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Lesion Formation Using a Dual-Energy Lattice-Tip Ablation Catheter: Effects of Repeated Application, Timing, and Spatial Arrangement

Short running title: Lesions with Dual-Energy Lattice-Tip Ablation Catheter

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Capsule Summary

Using a dual-energy lattice-tip catheter in ex vivo models, repeated pulsed field and radiofrequency applications increased lesion depth. Longer inter-application intervals attenuated this effect, while greater inter-lesion distances reduced lesion continuity at depth, demonstrating the influence of application timing and spacing on lesion formation.

Abstract

Purpose: The dual-energy lattice-tip catheter enables point-by-point ablation using pulsed field (PF) or radiofrequency (RF) energy. In this study, we characterized PF- and RF-induced lesion formation and assessed the effects of repeated applications, inter-application timing, and inter-lesion distance in an ex vivo model.

Methods: Lesion dimensions were compared after single and repeated PF and RF applications. Inter-application intervals of 0, 30, 60, and 300 s were evaluated. Lesion continuity at depth was assessed using gap depth between adjacent lesions at different inter-lesion distances. RF lesions at 73 and 68°C were also compared.

Results: Single PF applications produced greater surface lesion length than RF. Repeated applications increased lesion depth with both PF and RF, whereas their effects on surface lesion length differed between the two energy modalities. Compared with immediate repetition, lesion depth did not differ significantly at 30 s but was significantly shallower at 60 and 300 s with both energies, whereas surface dimensions showed no clear time dependence. Increasing inter-lesion distance reduced continuity at depth; gap depth decreased significantly at ≥6 mm for PF compared with 4 mm and at 10 mm for RF compared with 7 mm. RF at 68°C produced shorter and shallower lesions than at 73°C.

Conclusions: Lattice-tip lesion formation is influenced by energy modality and the temporal and spatial pattern of delivery. Repetition increases lesion depth, while delayed additional applications and greater inter-lesion distance reduce depth augmentation and lesion continuity, respectively.

Keywords: Catheter ablation; Lattice-tip catheter; Lesion formation; Pulsed field ablation; Radiofrequency ablation

INTRODUCTION

Catheter ablation for atrial fibrillation may require posterior wall isolation and linear ablation in addition to

pulmonary vein isolation (PVI). A dual-energy lattice-tip catheter with a compressible 9-mm tip has recently been introduced, enabling three-dimensional electroanatomic mapping and point-by-point ablation using either radiofrequency (RF) or pulsed field (PF) energy with a single catheter. Clinical studies and real-world registry data have demonstrated high acute success rates for PVI, posterior wall isolation, and various linear lesion sets, supporting its feasibility and efficiency for complex lesion creation [1, 2]. However, acute conduction block does not guarantee long-term lesion durability. Invasive remapping has demonstrated high durability of roof lines, posterior box lesions, and cavotricuspid isthmus lines, whereas anterior and mitral isthmus lines showed substantially lower durability [3]. These findings suggest that successful linear ablation requires not only acute conduction block but also the generation of irreversible lesions that are continuous at sufficient depth.

Lesion formation using a lattice-tip catheter is influenced by energy modality and delivery pattern. RF energy delivered through large-surface area lattice electrodes can create broad thermal lesions within a short application duration [4]. With PF energy, repeated applications at the same site reportedly increase lesion depth and volume [5, 6]. PF and RF also exhibit different lesion characteristics, and lesion formation can be further modified by repeated applications [5-7]. Nevertheless, previous studies have focused primarily on individual lesion characteristics. The effects of inter-application interval and inter-lesion distance on lesion formation and lesion continuity at depth remain incompletely understood. A systematic assessment incorporating these temporal and spatial determinants may provide further insight into lesion formation using a lattice-tip catheter.

In this *ex vivo* study, we aimed to characterize PF- and RF-induced lesion formation using a lattice-tip catheter by evaluating (1) lesion dimensions and geometry and their changes with repeated applications, (2) the effect of inter-application timing on lesion formation, and (3) the relationship between inter-lesion distance and lesion continuity.

MATERIALS & METHODS

Dual-energy lattice-tip ablation system

Ablation was performed using the Sphere-9 catheter (Medtronic, Minneapolis, MN, USA), which features a 9-mm spherical lattice-tip electrode and enables delivery of either PF or RF energy through a single irrigated catheter. PF applications were delivered for 4 s at an irrigation flow rate of 15 mL min^{-1} and a current limit of 95%. RF applications were delivered in a temperature-controlled mode for 5 s at an irrigation flow rate of 30 mL min^{-1}, a target temperature of 73°C, and a current limit of 80%. For the assessment of the effect of RF temperature setting on

lesion formation, the target temperature was reduced to 68°C while maintaining the current limit at 80%; all other RF application settings remained unchanged.

Experimental model and study design

This *ex vivo* study was designed to characterize individual lesions created using PF and RF energy and to evaluate the effects of repeated applications, inter-application timing, and inter-lesion distance on lesion formation using a Sphere-9 catheter. The overall study protocol is illustrated in Figure 1. Potato slices were used for PF lesion generation, whereas commercially available porcine left ventricular myocardium intended for food consumption was used for RF lesion generation. As only commercially obtained porcine tissue intended for food consumption was used and no live animals were involved, ethical approval was not required. The specimens were fixed in an experimental chamber, and the Sphere-9 catheter was positioned perpendicular to the tissue surface for all PF and RF applications. To standardize catheter–tissue contact, an electronic scale was placed beneath the specimen, and the change in weight during catheter contact was monitored to maintain consistent contact conditions. The experimental chamber was filled with tap water, and sodium chloride was added until the baseline impedance displayed on the Affera system reached 50 Ω. Solution temperature was monitored using a thermometer and maintained at 36°C. The same dispersive electrode was incorporated into the experimental circuit for both PF and RF applications.

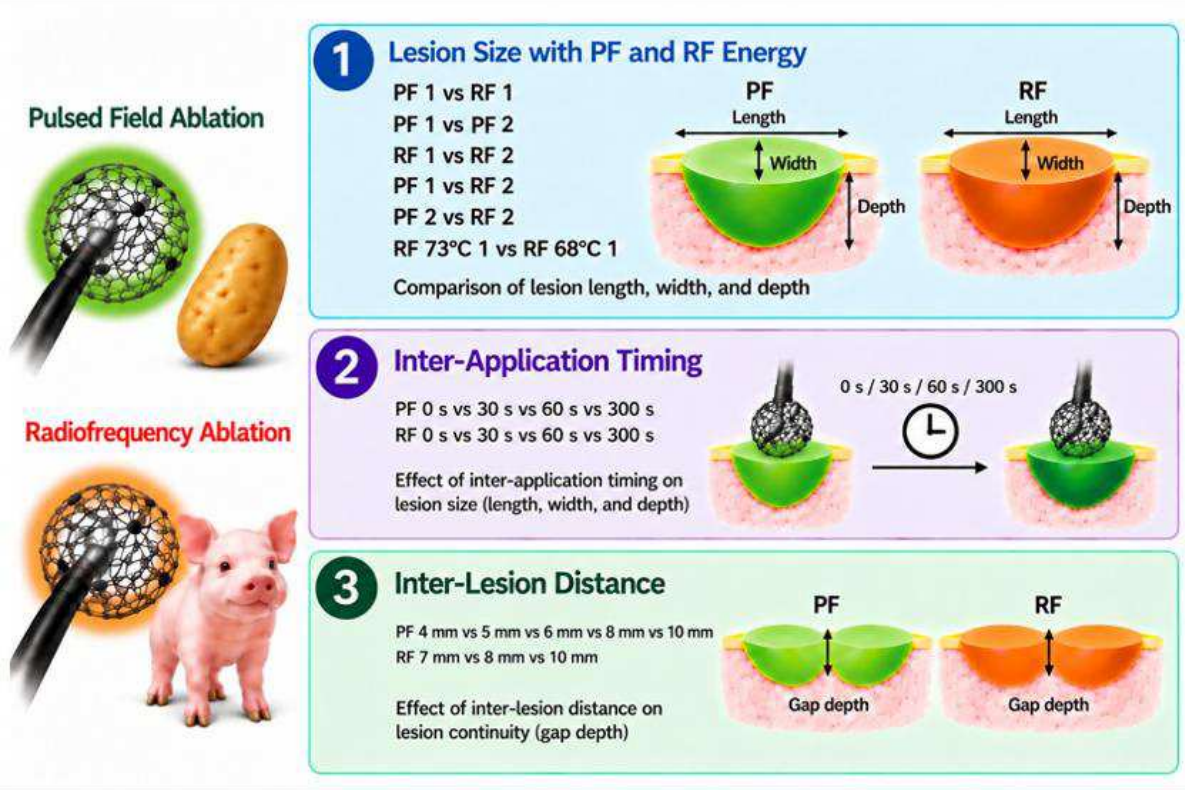

Fig. 1 Study protocol. Overview of the experimental protocol. Lesion formation using a dual-energy lattice-tip catheter was evaluated under three experimental settings. (1) Lesion dimensions after PF and RF applications were assessed by lesion length, width, and depth, including comparisons between single and repeated applications and between RF applications at target temperatures of 73 and 68°C. (2) The effects of inter-application timing were evaluated by delivering an additional PF or RF application at the same site after inter-application intervals of 0, 30, 60, or 300 s. (3) The effects of inter-lesion distance on lesion continuity were evaluated at distances of 4, 5, 6, 8, and 10 mm for PF and 7, 8, and 10 mm for RF, using gap depth as the measure of lesion continuity at depth. PF, pulsed field; RF, radiofrequency

Lesion dimensions with PF and RF energy

PF lesions were created in potato tissue slices. After PF application, the specimens were immersed in commercially available food dye for 3 h to visualize lesion boundaries. The staining protocol was determined through repeated preliminary experiments to provide reproducible and clearly identifiable lesion boundaries. RF lesions were created in commercially available porcine left ventricular myocardium and subsequently sectioned and measured immediately after RF application. For each lesion, length, width, and depth were measured directly to the nearest millimeter using a ruler. Length and width were defined as the major and minor diameters of the lesion at the tissue surface, respectively. Depth was defined as the maximum perpendicular distance from the tissue surface to the deepest extent of the lesion. Lesion dimensions were initially assessed after a single PF application (PF1) and a single RF application (RF1). To evaluate the effect of repeated applications, two consecutive applications of the same energy were delivered at the same site to create PF2 and RF2 lesions. Lesion length, width, and depth were compared as illustrated in Figure 1. The effect of RF temperature setting on lesion formation was additionally evaluated by comparing lesions created using a single RF application at target temperatures of 73 and 68°C.

Inter-application timing

The effect of inter-application timing on lesion dimensions during repeated applications at the same site was evaluated for both PF and RF energy. For each energy modality, a second application was delivered at the same site after the initial application at inter-application intervals of 0, 30, 60, or 300 s. The second application was delivered at the same location as that of the first application while maintaining catheter orientation and contact conditions as consistently as possible. Lesion length, width, and depth were measured at each inter-application interval to assess

the effect of the timing of additional applications on lesion dimensions.

Inter-lesion distance

The effect of inter-lesion distance on lesion continuity was evaluated by creating two adjacent lesions at predefined center-to-center distances. For PF energy, inter-lesion distances of 4, 5, 6, 8, and 10 mm were evaluated. For RF energy, inter-lesion distances of 7, 8, and 10 mm were evaluated. After creation of the two adjacent lesions, the specimens were sectioned through both lesions, and gap depth was measured at the midpoint between the two lesions. Gap depth was defined as the perpendicular distance from the tissue surface at the central junction to the deepest extent at which the two lesions remained continuous (Figure 1). Gap depth was compared across inter-lesion distances to evaluate the relationship between inter-lesion distance and lesion continuity at depth.

Statistical analysis

Continuous variables are presented as mean ± standard deviation. Differences between two groups were evaluated using the Mann–Whitney U test, with the Bonferroni correction applied to adjust for multiple comparisons. For comparisons among three or more groups, the Kruskal–Wallis test was performed. When a significant difference was identified, post hoc pairwise comparisons were conducted using the Mann–Whitney U test with Bonferroni adjustment.

To assess group interactions, linear regression models including interaction terms were constructed to estimate the effect size (β) with 95% confidence intervals for each group, as well as the *p*-value for the interaction between groups. All statistical tests were two-tailed, and significance was defined as a p-value < 0.05. All statistical analyses were performed using R (version 4.6.0; R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

A total of 190 lesions (100 PF and 90 RF lesions) were analyzed. Each experimental condition comprised 10 lesions. Therefore, comparisons between conditions were performed using 10 lesions per group.

Lesion dimensions with PF and RF energy

Lesion characteristics after single PF and RF applications

Lesion dimensions following single PF and RF applications are shown in Figure 2a. With a single PF application (PF1), lesion length, width, and depth were 22.7 ± 0.7, 14.8 ± 2.3, and 5.5 ± 0.5 mm, respectively. With a single RF

application (RF1), the corresponding dimensions were 16.1 ± 0.7, 14.7 ± 0.7, and 4.8 ± 0.6 mm, respectively. Compared with RF1, PF1 resulted in a significantly greater lesion length (22.7 ± 0.7 vs. 16.1 ± 0.7 mm, $p < 0.001$) and depth (5.5 ± 0.5 vs. 4.8 ± 0.6 mm, $p = 0.023$), whereas lesion width did not differ significantly between PF1 and RF1 (14.8 ± 2.3 vs. 14.7 ± 0.7 mm, $p = 0.877$) (Figure 2a).

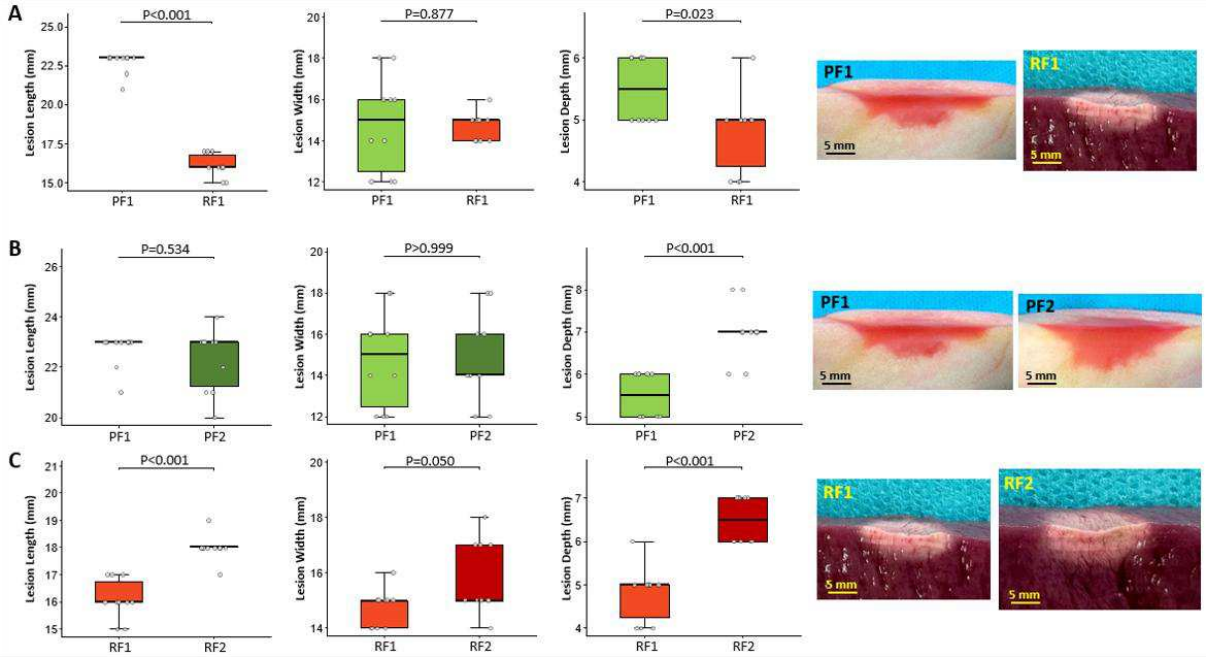

Fig. 2 Effects of energy modality and repeated applications on lesion dimensions. Comparison of lesion dimensions according to energy modality and repeated applications. Ten lesions were evaluated under each condition. (a) Comparison between a single PF application (PF1) and a single RF application (RF1). (b) Comparison between single (PF1) and repeated PF (PF2) applications. (c) Comparison between single (RF1) and repeated RF (RF2) applications. Lesion length, width, and depth are shown from left to right, with representative cross-sectional lesion images for each condition. *p*-values indicate the comparisons shown in each panel. Scale bars = 5 mm. PF, pulsed field; PF1, single PF application; PF2, repeated PF applications; RF, radiofrequency; RF1, single RF application; RF2, repeated RF applications

Effects of repeated applications on lesion dimensions

With PF energy, a second application significantly increased lesion depth from 5.5 ± 0.5 mm with PF1 to 7.0 ± 0.7 mm with PF2 ($p < 0.001$). In contrast, neither lesion length (22.7 ± 0.7 vs. 22.3 ± 1.3 mm, $p = 0.534$) nor lesion width (14.8 ± 2.3 vs. 14.8 ± 2.1 mm, $p > 0.999$) changed significantly after the second PF application (Figure 2b).

With RF energy, a second application significantly increased lesion length from 16.1 ± 0.7 to 18.0 ± 0.5 mm (p < 0.001) and lesion depth from 4.8 ± 0.6 to 6.5 ± 0.5 mm (p < 0.001). Lesion width increased from 14.7 ± 0.7 to 15.8 ± 1.3 mm, although the difference did not reach significance (p = 0.050) (Figure 2c). Interaction analysis demonstrated that the effect of repeated applications on lesion length differed significantly between PF and RF (interaction p < 0.001), whereas no significant interactions were observed for lesion width or depth (interaction p = 0.328 and p = 0.596, respectively).

When PF1 was compared with RF2, lesion length remained significantly greater with PF1 (22.7 ± 0.7 vs. 18.0 ± 0.5 mm, p < 0.001), while lesion depth was significantly greater during RF2 (5.5 ± 0.5 vs. 6.5 ± 0.5 mm, p = 0.002). Lesion width did not differ significantly between the groups (14.8 ± 2.3 vs. 15.8 ± 1.3 mm, p = 0.377) (Figure 3a).

When PF2 was compared with RF2, lesion length was significantly greater during PF2 (22.3 ± 1.3 vs. 18.0 ± 0.5 mm, p < 0.001), whereas no significant differences were observed in lesion width (14.8 ± 2.1 vs. 15.8 ± 1.3 mm, p = 0.204) or depth (7.0 ± 0.7 vs. 6.5 ± 0.5 mm, p = 0.098) (Figure 3b).

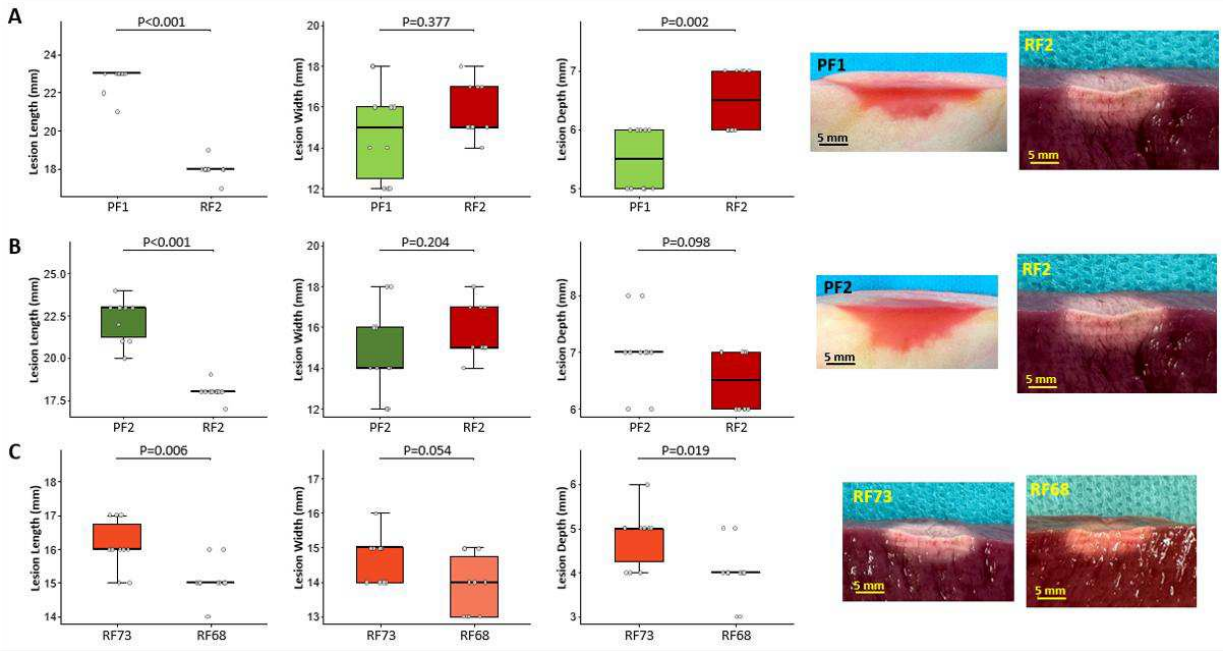

Fig. 3 Lesion characteristics across energy delivery strategies and RF temperature settings. Comparison of lesion dimensions across different energy delivery strategies and RF temperature settings. Ten lesions were evaluated under each condition. (a) Comparison between single PF (PF1) and repeated RF (RF2) applications. (b) Comparison between repeated PF (PF2) and repeated RF (RF2) applications. (c) Comparison between single RF applications at target temperatures of 73°C (RF73) and 68°C (RF68). Lesion length, width, and depth are shown

from left to right, with representative cross-sectional lesion images for each condition. *p*-values indicate the comparisons shown in each panel. Scale bars = 5 mm. PF, pulsed field; PF1, single PF application; PF2, repeated PF applications; RF, radiofrequency; RF2, repeated RF applications; RF73, RF application at a target temperature of 73°C; RF68, RF application at a target temperature of 68°C

Effects of RF temperature setting on lesion dimensions

Lesion formation with RF applications at target temperatures of 73 and 68°C was compared (Figure 3c). Compared with RF at 73°C, RF at 68°C produced significantly shorter surface lesion length (15.1 ± 0.6 vs. 16.1 ± 0.7 mm, p = 0.006) and shallower lesion depths (4.0 ± 0.7 vs. 4.8 ± 0.6 mm, p = 0.019). Lesion width did not differ significantly between the 68 and 73°C settings (13.9 ± 0.9 vs. 14.7 ± 0.7 mm, p = 0.054).

Effects of inter-application timing on repeated lesion formation

PF energy

The relationship between inter-application timing and lesion dimensions following repeated PF applications is shown in Figure 4. At inter-application intervals of 0, 30, 60, and 300 s, lesion lengths were 22.3 ± 1.3, 22.5 ± 1.2, 21.6 ± 1.6, and 21.5 ± 1.1 mm, respectively; lesion widths were 14.8 ± 2.1, 14.8 ± 1.0, 14.5 ± 0.9, and 13.8 ± 1.3 mm, respectively; and lesion depths were 7.0 ± 0.7, 6.6 ± 0.5, 5.4 ± 0.5, and 5.4 ± 0.5 mm, respectively.

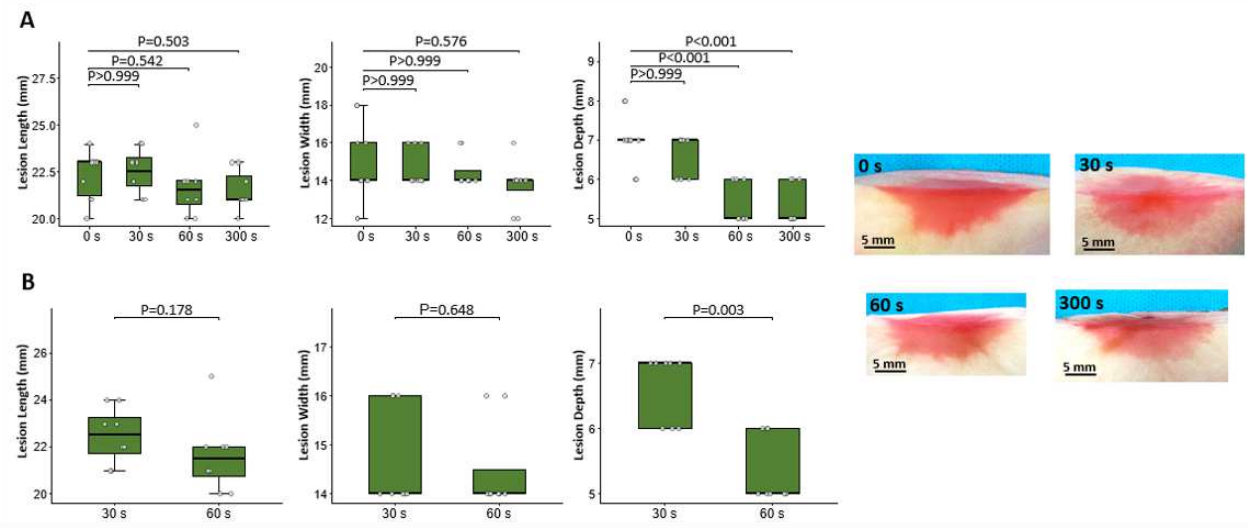

Fig. 4 Effects of inter-application timing on repeated PF lesion formation. Effects of inter-application timing on

lesion formation during repeated PF applications. Following the initial PF application, an additional application was delivered at the same site after 0-, 30-, 60-, or 300-s intervals. Ten lesions were evaluated under each condition. (A) Lesion length, width, and depth at each inter-application interval, with comparisons against the 0-s inter-application interval. (B) Direct comparison between the 30- and 60-s inter-application intervals. Representative cross-sectional lesion images for each inter-application interval are shown on the right. *p*-values indicate the comparisons shown in each panel. Scale bars = 5 mm. PF, pulsed field

Compared with an immediate second application (0 s), lesion depth did not differ significantly at 30 s ($p > 0.999$) but was significantly shallower at both 60 and 300 s (both $p < 0.001$). No significant differences in lesion length or width were observed between the 0-s group and any of the other timing groups (Figure 4a).

In the direct comparison between the 30- and 60-s groups, lesion depth decreased significantly from 6.6 ± 0.5 to 5.4 ± 0.5 mm ($p = 0.003$), whereas neither lesion length (22.5 ± 1.2 vs. 21.6 ± 1.6 mm, $p = 0.178$) nor width (14.8 ± 1.0 vs. 14.5 ± 0.9 mm, $p = 0.648$) differed significantly (Figure 4b).

RF energy

A similar relationship between inter-application timing and lesion depth was observed with repeated RF applications (Figure 5). At inter-application intervals of 0, 30, 60, and 300 s, lesion lengths were 18.0 ± 0.5, 18.3 ± 0.9, 17.2 ± 1.4, and 18.4 ± 0.5 mm, respectively; lesion widths were 15.8 ± 1.3, 16.7 ± 1.9, 16.4 ± 0.8, and 16.2 ± 0.4 mm, respectively; and lesion depths were 6.5 ± 0.5, 5.6 ± 0.5, 4.4 ± 0.5, and 3.8 ± 0.4 mm, respectively.

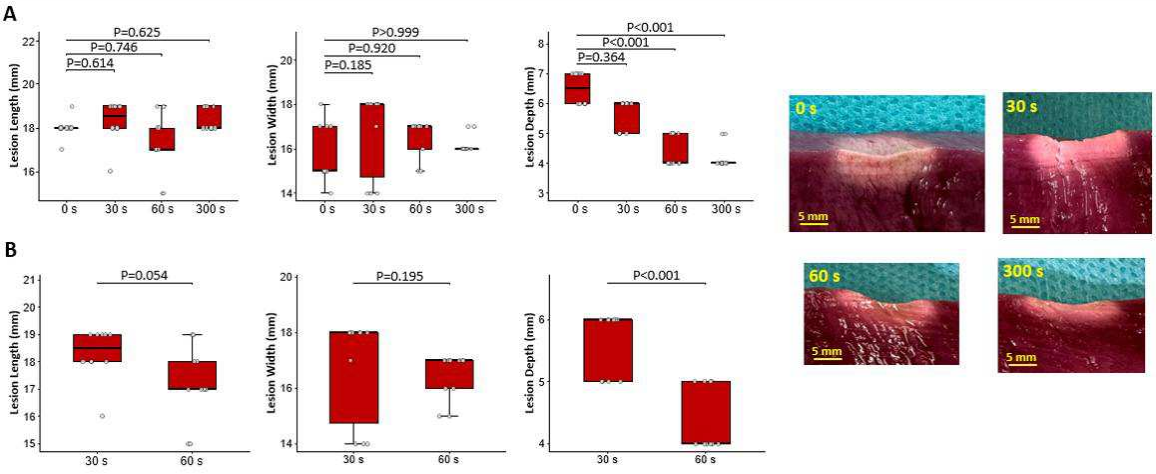

Fig. 5 Effects of inter-application timing on repeated RF lesion formation. Effects of inter-application timing on lesion formation during repeated RF applications. Following the initial RF application, an additional application was delivered at the same site after 0-, 30-, 60-, or 300-s intervals. Ten lesions were evaluated under each condition. (a) Lesion length, width, and depth at each inter-application interval, with comparisons against the 0-s inter-application interval. (b) Direct comparison between the 30- and 60-s inter-application intervals. Representative cross-sectional lesion images for each inter-application interval are shown on the right. *p*-values indicate the comparisons shown in each panel. Scale bars = 5 mm. RF, radiofrequency

Compared with an immediate second application, lesion depth did not differ significantly at 30 s ($p = 0.364$) but was significantly shallower at both 60 and 300 s (both $p < 0.001$). No significant differences in lesion length or width were observed between the 0-s group and any of the other timing groups (Figure 5a).

In the direct comparison between the 30- and 60-s groups, lesion depth decreased significantly from 5.6 ± 0.5 to 4.4 ± 0.5 mm ($p < 0.001$). Lesion length decreased from 18.3 ± 0.9 to 17.2 ± 1.4 mm, although this difference did not reach significance ($p = 0.054$), while lesion width did not differ significantly (16.7 ± 1.9 vs. 16.4 ± 0.8 mm, $p = 0.195$) (Figure 5b). Time-dependent changes in lesion depth did not differ significantly between PF and RF (interaction $P = 0.080$).

Effects of inter-lesion distance on lesion continuity

The relationship between inter-lesion distance and lesion continuity at depth between two adjacent lesions was assessed using gap depth (Figure 6).

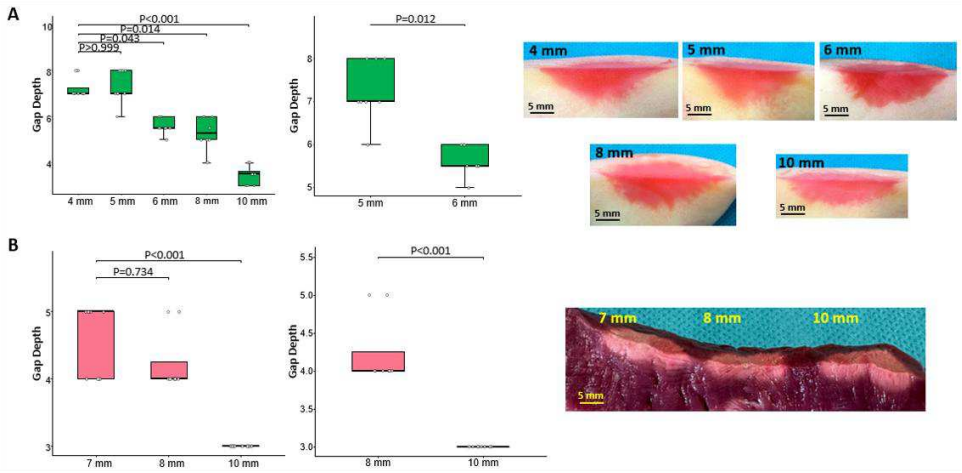

Fig. 6 Effects of inter-lesion distance on lesion continuity. Effects of inter-lesion distance on deep continuity between adjacent lesions. Ten pairs of adjacent lesions were evaluated under each condition. (a) For PF, gap depth was assessed at inter-lesion distances of 4, 5, 6, 8, and 10 mm. Comparisons with the 4-mm distance and a direct comparison between the 5- and 6-mm distances are shown, together with representative cross-sectional lesion images. (b) For RF, gap depth was assessed at inter-lesion distances of 7, 8, and 10 mm. Comparisons with the 7-mm distance and a direct comparison between the 8- and 10-mm distances are shown, together with a representative cross-sectional image. Gap depth was defined as the vertical distance from the tissue surface at the midpoint between two adjacent applications to the deepest point of the fused lesion at the junction. *p*-values indicate the comparisons shown in each panel. Scale bars = 5 mm. PF, pulsed field; RF, radiofrequency

PF energy

With PF, gap depths at inter-lesion distances of 4, 5, 6, 8, and 10 mm were 7.3 ± 0.5, 7.3 ± 0.7, 5.6 ± 0.4, 5.3 ± 0.7, and 3.4 ± 0.4 mm, respectively. Using 4 mm as the reference, gap depth did not differ significantly at 5 mm ($p > 0.999$) but was significantly shallower at 6 mm ($p = 0.043$), 8 mm ($p = 0.014$), and 10 mm ($p < 0.001$). In a direct comparison between 5 and 6 mm, gap depth decreased significantly from 7.3 ± 0.7 to 5.6 ± 0.4 mm ($p = 0.012$) (Figure 6a).

RF energy

With RF, gap depths at inter-lesion distances of 7, 8, and 10 mm were 4.6 ± 0.5, 4.3 ± 0.5, and 3.0 ± 0.0 mm, respectively. Gap depth did not differ significantly between inter-lesion distances of 7 and 8 mm ($p = 0.734$), whereas it was significantly shallower at 10 mm than at 7 mm ($p < 0.001$). In a direct comparison between 8 and 10 mm, gap depth decreased significantly from 4.3 ± 0.5 to 3.0 ± 0.0 mm ($p < 0.001$) (Figure 6b).

DISCUSSION

Main findings

In this *ex vivo* study, we characterized lesion formation using a dual-energy lattice-tip catheter and evaluated the effects of repeated applications, inter-application timing, and inter-lesion distance. The principal findings were as follows. First, PF and RF produced distinct lesion geometries: PF created a broad surface lesion following a single application, whereas repeated RF applications increased both lesion depth and surface lesion length. Second,

repeated applications significantly increased lesion depth during both PF and RF. Third, the effect of repeated applications on lesion depth was dependent on inter-application timing. Lesion depth did not differ between immediate repeat application and a 30-s inter-application interval, whereas intervals of 60 s or longer resulted in significantly shallower lesions. Fourth, increasing inter-lesion distance progressively reduced the depth of continuity between adjacent lesions. Collectively, these findings indicate that lesion formation using a lattice-tip catheter is determined not only by energy modality, but also by the temporal and spatial arrangement of energy delivery.

Lesion characteristics and effects of repeated applications

With a single application, PF produced significantly greater surface lesion length and depth than those during RF, whereas surface lesion width did not differ significantly. Previous studies using a lattice-tip catheter have similarly demonstrated distinct lesion characteristics between PF and RF, with PF producing a broader surface footprint [7]. Our findings further support the characteristic large-footprint lesion geometry of PF following a single application. Repeated applications significantly increased lesion depth with both PF and RF; however, their effects on surface dimensions differed. During PF, neither surface lesion length nor width significantly increased after a second application. In contrast, repeated RF applications significantly increased both surface lesion length and lesion depth. Consistent with these findings, interaction analysis confirmed that the effect of repeated applications on lesion length differed significantly between PF and RF, whereas no significant interaction was observed for lesion depth. Thus, PF created broad lesions after a single application, with the incremental effect of repeated applications occurring predominantly in the depth dimension, whereas repeated RF applications promoted lesion expansion in both the depth and surface dimensions.

Previous preclinical studies have demonstrated that repeated PF applications increase lesion depth, supporting a repeated application–dependent effect of PF energy [5,6]. More recently, repeated PF delivery using a lattice-tip catheter produced the greatest mean lesion depth, although the difference compared with a single PF application did not reach significance [7]. In the present study, repeated PF applications produced a significant increase in lesion depth, further supporting a depth-augmenting effect of repeated PF applications.

Studies using conventional RF catheters have reported inconsistent effects of repeated RF applications on lesion depth. In a previous *ex vivo* study, additional RF applications did not significantly increase lesion width or depth in atrial tissue with either high-power short-duration or conventional RF, with a significant increase in ventricular

lesion depth observed only under prolonged RF delivery conditions [8]. These findings suggest that the incremental effect of repeated conventional RF applications may depend strongly on tissue characteristics and energy-delivery parameters. However, in the present study, repeated lattice-tip RF applications significantly increased lesion depth and surface lesion length. The large-footprint electrode and distinct energy-delivery characteristics of lattice-tip RF, including temperature-controlled energy delivery, irrigation, and current-density distribution, may contribute to the observed response to repeated applications.

RF temperature settings

Reducing the RF temperature setting from 73 to 68°C significantly reduced both surface lesion length and lesion depth. The SAFE-Ablation Registry reported that attenuated RF settings with a lattice-tip catheter were associated with reduced procedure-related stroke compared with the initial default RF strategy [9]. Our findings demonstrate that attenuation of the RF setting also reduces lesion dimensions. Therefore, although attenuated RF delivery may improve safety, its potential effect on lesion formation, particularly the ability to achieve sufficient lesion depth, should also be considered.

Inter-application timing and lesion formation

An important finding of the present study was that the depth-augmenting effect of repeated applications was dependent on inter-application timing for both PF and RF. During both energy modalities, lesion depth did not differ significantly between immediate repeat application and a 30-s inter-application interval, whereas inter-application intervals of 60 and 300 s produced significantly shallower lesions than those following immediate repeat application. In contrast, surface lesion dimensions showed no clear time-dependent change. These findings suggest that inter-application timing primarily influences the additional extension of the lesion in the depth dimension. Following RF energy delivery, computer simulation of consecutive applications at the same site demonstrated that a second RF application increased lesion depth and that shorter inter-application intervals resulted in greater lesion enlargement and higher maximum tissue temperatures [10]. These findings are consistent with the time-dependent effect observed in the present study and support the notion that residual heat from the preceding application may contribute to the effect of early repeated RF applications.

A similar time-dependent effect was observed with PF in the present study. Although PF ablation is considered a

predominantly nonthermal ablation modality, repeated high-voltage applications can generate Joule heating. A recent *in vitro* study demonstrated that temperature increased with repeated PF applications and that a 10-s inter-application interval attenuated this temperature rise [11]. These findings suggest that residual heat or thermal accumulation from preceding PF applications may partly contribute to the greater depth achieved with early repeat applications in the present study.

In the aforementioned study, attenuation of the temperature rise by introducing a 10-s inter-application interval did not produce a significant difference in lesion depth at the same number of PF applications [11]. Therefore, the time-dependent PF effect observed in the present study is unlikely to be explained solely by thermal accumulation. Changes in tissue state induced by preceding PF applications, including electroporation-related cellular and tissue alterations, may also modify the effect of subsequent applications. Collectively, these findings suggest that for both PF and RF, not only the number of applications but also when additional applications are delivered may be an important determinant of deep lesion formation.

Inter-lesion distance and lesion continuity at depth

For linear ablation, the dimensions of individual lesions represent only one component of lesion-set formation; adjacent lesions must also maintain sufficient continuity at depth. In the present study, gap depth decreased as inter-lesion distance increased during both PF and RF. With PF, lesion continuity at depth was maintained at inter-lesion distances of 4–5 mm, whereas gap depth was significantly reduced at distances of 6 mm or greater compared with that at 4 mm. With RF, gap depth also decreased with increasing inter-lesion distance and was significantly shallower at 10 mm than that at 7 mm. Thus, even when adjacent lesions appeared continuous at the surface, increasing inter-lesion distance progressively reduced lesion overlap at depth.

The importance of lesion contiguity has previously been demonstrated in RF-guided PVI. The CLOSE protocol incorporated an inter-lesion distance of ≤6 mm, based on the concept that insufficient lesion depth and discontinuity between adjacent lesions contribute to pulmonary vein reconnection [12]. The present study extends this concept by providing a morphological assessment of the relationship between inter-lesion distance and lesion continuity at depth during both PF and RF. These findings suggest that linear lesion generation requires not only surface contiguity but also sufficient spatial overlap between adjacent lesions to preserve continuity at depth.

Implications for linear lesion generation

Clinical studies using a lattice-tip catheter have demonstrated high acute success rates for PVI, posterior wall isolation, and linear ablation [1,2]. However, invasive remapping has shown substantial differences in chronic durability among lesion sets, with high durability of roof, posterior box, and cavotricuspid isthmus lines but lower durability of anterior and mitral isthmus lines [3]. Thus, acute conduction block does not necessarily predict uniform chronic lesion durability.

The present findings identify two modifiable components of lesion-set formation. First, when additional lesion depth is required, repeated application can increase lesion depth during both PF and RF; this effect is greater when additional applications are delivered early. Second, increasing inter-lesion distance reduces the depth of continuity between adjacent lesions. Accordingly, linear ablation with a lattice-tip catheter should be considered not simply as the generation of a series of individual lesions, but as the formation of a three-dimensional lesion set in which energy-specific lesion geometry, repeated application and its timing, and the spatial arrangement of adjacent lesions collectively determine lesion continuity at depth.

Limitations

This study has several limitations. First, as an *ex vivo* study, the present study did not fully replicate the *in vivo* environment. Physiological factors that may affect lesion formation *in vivo*, including convective cooling by blood flow, tissue perfusion, and cardiac and respiratory motion, were not represented. Therefore, caution is required when extrapolating the lesion dimensions and effects of additional applications observed in the current study directly to *in vivo* settings.

Second, the sample size for each experimental condition was limited. The statistical power to detect small differences between groups may therefore have been limited, and further studies with larger sample sizes are warranted to assess the variability and reproducibility of these findings.

Third, lesion dimensions were assessed primarily using macroscopic measurements. Determination of lesion boundaries may therefore have involved some degree of subjectivity, and lesion boundaries were not validated by histological assessment or digital image analysis.

Fourth, the assessment of inter-lesion distance was based on the morphological continuity of adjacent lesions at depth, rather than on direct electrophysiological assessment of conduction. Therefore, the threshold at which a

reduction in gap depth results in an actual conduction gap could not be determined in this study.

Finally, the present study evaluated acute lesion formation and did not assess chronic lesion maturation or durability. Acutely created lesions may change over time as edema resolves and tissue healing and remodeling occur. Further *in vivo* studies are warranted to determine whether the observed relationships between lesion formation and repeated applications, inter-application timing, and inter-lesion distance are maintained during chronic follow-up.

CONCLUSION

Lesion formation using a lattice-tip catheter was determined not only by energy modality but also by the temporal and spatial pattern of energy delivery. Repeated applications increased lesion depth with both PF and RF energy, whereas their effects on surface lesion dimensions differed between the two energy modalities. Importantly, the effect of additional applications on lesion depth decreased with increasing inter-application time, and greater inter-lesion distances resulted in reduced lesion continuity at depth. These findings highlight the importance of energy-specific lesion geometry, timely additional applications, and appropriate inter-lesion distances for generating deep and continuous lesion sets using a lattice-tip catheter.

Statements and Declarations

Competing interests

The authors have no conflicts of interest to disclose.

Data availability statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics approval statement: As only commercially obtained porcine tissue intended for food consumption was used and no live animals were involved, ethical approval was not required.

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intellectual content, approved the final version of the manuscript, and agreed to be accountable for all aspects of the work.

References

1. Reddy VY, Anter E, Rackauskas G, et al. Lattice-tip focal ablation catheter that toggles between radiofrequency and pulsed field energy to treat atrial fibrillation: a first-in-human trial. Circ Arrhythm Electrophysiol. 2020;13:e008718.
2. Vetta G, Della Rocca DG, Sarkozy A, et al. A novel focal lattice-tip catheter toggling between pulsed field energy and radiofrequency for atrial arrhythmia ablation: results from a real-world, multicenter registry. Heart Rhythm. 2025;22:e13–e22.
3. Nies M, Benesch Vidal ML, My I, et al. Durability of atrial linear lesion sets using a dual-energy lattice-tip catheter: data from invasive remapping. Heart Rhythm. 2026;23:2114–22.
4. Barkagan M, Leshem E, Rottmann M, Sroubek J, Shapira-Daniels A, Anter E. Expandable lattice electrode ablation catheter: a novel radiofrequency platform allowing high current at low density for rapid, titratable, and durable lesions. Circ Arrhythm Electrophysiol. 2019;12:e007090.
5. Yavin HD, Higuchi K, Sroubek J, Younis A, Zilberman I, Anter E. Pulsed-field ablation in ventricular myocardium using a focal catheter: the impact of application repetition on lesion dimensions. Circ Arrhythm Electrophysiol. 2021;14:e010375.
6. Kawamura I, Reddy VY, Wang BJ, et al. Pulsed field ablation of the porcine ventricle using a focal lattice-tip catheter. Circ Arrhythm Electrophysiol. 2022;15:e011120.
7. Watanabe K, Shinohara M, Yu F, Reddy VY, Koruth JS. Maximizing lesion depth with the lattice-tip catheter: a preclinical comparison of single, double, and mixed pulsed-field and radiofrequency applications. Circ Arrhythm Electrophysiol. 2026;19:e014799.
8. Toloczko A, Buchan S, John M, Post A, Razavi M. Insurance lesions: does a second lesion make a difference? J Cardiovasc Electrophysiol. 2022;33:1507–12.
9. Oates CP, Power J, Whang W, et al. Left atrial ablation using the dual-energy, lattice-tip catheter in the SAFE-ablation Registry: how to avoid procedure-related stroke? Heart Rhythm. 2026;23:e2376-88.
10. Sánchez-Muñoz EJ, Berjano E, González-Suárez A. Computer simulations of consecutive radiofrequency pulses

applied at the same point during cardiac catheter ablation: implications for lesion size and risk of overheating. Comput Methods Programs Biomed. 2022;220:106817.

11. Okumura M, Yamagami S, Akiyama M, et al. Impact of application repetition on Joule heating and lesion formation using a circular-shaped pulsed field catheter. J Interv Card Electrophysiol. 2026;69:1563–6.
12. Taghji P, El Haddad M, Phlips T, et al. Evaluation of a strategy aiming to enclose the pulmonary veins with contiguous and optimized radiofrequency lesions in paroxysmal atrial fibrillation: a pilot study. JACC Clin Electrophysiol. 2018;4:99–108.