Received: 11 November 2023 | Revised: 22 May 2024 | Accepted: 9 July 2024

DOI: 10.1111/pace.15046

PACE WILEY

ORIGINAL ARTICLE

Role of impedance drop and lesion size index (LSI) to guide catheter ablation for atrial fibrillation

Milena Leo MD[1] | Abhirup Banerjee PhD[2] | Andre Briosa e Gala MD[3] | Michael Pope MD[3] | Michala Pedersen MD, PhD[3] | Kim Rajappan MD[3] | Matthew Ginks MD[3] | Yaver Bashir MD[3] | Ross J. Hunter MD, PhD[4] | Tim Betts MD[3]

[1]Queen Alexandra Hospital, Portsmouth Hospitals University NHS Trust, Portsmouth, UK

[2]Institute of Biomedical Engineering, Department of Engineering Science, University of Oxford, Oxford, UK

[3]John Radcliffe Hospital, Oxford University Hospitals NHS Foundation Trust, Oxford, UK

[4]Barts Heart Centre, London, UK

Correspondence

Abhirup Banerjee, PhD, Institute of Biomedical Engineering, Department of Engineering Science, University of Oxford, Oxford, UK.
Email: abhirup.banerjee@eng.ox.ac.uk

Funding information

NIHR Oxford Biomedical Research Centre; Abbott Medical; Oxfordshire Health Services Research Committee, Grant/Award Number: OHSRC; Royal Society, Grant/Award Number: URF\R1\221314

Abstract

Background: When using lesion size index (LSI) to guide catheter ablation, it is unclear what combination of power, contact force and time would be preferable to use and what LSI target value to aim for. This study aimed at identifying desirable ablation settings and LSI targets by using tissue impedance drop as indicator of lesion formation.

Methods: Consecutive patients, undergoing their first left atrial (LA) catheter ablation for atrial fibrillation, with radiofrequency energy (RF) powers of 20, 30 and 40 W were enrolled. Tissue impedance, contact force (CF), Force Time Integral (FTI) and LSI values were continuously recorded during ablation and sampled at 100 Hz. Mean CF and Contact Force Variability (CFV) were calculated for every lesion. The effect of RF power, ablation time, CF and CFV on impedance drop and LSI were assessed.

Results: A total of 3258 lesions were included in the analysis. For any target LSI value, use of higher RF powers translated into progressively higher impedance drops. The impact of lower CF and higher CFV on impedance drop was more relevant when using lower powers. Target LSI values corresponding to maximum impedance drop were identified depending on RF power, mean CF and CFV used.

Conclusions: Even in the context of an LSI-guided ablation strategy, use of lower or higher powers might lead to different lesion sizes. Different LSI targets might be needed depending on the combination of RF power, CF and CFV used for ablation. Incorporating indicators of catheter stability, like CFV, in the LSI formula could improve the predictive value of LSI for lesion size. Studies with clinical outcomes are required to confirm the clinical relevance of these findings.

KEYWORDS

contact force, contact force variability, high RF power, left atrial ablation, lesion size index, tissue impedance drop

Abbreviations: AF, atrial fibrillation; AI, ablation index; CF, contact force; CFV, contact force variability; FTI, force time integral; LA, left atrium; LSI, lesion size index; Max-Imp-%, maximum percentage impedance drop; Max-Imp-Δ, maximum absolute impedance drop; PVI, pulmonary vein isolation; PVs, pulmonary veins; RF, radiofrequency energy; SD, standard deviation; STL, seasonal-trend decomposition of time series by Loess.

1 | BACKGROUND

Reliable creation of durable transmural lesions is the key for successful catheter ablation procedures. To this aim, acute markers of lesion formation are needed for real-time estimation of lesion width and depth.

When using radiofrequency energy (RF) for catheter ablation, tissue impedance is traditionally assessed as a real-time surrogate marker of lesion formation. Local tissue heating during ablation produces increased ion mobility and reduced myocardial resistivity that translate into a drop in tissue impedance.[1,2] The impedance reduction is typically rapid in the first seconds of RF delivery, as result of faster resistive heating of the superficial tissue layers from the catheter tip; it then progressively slows down thereafter, due to slower conductive heating of deeper tissue layers, until a plateau is reached.

The magnitude of impedance drop at the plateau point (maximum impedance drop) correlates with lesion size[3] and lesion depth[4] in in-vitro studies. Similarly to impedance drop, lesion growth is highest in the first seconds of RF application, with a slowing approximation to a maximum regardless of the power. Seventy-five percent of final lesion size is achieved after 12–25 s of RF delivery, and earlier with higher power compared to lower power.[5] Moreover, lesion growth plateaus even before the termination of RF delivery.[6] Based on these findings, maximum impedance drop is often assumed a surrogate marker of lesion "maturity", that is, no further significant lesion expansion is obtained by prolonging RF delivery once maximum impedance drop has been achieved, and the chance of steam pops and collateral damage inevitably increases.

Ablation indexes such as Force Time Integral (FTI), Ablation Index (AI), and lesion size index (LSI) are now available in clinical settings as markers of lesion formation.[7,8] When using Abbott Medical contact force (CF)-sensing catheters, both FTI and LSI are continuously displayed and can be monitored during ablation. Compared to FTI, which includes CF and time, LSI combines in a non-linear formula all three main determinants of RF lesion formation: power, CF and ablation duration. In in-vitro studies, LSI is highly predictive of lesion width and depth, exhibiting a stronger correlation with lesion dimensions compared to FTI. Moreover, the correlation between LSI and lesion size is linear and independent from the power used, meaning that it is theoretically possible to achieve the same LSI—and therefore possibly the same lesion size—with lower powers by using a higher CF or by ablating for longer.[8] However, in-vitro data also suggest that ablation lesions reach maturity after 20–30 s of energy delivery without any further increase thereafter despite more prolonged ablation.[5–9]

This study was conducted to investigate the relationship between ablation parameters and impedance drop in the context of an LSI-guided left atrial (LA) catheter ablation strategy. We hypothesized that impedance drop, as a surrogate marker of lesion size, could help to establish ideal ablation settings and optimal target LSI indices for ablation.

2 | METHODS

The trial was approved by the local ethics committees, and it complied with the Declaration of Helsinki.

2.1 | Atrial fibrillation ablation protocol

Data were collected from the PiLOT-AF trial (Power, Lesion Size Index and Oesophageal Temperature Alerts during Atrial Fibrillation ablation),[10] which was a randomized study enrolling patients undergoing their first LA ablation for symptomatic paroxysmal or persistent atrial fibrillation (AF) (see supplementary materials section for more details).

Tissue CF, FTI, and LSI were sampled at 100 Hz, displayed in real time during ablation and automatically recorded for further analysis. Tissue impedance was measured between the tip of the ablation catheter and the ground patch (on the patient's left thigh) by using a 50 kHz current at the same sampling rate of 100 Hz.

Any steam pops occurring during the procedures were noted.

2.2 | Data analysis

The tissue impedance data recorded during RF delivery were processed offline using the R statistical software (version 4.0.3) to remove noise (see supplementary materials section).

Ablation lesions were excluded if any of the following occurred: short duration of less than 5 s (as no LSI value is generated before 5 s of RF delivery); sudden and progressive impedance rise, suggestive of catheter tip or tissue overheating with charring formation.[11]

After processing of the raw data, the maximum absolute impedance drop (Max-Imp-Δ), the maximum percentage impedance drop (Max-Imp-%), the mean CF, and the contact force variability (CFV) were calculated for each study ablation lesion. The maximum absolute impedance drop (Max-Imp-Δ) was calculated as the difference between maximum impedance value per lesion, which corresponded to the impedance at the beginning of the ablation, and minimum impedance reached during ablation. The Max-Imp-% was calculated by converting the Max-Imp-Δ into a percentage of the starting impedance to minimize any influence from the initial impedance value. The CFV was calculated as difference between mean of the peaks and mean of the troughs of CF during ablation, as previously described[12] (Figure 1).

The ablation lesions were grouped by RF power used (20, 30 and 40 W), by mean CF used (< 5, 5–10, 10–15 or > 15 g) and by CFV (≤ 5 g or > 5 g) and the Max-Imp-% values in each group were compared.

The variation of impedance drop over ablation time was investigated by dividing each ablation delivery into consecutive, cumulative 0.5 s time intervals and calculating the mean and the standard deviation (SD) of all lesions Max-Imp-% at each interval compared to the initial impedance at the start of ablation. The relative plateaus of Max-Imp-% and the corresponding times at plateau for each group of study

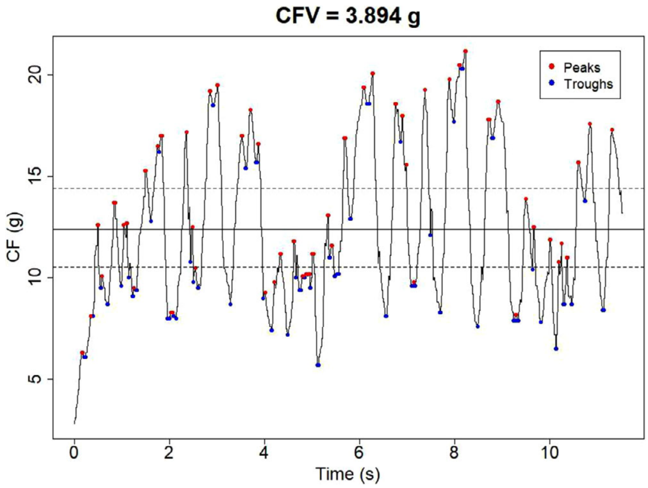


FIGURE 1 CFV: example of automated measurement from CF waveform over ablation time. The continuous horizontal line corresponds to the mean CF, the superior dotted line to the mean of the peaks and the inferior dotted line to the mean of the troughs. CF, contact force; CFV, contact force variability. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Patients' baseline characteristics.

Total number of patients	**44**
Age (years) *Mean (± SD)*	58.17 ± 9.57
Sex (males) *Number of patients (%)*	32 (73%)
Paroxysmal AF patients *Number of patients (%)*	19 (43.2%)
AF duration (months) *Median (IQR)*	27.5 (18–48)
EHRA class *Median (IQR)*	3 (3–3)
BMI *Mean (± SD)*	28.4 ± 6.6
CHA_2DS_2VASC score *Median (IQR)*	1 (0–2)
HAS-BLED score *Median (IQR)*	0 (0–2)
LA dimension (mm) *Mean (± SD)*	42.5 ± 7.3
LV systolic function (%) *Mean (± SD)*	56.8 ± 9.7

Abbreviations: AF, atrial fibrillation; BMI, body mass index; IQR, interquartile range; LA, left atrium; LV, left ventricle; SD, standard deviation.

ablations were identified by finding the point after which the SD of the Max-Imp-% at each time interval became negligible (less than 0.1) and the difference between Max-Imp-% at that point and Max-Imp-% at the end of ablation was very low (less than 0.25).

The relation between impedance drop and FTI was assessed as described in the supplementary section.

The relationship between impedance drop and LSI was assessed by dividing the ablation lesions into consecutive, cumulative 0.1 LSI intervals and calculating the Max-Imp-% of each interval compared to the initial impedance at the start of ablation. The mean and SD of Max-Imp-% were calculated for each interval. The relative plateaus of impedance drop and the corresponding LSI values at plateau were identified by finding the point after which the SD of the Max-Imp-% at each LSI interval became negligible (less than 0.1) and the difference between Max-Imp-% at that point and Max-Imp-% at the end of ablation was very low (less than 0.25). To confirm the accuracy of the technique used to identify the plateau values of the FTI/LSI over time curves, both per-patient analyses and combined analyses of all-patients lesions were performed, and their results were compared.

2.3 | Statistical analysis

Categorical variables were expressed as absolute number and percentage (%). Continuous variables were expressed as mean ± SD or median and interquartile range (IQR), as appropriate after checking for normality by using the Shapiro-Wilk test. Categorical variables were compared with the use of the Pearson's Chi-square test or Fisher's exact test, as appropriate. Continuous variables were compared with the use of one-way ANOVA test or Kruskal-Wallis test, as appropriate based on data distribution. Correlation between variables was assessed using Pearson's product-moment correlation coefficient (r) or Spearman's rank correlation coefficient (ρ), as appropriate.

A two-sided p-value of less than .05 was considered to indicate statistical significance. Data were analyzed with the use of R statistical software version 4.0.3 and SPSS software version 24 (IBM Statistics, Chicago, Illinois).

3 | RESULTS

3.1 | Ablation settings (RF power, time, CF and CFV) and relative tissue impedance drop changes

A total of 4406 ablation lesions were screened for the analysis. Among them, 274 lesions were removed due to short duration and non-availability of LSI values and 874 lesions due to sudden and progressive impedance rise during RF delivery [20 W: 95 lesions (11%); 30 W: 69 lesions (20%); 40 W: 710 (24%)]. The final analysis considered 3258 study ablations lesions. The baseline characteristics of the study patients are showed in Table 1. Of note, no steam pops were recorded during the study ablation procedures.

As presented in Table 2, use of higher RF powers translated into progressively higher Max-Imp-Δ and Max-Imp-% despite shorter ablation durations.

The incremental time analysis showed a logarithmic relation between impedance drop and time in each RF power group, consisting in a first steep increase in impedance drop followed by a progressively slower impedance drop until plateau. The per-patient analysis showed progressively higher percentage impedance drop values at time of plateau with the use of higher power (20 W = 8.6% ± 2.2%;

TABLE 2 Ablation parameters in the different RF power groups.

	20 W (763 lesions)	30 W (272 lesions)	40 W (2223 lesions)	*p*-Value
Max-Imp-Δ (Ω) Mean ± SD	10.16 ± 5.32	11.65 ± 6.63	12.53 ± 6.81	**<.0001**
Max-Imp-% (%) Mean ± SD	8.81 ± 4.27	10.08 ± 5.3	11 ± 5.23	**<.0001**
Ablation duration (s) Mean ± SD	27.44 ± 16.04	24.49 ± 16.3	16.95 ± 11.03	**<.0001**
CF (g) Mean ± SD	17.5 ± 9.4	19.4 ± 14	14.8 ± 8.6	**<.0001**
CFV (g) Mean ± SD	5.1 ± 4.1	4.5 ± 3.6	4.8 ± 3.4	.083

Abbreviations: CF, contact force; CFV, contact force variability; Max-Imp-% (%), maximum percentage impedance drop; Max-Imp-Δ, maximum absolute impedance drop; RF, radiofrequency energy; SD, standard deviation.

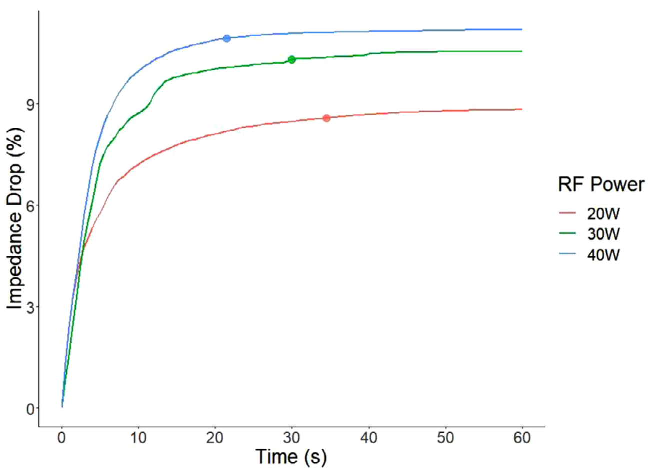


FIGURE 2 Variation of percentage impedance drop over time in the different RF power groups. Each data point represents the average percentage of impedance drop. The dots on each curve correspond to the plateau of percentage impedance drop. RF, radiofrequency energy. [Color figure can be viewed at wileyonlinelibrary.com]

30 W = 10.4% ± 3.8%; 40 W = 11% ± 2.5%; p = .0057) which also corresponded to shorter times to plateau (20 W RF time at plateau = 30.9 ± 9.5 s; 30 W RF time at plateau = 25.1 ± 12.7 s; 40 W RF time at plateau = 21 ± 7 s; p < .0005). As shown in Figure 2, the combined analysis of all-patients lesions showed the same trends. The plateau values of the curves corresponded to percentage impedance drop values of 8.59% at 34.5 s, 10.32% at 30 s, and 10.94% at 21.5 s for RF powers of 20, 30, and 40 W respectively. In all cases, the average maximum impedance drops and times to plateau for all patients fell very near to the mean values computed from individual patients and well within their SDs.

In all RF power groups, weak correlations were observed between mean CF and impedance drop (20 W RF power: ρ = 0.061, p = .094; 30 W RF power: ρ = 0.148, p = .015; 40 W RF power: ρ = 0.205, p < .0001) and between CFV and impedance drop (20 W RF power: ρ = –0.202, p < .0005; 30 W RF power: ρ = 0.225, p = .0002; 40 W RF power: ρ = 0.021, p = .316). However, if grouping the ablation lesions according to range of mean CF used and to range of CFV, progressively higher Max-Imp-% values were seen with higher mean CF and lower CFV in the 20 W and the 40 W group, as showed in Table 3. In the 30 W group, increase of mean CF from 10–15 g to > 15 g and reduction of CFV from > 5 to ≤ 5 g in the 5–10 g and > 15 g CF sub-groups translated in reduction rather than in increase of Max-Imp-%, however the number of observations in these subgroups was quite small with a larger variance of the data. In each power group the largest Max-Imp-% increase was observed when increasing the mean CF from < 5 g to 5–10 g.

The independent effect of mean CF and CFV on impedance drop within each RF power group was also confirmed by a mixed-effect model analysis (see supplementary section).

3.2 | Relationships between impedance drop and FTI/LSI

Correlation analyses showed a stronger correlation of LSI with impedance drop (ρ = 0.319; p < .0001) compared to FTI with impedance drop (ρ = 0.263; p < .0001).

The incremental FTI analysis showed progressively lower FTI values corresponding to higher percentage impedance drop values at plateau with increasing RF power (see supplementary section).

The incremental LSI analysis showed a first linear phase of impedance drop increase over LSI followed by a plateau phase. Due to unavailability of LSI data in the first few seconds of RF delivery, the LSI curves started with a minimum LSI of 2. At any LSI stage, impedance drop was progressively higher with increasing RF power. The per-patient analysis showed progressively higher LSI values required to reach plateau of impedance drop with increasing RF power used (20W: LSI = 4.2 ± 0.5; 30W: LSI = 4.6 ± 1.5; 40W: LSI = 5.4 ± 0.5; overall p < .0015), with higher impedance drop reached at plateau (20 W = 8.6% ± 2.2%; 30 W = 10.4% ± 3.8%; 40 W = 11% ± 2.6%; overall p = .0062). As shown in Figure 3, the combined analysis of all patients' lesions showed the same trends of the per-patient analysis. The 20, 30 and 40 W curves reached plateaus corresponding to percentage impedance drop values of 8.71% at LSI 4.7, 10.43% at LSI 5.5,

TABLE 3 Maximum percentage impedance drop achieved during ablation in the different RF power groups depending on mean contact force only and on combination of mean CF and contact force variability.

	20 W RF power	30 W RF power	40 W RF power	*p*-Value
Mean CF ≤ 5 g	7.54 ± 5.25	5.28 ± 3.30	7.88 ± 4.63	.043
5 g < Mean CF ≤ 10 g	8.38 ± 4.79	9.99 ± 5.01	10.2 ± 4.78	.002
10 g < Mean CF ≤ 15 g	8.88 ± 4.22	11.4 ± 5.36	10.9 ± 5.13	<.0001
Mean CF > 15 g	8.95 ± 4.08	10.4 ± 5.27	12.1 ± 5.40	<.0001
***p*-Value**	.309	<.0001	<.0001	
Mean CF ≤5 g and:				
- CFV ≤ 5 g	7.54 ± 5.25	5.28 ± 3.30	7.88 ± 4.63	.043
- CFV > 5 g	–	–	–	–
***p*-Value**	–	–	–	
5 g < Mean CF ≤ 10 g and:				
- CFV ≤ 5 g	8.97 ± 4.93	9.74 ± 5.12	10.3 ± 4.73	.055
- CFV > 5 g	5.55 ± 2.70	10.6 ± 4.81	9.84 ± 5.08	.002
***p*-Value**	.005	.554	.398	
10 g < Mean CF ≤ 15 g and:				
- CFV ≤ 5 g	9.74 ± 4.56	12.2 ± 5.41	11.0 ± 5.21	.007
- CFV > 5 g	7.23 ± 2.84	9.60 ± 4.95	10.7 ± 4.97	<.0001
***p*-Value**	<.0001	.101	.445	
Mean CF > 15 g and:				
- CFV ≤ 5 g	9.71 ± 4.53	9.74 ± 5.60	13.0 ± 5.17	<.0001
- CFV > 5 g	8.13 ± 3.37	11.3 ± 4.71	11.4 ± 5.48	<.0001
***p*-Value**	<.0001	.087	<.0001	

Abbreviations: CF, contact force; CFV, contact force variability; RF, radiofrequency energy.

and 11.07% at LSI 5.9 respectively. In all cases, the average maximum impedance drops and LSI values to plateau for all patients fell very near to the mean values computed from individual patients and well within their SDs.

Figure 4 represents graphically the impact of different combinations of RF power, CF and CFV on Max-Imp-% and the corresponding LSI. Each line represents a combination of RF power and range of CFV, while the various points of the lines are the mean CF. Mean CF showed a larger effect on impedance drop in the 40 W group than in the 20 W group. Vice versa, CFV showed a more pronounced effect on impedance drop in the 20 W group than in the 40 W one. Provided a mean CF of at least 5 g, use of 40 W produced a bigger impedance drop irrespective of target LSI or CFV. In each RF power group, approximate LSI values indicative of achievement of Max-Imp-% could be identified for the different ranges of CF. However, depending on the range of CFV, each LSI value corresponded to two different actual values of Max-Imp-% achieved.

4 | DISCUSSION

This study assessed the relationship between ablation settings and tissue impedance drop in the context of an LSI-guided catheter ablation strategy. The main findings of the study were:

- for any target LSI value, higher RF powers produced progressively greater impedance drops and prolonging ablation time when using lower powers did not compensate;
- increasing the mean CF to at least 5 g produced the largest increase in impedance drop in all RF power groups;
- higher CFV > 5 g translated in a lower impedance drop regardless of the power and of the CF used;
- although LSI was found to be a better predictor of Max-Imp-% compared to FTI, its correlation with Max-Imp-% was found to depend on combination of RF power, mean CF and also CFV used.

As shown in Figures 2 and 3, in our study higher powers translated into larger impedance drops regardless of ablation duration and of LSI value achieved. These data suggest that the use of LSI targets does not fully compensate for higher powers, which might be due to the plateau of lesion growth over time and to the less relevant effect of CF at lower powers. If considering impedance drop as a surrogate marker of lesion size, they are in keeping with the growing body of evidence on high RF power. Increases in RF power produce larger lesions as result of a shift to more effective resistive heating, whereas an increase in ablation duration simply gives more time for convective heating, which reaches

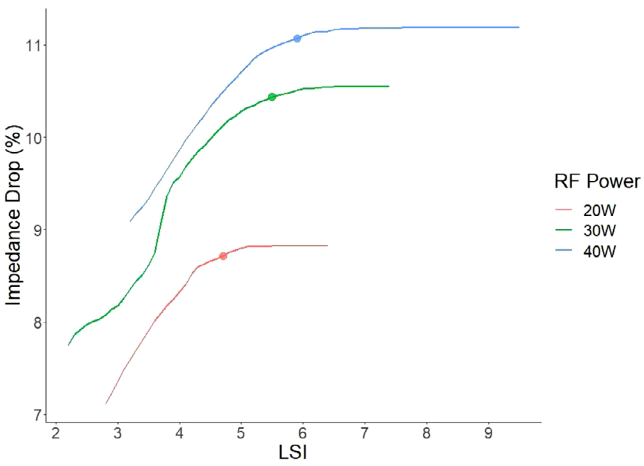
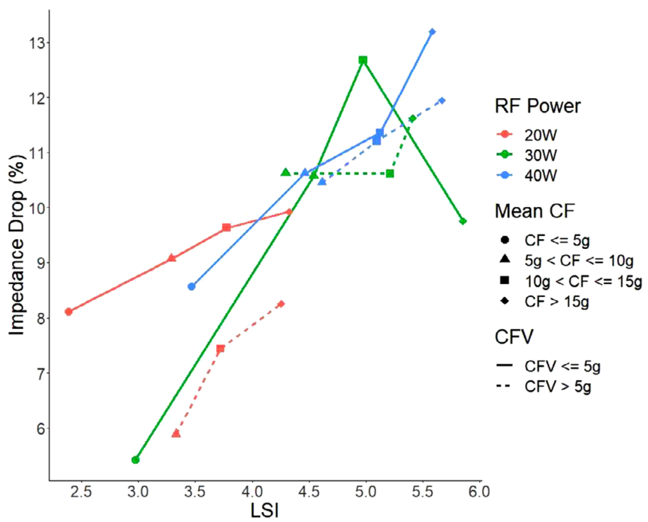


FIGURE 3 Relationship between LSI and percentage impedance drop in the different RF power groups. Each data point represents the average percentage of impedance drop. The dots on each curve represent the plateau of percentage impedance drop. LSI, lesion size index; RF, radiofrequency energy. [Color figure can be viewed at wileyonlinelibrary.com]



LSI values corresponding to maximum Percentage Impedance Drop			
	20 W	30W	40W
Mean CF ≤ 5 g	2.5	3	3.5
5 g < Mean CF ≤ 10 g	3.5	4.5	4.5
10 g < Mean CF ≤ 15 g	4	5	5
Mean CF > 15 g	4.5	5.5	5.5

FIGURE 4 Relationship between maximum percentage impedance drop and corresponding LSI depending on RF power, mean CF and CFV. Each line represents a combination of power (depending on the color: red for 20 W, green for 30 W, and blue for 40 W) and CFV (depending on if dotted = CFV > 5 or continuous = CFV ≤ 5). The different symbols on each line instead correspond to a different mean CF, as indicated in the legend. CF, contact force; CFV, contact force variability; LSI, lesion size index; RF, radiofrequency energy. [Color figure can be viewed at wileyonlinelibrary.com]

its limit after a 30–40 s period.[13] High-power short-duration ablation produces wider, albeit slightly shallower lesions, which are generally still transmural when ablating on thin walls like the LA, thus achieving a better compromise between clinical outcomes and risk of collateral damage.[10,14,15] More RF applications however might be required in thicker areas, like the left ridge, as suggested by a reduced incidence of first pass pulmonary vein isolation on the left side compared to the right side when using high-power short-duration ablation.[16] In these cases, lower-power longer-duration ablation might still be useful to increase the chance of a transmural lesion.

Although sudden impedance rise during RF delivery was observed more frequently with use of increasing power (11% of 20 W power lesions vs. 24% of 40 W power lesions), no steam pops were recorded in our study ablation procedures, possibly due to prompt termination of RF delivery in the case of an impedance rise.

In keeping with previous data,[17–19] we generally observed a progressive increase of Max-Imp-% with use of higher mean CF in the different RF power groups. In all groups the largest increase in percentage impedance drop was observed by increasing the mean CF from less than 5 g to more than 5 g, which may suggest the importance of a minimum mean CF of at least 5 g for effective ablation. The effect of increasing CF on Max-Imp-% was progressively larger with use of increasing power, as expected as both factors play a role in maintaining a constant catheter electrode-tissue interface temperature required for RF lesion formation,[20] and in keeping with previous data.[21] As result, higher CF values were required to achieve the same impedance drop when using lower powers. As previously demonstrated by Ullah et al.,[12] CFV was found to play a role on Max-Imp-%: this is not surprising considering that CFV is an indicator of catheter stability. Of note, the effect of increasing CFV on Max-Imp-% was progressively smaller with use of higher powers. Taken all together, these data might suggest that CF and CFV are more important when using lower powers. Switching to higher power could be considered in case of catheter instability or in case of difficulty to increase CF, like during sedation cases or if performing LA ablation without steerable sheaths.

The relation between impedance drop and LSI was found to be similar to the relation observed between impedance drop and AI by Ullah et al.,[22] apart from the lack of an initial lag phase of impedance drop which might just not have been visible due to unavailability of LSI data in the first few seconds of RF delivery. As expected, given the crucial role of RF power on Max-Imp-%, LSI showed a stronger correlation than FTI with impedance drop. However, as shown in Figure 4, each LSI value was found to correspond to different impedance drop values depending on combination of RF power, mean CF ad also CFV. Progressively higher LSI values were found to be required to achieve plateau of impedance drop with higher powers, higher mean CF and lower CFV. Target LSI values corresponding to achievement of Max-Imp-% were identified for each combination of RF power and mean CF, but they were found to correspond to different Max-Imp-% values depending on CFV. In its current formula not including CFV, LSI could represent more an indicator of lesion maturity (corresponding to plateau of impedance drop) rather than of lesion size (correlating with the value of impedance drop at plateau).

5 | LIMITATIONS

5.1 | The study has several limitations

First of all, no histological assessment of the ablation lesions was performed. Although previous studies showed a good correlation of impedance drop with lesion size, the correlation is not perfect. Tissue impedance at the catheter-tissue interface was classically measured as transthoracic impedance of the energy delivery pathway from the ablation catheter tip electrode to an indifferent electrode on the skin. This approach is known to be influenced by variation of thoracic impedance and in fact local tissue impedance measurements, now provided by innovative catheters with miniature electrodes, seem to correlate better with lesion size.[23] Nevertheless, impedance changes during RF ablation are almost entirely due to variations in local tissue impedance, and thus the variations of impedance and especially the percentage variations of impedance should remain a useful measure.

Without measuring directly the lesion sizes, it is difficult to be certain that the discrepancy between LSI and impedance drop with different powers reflects true differences in lesion size (as indicated by different impedance drops) or rather a different relationship between impedance drop and lesion size with different RF powers.

The use of different catheter irrigation rates for different RF powers, as per Tacticath manufacture instructions, could have had an impact on the percentage impedance drop values recorded with the different powers. Irrigation may impact on impedance drop by preventing heating of the endocardial surface and therefore making impedance drop less predictive of lesion depth progression. However, the greater impedance falls in the higher power lesions despite higher irrigation rate suggest that this is a genuine effect of high power compared to low power.

No information was collected about location of each RF lesion and current driven during each ablation lesion.

The correlation of ablation settings with clinical outcomes could not be analyzed due to the extreme variability of ablation settings used in each patient and for each ablation lesion set, thus limiting the chance of investigating the effect of each specific ablation parameter on clinical outcomes.

6 | CONCLUSIONS

Even in the context of an LSI guided ablation strategy, use of lower or higher powers might lead to different lesion sizes. Use of higher powers might be preferrable in case of catheter instability or in case of difficulty to increase CF. Different LSI targets might be needed, depending on power and mean CFV used, to prevent unnecessary ablation and reduce the risk of collateral damage. Incorporating indicators of catheter stability, like CFV, in the LSI formula could improve the predictive value of LSI for lesion size. Larger studies with clinical outcomes are required to confirm the clinical relevance of these findings.

AUTHOR CONTRIBUTIONS

Milena Leo: Concept/design; data analysis/interpretation; drafting article; critical revision of article; data collection.

Abhirup Banerjee: Concept/design; statistics; data analysis/interpretation; drafting article; critical revision of article. **Andre Briosa e Gala**: Concept/design; data analysis/interpretation; critical revision of article. **Michael Pope**: Concept/design; data analysis/interpretation; critical revision of article. **Michala Pedersen**: critical revision of article. **Kim Rajappan**: critical revision of article. **Matthew Ginks**: critical revision of article. **Yaver Bashir**: critical revision of article. **Ross J. Hunter**: concept/design; data interpretation; critical revision of article. **Tim Betts**: concept/design; data interpretation; critical revision of article.

ACKOWLEDGMENTS

We thank the John Radcliffe Hospital Cardiac Angiography Suite Team and the Oxford Cardiac Research Team for their invaluable help and support for the conduction of the study. Prof. Betts is supported by the NIHR Oxford Biomedical Research Centre. Dr Leo's salary was supported by an unrestricted research grant from Abbott Medical. The study was partially supported by an Oxfordshire Health Services Research Committee (OHSRC) research grant (reference 1182). Dr Banerjee is a Royal Society University Research Fellow and is supported by the Royal Society grant number URF\R1\221314.

CONFLICT OF INTEREST STATEMENT

Dr Ginks has received speaker's fees from Abbott and Biosense Webster. Dr Rajappan has received speaker's fees from Abbott. Prof. Hunter has received research grants, educational grants and speaker's fees from Biosense Webster and Medtronic; he is an inventor of the STAR Mapping system and shareholder in Rhythm AI Ltd. Prof. Betts has received research funding, speaker's fees and advisory board fees from Abbott. The other authors have no conflict of interests to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

PATIENT CONSENT TO PARTICIPATE

All patients provided informed consent for participation in the study.

PERMISSION TO REPRODUCE MATERIAL FROM OTHER SOURCES

It was not required.

CLINICAL TRIAL REGISTRATION

Data for the study were collected from the PiLOT-AF trial (Power, Lesion Size Index and Oesophageal Temperature Alerts during Atrial Fibrillation ablation), which was registered (NCT02619396).

ORCID

Abhirup Banerjee PhD https://orcid.org/0000-0001-8198-5128
Andre Briosa e Gala MD https://orcid.org/0000-0002-9145-6374

REFERENCES

1. Hartung WM, Burton ME, Deam AG, Walter PF, McTeague K, Langberg JJ. Estimation of temperature during radiofrequency catheter ablation using impedance measurements. *Pacing Clin Electrophysiol: PACE*. 1995;18:2017-2021.
2. Nsah E, Berger R, Rosenthal L, et al. Relation between impedance and electrode temperature during radiofrequency catheter ablation of accessory pathways and atrioventricular nodal reentrant tachycardia. *Am Heart J*. 1998;136:844-851.
3. Avitall B, Mughal K, Hare J, Helms R, Krum D. The effects of electrode-tissue contact on radiofrequency lesion generation. *Pacing Clin Electrophysiol: PACE*. 1997;20:2899-2910.
4. Eick OJ, Gerritse B, Schumacher B. Popping phenomena in temperature-controlled radiofrequency ablation: when and why do they occur. *Pacing Clin Electrophysiol: PACE*. 2000;23:253-258.
5. Bahlke F, Wachter A, Krafft H, et al. Lesion formation in irrigated RF-ablation is not linear but monoexponential. *EP Europace*. 2023;25:euad122709.
6. Bhaskaran A, Chik W, Nalliah C, et al. Observations on attenuation of local electrogram amplitude and circuit impedance during atrial radiofrequency ablation: an in vivo investigation using a novel direct endocardial visualization catheter. *J Cardiovasc Electrophysiol*. 2015;26:1250-1256.
7. Das M, Loveday JJ, Wynn GJ, et al. Ablation index, a novel marker of ablation lesion quality: prediction of pulmonary vein reconnection at repeat electrophysiology study and regional differences in target values. *Europace*. 2017;19:775-783.
8. Calzolari V, De Mattia L, Indiani S, et al. In vitro validation of the lesion size index to predict lesion width and depth after irrigated radiofrequency ablation in a Porcine model. *JACC Clinical electrophysiology*. 2017;3:1126-1135.
9. Wittkampf FH, Hauer RN, Robles de Medina EO. Control of radiofrequency lesion size by power regulation. *Circulation*. 1989;80:962-968.
10. Leo M, Pedersen M, Rajappan K, et al. Power, lesion size index and oesophageal temperature alerts during atrial fibrillation ablation: a randomized study. *Circ Arrhythm Electrophysiol*. 2020;13:e008316.
11. Haines DE, Verow AF. Observations on electrode-tissue interface temperature and effect on electrical impedance during radiofrequency ablation of ventricular myocardium. *Circulation*. 1990;82:1034-1038.
12. Ullah W, Hunter RJ, Baker V, et al. Factors affecting catheter contact in the human left atrium and their impact on ablation efficacy. *J Cardiovasc Electrophysiol*. 2015;26:129-136.
13. Borne RT, Sauer WH, Zipse MM, Zheng L, Tzou W, Nguyen DT. Longer duration versus increasing power during radiofrequency ablation yields different ablation lesion characteristics. *JACC Clin Electrophysiol*. 2018;4:902-908.
14. Leshem E, Zilberman I, Tschabrunn CM, et al. High-Power and short-duration ablation for pulmonary vein isolation: biophysical characterization. *JACC Clin Electrophysiol*. 2018;4:467-479.
15. Winkle RA. HPSD ablation for AF high-power short-duration RF ablation for atrial fibrillation: a review. *J Cardiovasc Electrophysiol*. 2020.
16. Sciacca V, Fink T, Körperich H, et al. Magnetic resonance assessment of left atrial scar formation following a novel very high-power short-duration workflow for atrial fibrillation ablation. *Europace*. 2023;25:1392-1399.
17. Kumar S, Haqqani HM, Chan M, et al. Predictive value of impedance changes for real-time contact force measurements during catheter ablation of atrial arrhythmias in humans. *Heart rhythm*. 2013;10:962-969.
18. Ullah W, Hunter RJ, Baker V, et al. Target indices for clinical ablation in atrial fibrillation: insights from contact force, electrogram, and biophysical parameter analysis. *Circ Arrhythm Electrophysiol*. 2014;7:63-68.
19. De Bortoli A, Sun LZ, Solheim E, et al. Ablation effect indicated by impedance fall is correlated with contact force level during ablation for atrial fibrillation. *J Cardiovasc Electrophysiol*. 2013;24:1210-1215.
20. Haines DE. Determinants of lesion size during radiofrequency catheter ablation: the role of electrode-tissue contact pressure and duration of energy delivery. *J Cardiovasc Electrophysiol*. 1991;2:509-515.
21. Ikeda A, Nakagawa H, Lambert H, et al. Relationship between catheter contact force and radiofrequency lesion size and incidence of steam pop in the beating canine heart: electrogram amplitude, impedance, and electrode temperature are poor predictors of electrode-tissue contact force and lesion size. *Circ Arrhythm Electrophysiol*. 2014;7:1174-1180.
22. Ullah W, Hunter RJ, Finlay MC, et al. Ablation index and surround flow catheter irrigation: impedance-based appraisal in clinical ablation. *JACC Clin electrophysiol*. 2017;3:1080-1088.
23. Gunawardene M, Münkler P, Eickholt C, et al. A novel assessment of local impedance during catheter ablation: initial experience in humans comparing local and generator measurements. *Europace*. 2019;21:i34-i42.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Leo M, Banerjee A, Gala ABE, et al. Role of impedance drop and lesion size index (LSI) to guide catheter ablation for atrial fibrillation. *Pacing Clin Electrophysiol*. 2024;47:1404–1411. https://doi.org/10.1111/pace.15046