.0

HBF = high blood flow; LBF = low blood flow; other abbreviations as in Table 1.

available catheters (Ablation Index for CARTO3, Biosense Webster, Inc., Diamond Bar, CA; Lesion Size Index [LSI] for Ensite Precision, Abbott Laboratories, Abbott, IL), similar to those considered in our study.⁴ Lozano Granero et al⁴ also observed an inversion in lesion size according to CF and attributed to a suboptimal prediction ability of the LSI when using a spherical catheter in a low-CF setting. Our results suggest that, in line with previous publications,¹⁵ lesion size indicators should account for reliable estimators of contact surface between the tip and the tissue, beyond the CF.

Safety

Both electrode tips show an increasing risk of steam pop occurrence with increased CF and power. However, for the cylindrical tip the risk of pop depends more on power than on CF, whereas for the spherical tip both CF and power are equally important. Thus, greater powers can be applied with the spherical tip if the CF is kept low, and vice versa. In contrast, for the cylindrical tip, setting the power up to 30 W will be mostly safe, independent of CF. Because power is a selected parameter in contrast to CF, which may vary abruptly during the ablation, the behavior of the cylindrical tip seems overall more predictable than that of the spherical tip.

Knecht et al¹⁶ described differences in 2 catheters having different tip shapes and irrigation in terms of safety. In their study, the spherical tip shape showed a higher risk of pop, and they related the difference to a more efficient irrigation system that, by underestimating tissue temperature feedback, would enable higher power delivery. Iles et al¹⁷ observed an increase in pop occurrence at power >40 W delivered by a spherical tip on a reanimated porcine cardiac model. Although the authors did not consider CF, they did consider >50% of the electrode tip surface to be in contact with the endocardium, which is more than twice the maximal percentage we studied. In other studies comparing many catheter tip designs, a trend toward more frequent pops with spherical tips also was found.^{2,18} Although in a recent study by Lozano et al⁴ more pops were observed with lesions performed by a cylindrical tip, the main factor for the occurrence was the applied power (from 30 to 60 W at 10g). In contrast, for

the spherical catheter, the only observed pop was at a greater CF (20g).

Our observations suggest the need for a tailored power setting based on the anatomic region and the catheter tip design. Use of a spherical tip with low power may be suitable for the atrial wall where abrupt changes in CF are foreseeable, thus avoiding the risk of pop or perforation. In contrast, use of cylindrical tips may be appropriate for reaching deeper ventricular arrhythmogenic substrates, allowing greater heat transfer and larger lesions.

Impact of blood flow and catheter irrigation

We observed no significant influence on tissue temperature from variations in blood flow or irrigation rate for the electrode tips used in our study. Available clinical and experimental data also support that the type of irrigation (ie, discrete number of pores or surround flow designs) has no significant impact on lesion size.^{2,3,10,18–20}

Our study also suggests that the incidence of steam pops is not directly related to the amount of irrigation. Whether the type of irrigation (discrete vs surround flow) has an impact on pop occurrence remains unclear. Although clinical studies have not reported significant differences,²¹ *in vitro* results have shown discrepancies.^{2,3,18,19}

Clinical implications

Electrode tip shape plays a crucial role in terms of safety and efficacy. The cylindrical tip shape has a more predictable behavior at a wide range of CF values, although it seems to be more prone to steam pop generation at higher powers. However, its low sensitivity to CF favors the generation of more homogeneous lesions, thus helping to standardize the ablation procedures.

Study limitations

Our calculations are based on ablations performed on a porcine slab of tissue representing an *in vitro* setting because that was the setting used to validate the computational model¹⁰; therefore, as in the case of *in vitro* experiments on animal models, direct extrapolation of the results to the human clinical setting should be taken with care. However,

the aim of the present work was not to directly provide guidelines for clinical settings to be used.

Our model considers only a perpendicular orientation of the catheter with respect to the tissue. Different orientations may have a considerable impact on the contact surface and, therefore, on the lesion geometry and the risk of pop. Our preliminary data suggest that for orientations ranging from perpendicular to 45° of inclination, the cylindrical tip would exhibit a significantly larger loss of contact surface in comparison to the spherical tip. From 45° to the parallel position, the contact surface is expected to increase for both catheter tips. The actual trend for each catheter tip also would depend on CF. This particular aspect could be of great clinical importance and requires extensive further investigation. Our results set the basis for such future research.

In our study, a power-controlled ablation mode without temperature cutoff was simulated. This may limit direct extrapolation of the results to the clinical setting, as current technology allows for power down-regulation upon reaching an upper limit temperature. However, because the aim of this study was to better understand the mechanisms behind the impact of tip shape on RF ablation, we consider this aspect to have little impact on the conclusions of the study.

Conclusion

Our findings from this *in silico* study demonstrate that catheter tip shape plays a critical role in the safety and efficacy of cardiac RF ablation. Lesion size and complications are determined mostly by the power for the cylindrical tip and by the combination of power and CF for the spherical tip. Pop occurrence is minimally affected by saline irrigation rate and blood flow for both shapes. Our results should help in designing new catheters and safe ablation protocols in the future.

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Disclosures: Dr Guerra has served as a consultant for Biosense Webster, Boston Scientific, and Abbott; received speaker fees from Boston Scientific and Abbott; and received research grants from Abbott, Medtronic, and Biosense Webster. All other authors have no conflicts to disclose.

Authorship: All authors attest they meet the current ICMJE criteria for authorship.

Ethics Statement: No patient data or animals were used in this study. The computer model was validated in a previous study by the authors.

Appendix

Supplementary data

Supplementary data associated with this article can be found in the online version at [10.1016/j.hroo.2022.07.014](https://doi.org/10.1016/j.hroo.2022.07.014).

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