Impact of a formula combining local impedance and conventional parameters on lesion size prediction

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Running Title: A Formula with LI to predict lesion characteristics

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ABSTRACT

Background: Although ablation energy (AE) and force-time integral (FTI) are well-known active predictors of lesion characteristics, these parameters do not reflect passive tissue reactions during ablation, which may instead be represented by drops in local impedance (LI). This study aimed to investigate if additional LI-data improves predicting lesion characteristics and steam-pops.

Methods: RF applications at a range of powers (30W, 40W, and 50W), contact forces (8g, 15g, 25g, and 35g), and durations (10-180s) using perpendicular/parallel catheter orientations, were performed in excised porcine hearts (N=30). The correlation between AE, FTI and lesion characteristics was examined and the impact of LI (%LI-drop [%LID] defined by the ΔLI/Initial LI) was additionally assessed.

Results: 375 lesions without steam-pops were examined. Ablation energy (W*s) and FTI (g*s) showed a positive correlation with lesion depth (ρ=0.824:P<0.0001 and ρ=0.708:P<0.0001), surface area (ρ=0.507:P<0.0001 and ρ=0.562:P<0.0001) and volume (ρ=0.807:P<0.0001 and ρ=0.685:P<0.0001). %LID also showed positive correlation individually with lesion depth (ρ=0.643:P<0.0001), surface area (ρ=0.547:P<0.0001) and volume (ρ=0.733, P<0.0001). However, the combined indices of AE*%LID and FTI*%LID provided significantly stronger correlation with lesion depth (ρ=0.834:P<0.0001 and ρ=0.809P<0.0001), surface area (ρ=0.529:P<0.0001 and ρ=0.656:P<0.0001) and volume (ρ=0.864:P<0.0001 and ρ=0.838:P<0.0001). This tendency was observed regardless of the catheter placement (parallel/perpendicular). AE (P=0.02) and %LID (P=0.002) independently remained as significant predictors to predict steam-pops (N=27). However, the AE*%LID did not increase the predictive power of steam-pops compared to the AE alone.

Conclusion: LI, when combined with conventional parameters (AE and FTI), may provide stronger correlation with lesion characteristics.

Keywords; catheter ablation, radiofrequency, power, contact force, impedance

INTRODUCTION

Radiofrequency (RF) current is the most frequently used energy source for catheter ablation of cardiac arrhythmias.[1] To prevent arrythmia recurrence, creating a durable lesion of optimal size is one of the most important factors.[2] To predict lesion characteristics, both active and passive factors should be taken into account. Active factors include power, catheter-tissue contact force (CF), ablation electrode temperature, duration of energy delivery and ablation energy (AE) or force-time integral (FTI), with an 'ablation index' combining some of these factors.[34] Several studies have reported a positive correlation between AE, FTI and lesion characteristics[3256]. In contrast, passive factors include tissue thickness, tissue architecture and myocardial blood flow. Impedance has been used as one of the most reliable parameters to predict lesion formation and has been used to provide practical feedback during ablation[789]. In addition, recent studies demonstrate that the LI decrease during RF application may be more strongly associated with the lesion size compared to the general impedance (GI)[10]. Moreover, we reported that %LI-drop (%LID) defined by the absolute LI drop/Initial LI is significantly more strongly associated with the lesion size than the absolute LI drop.[116]

We hypothesize that combining active and passive factors may more strongly predict the lesion size than using either of them alone. Therefore, this study investigates if LI provides additional data in predicting lesion characteristics and the incidence of steam-pop over conventional parameters such as AE and FTI.

METHODS

Ex-vivo model

Commercially obtained swine hearts (N=30) excised within 12-48 hours were preserved in a fresh and used for this ex-vivo model. A circulating saline bath (NaCl 3.5g/L) at 37°C, a submersible load cell (KW-201, Tanita, Tokyo, Japan), and a deflectable sheath were assembled. The load cell was installed on the bottom of the bath, and a section of left ventricular myocardium was placed on the ground plate on a load cell apparatus (Figure 1). Contact force (CF) applied to the overlying myocardial tissue through the ablation catheter was measured by the load cell. A 4.5mm tip open-irrigated ablation catheter with 3 mini-electrodes incorporated in the distal electrode (IntellaNav MiFi OI™, Boston Scientific) was positioned in both perpendicular and parallel orientations to the tissue through a plastic pipe with or without a deflectable sheath.

LI measurement

The LI was measured by a 4-electrode method with separate circuits for field creation and field measurements as previously described[8]: a non-stimulatory alternating current (5.0μA at 14.5kHz) was driven between the distal tip electrode and the proximal ring. Concurrently, voltage was measured between each of 3 mini-electrodes, 2.0mm away from the distal tip electrode and distal ring, and converted into impedance by dividing by the stimulatory current. Among the 3 LI measurements, the highest one was used for analysis.

Lesion creation

RF energies of 30W, 40W, and 50W were applied by the ablation catheter in 4 ranges of CF (8g, 15g, 25, and 35g), and duration (30W: 10-45s and 180s [or until a steam-pop occurred]; 40W/50W: 10-30s and 120s [or until a steam-pop occurred]). Additionally, these applications were performed at 2 different orientations (perpendicular and parallel to the tissue) (Figure 1A). These lesions were created at least 3mm away from each other. Steam-pops were defined as audible pops.

Lesion measurements

The lesion border was defined as the location of change in tissue color. The maximum length (a), maximum depth (b), depth to the point of maximum length (c), surface maximum length (d), and surface width (e) of the created lesion were measured. Lesion surface area and lesion volume were calculated from the following formulae: Lesion volume = $(1/6) \times \pi \times (a^2 \times b + c \times d^2/2)$[8].

Lesion surface area = $\pi \times d/2 \times e/2$, (Figure 1B).

Measured indices

Active parameters include the AE = power (W) * time (s) and FTI = CF (g) * time (s). In contrast, %LID = absolute LI-drop/initial LI just prior to RF application, represents a passive parameter. To assess the additional impact of LI data on lesion prediction, two simple indices were examined as combination parameters; AE*%LID and FTI*%LID. Correlation between these parameters and lesion depth, surface area, volume, and the incidence of steam-pop was assessed.

Statistical analysis

Continuous variables are expressed as mean ± standard deviation or median and 25thpercentile-75thpercentile. For categorical variables, data are described as numbers and percentages. Spearman’s rank correlation analysis was used to assess the correlation between variables[6]. Fisher’s Z transformation were performed to compare the strength of correlation. Parametric and nonparametric data were analyzed by Student t-tests and Mann-Whitney U tests, respectively. To compare groups, Chi-square analysis or Fisher’s exact test was used for categorical variables. Logistic regression analysis was used to determine individual predictors of steam-pops as multivariate analysis. Receiver operating characteristic (ROC) curve analysis was performed to assess the optimal cut-off value for predicting steam-pop. Statistical significance was defined as P-values<0.05.

RESULTS

Correlation between conventional active parameters and lesion characteristics.

Lesion size was analyzed in the 375 out of 402 (92.3%) lesions without steam-pops. Median lesion depth was 4.2[3.3-5.5]mm, lesion surface area was 31.8[25.7-38.9]mm^2 and lesion volume was 219[137-346]mm^3. Both AE and FTI showed a positive correlation with the lesion depth (ρ= 0.824:P<0.0001 and 0.708:P<0.0001, respectively), surface area (ρ= 0.507, P<0.0001 and 0.562, P<0.0001, respectively), and volume (ρ= 0.807, P<0.0001 and 0.685, P<0.0001, respectively). %LID (ΔLI/Initial LI), which represents a passive tissue reaction, also showed positive correlation to lesion depth (ρ= 0.643, P<0.0001), surface area (ρ= 0.547, P<0.001) and volume (ρ= 0.733, P<0.0001). Additionally, combination indices of active and passive factors, AE*%LID and FTI*%LID, generally increased the extent of correlation to the lesion size (Figure 2). Compared to AE alone, AE*%LID significantly increased the extent of correlation in surface lesion size (ρ= 0.507 vs 0.578, P<0.0001) and volume (ρ= 0.807 vs 0.864, P<0.0001), but did not reach significance in lesion depth (ρ= 0.824 vs 0.834, P=0.380). Compared to FTI alone, FTI*%LID significantly increased the extent of correlation in lesion depth (ρ= 0.708 vs 0.809, P<0.0001), surface area (ρ= 0.562 vs 0.656, P<0.0001) and volume (ρ= 0.685 vs 0.833, P<0.0001) as shown in Figure 3.

One example is shown in Figure 4, which demonstrates that lesion characteristics are different regardless of RF application with the same AE of 1800W*s (left panel). AE*%LID values are more strongly correlated with the lesion size. In addition, the right panel demonstrates that lesion characteristics are different regardless of RF application with the same FTI of 600g*s. FIT*%LID values are more strongly correlated to the lesion size.

Effect of catheter orientation

Lesion depth tended to be larger with a perpendicular catheter orientation (4.5 [3.4-5.5]mm vs 4.0 [3.2-5.3]mm, P=0.06), but surface area (28.8 [22.4-34.9]mm^2 vs 36.2 [28.7-42.1] mm^2, P<0.0001) and volume (201 [121-334]mm^3 vs 230 [155-362]mm^3, P=0.04) were significantly larger with a parallel catheter orientation.

The correlation between catheter-tissue angle and AE/FTI is summarized in Table 1. For AE, lesion depth (P=0.004) and surface area (P<0.0001) were more strongly correlated when the catheter was placed on the tissue in parallel rather than perpendicular, but this difference was not seen in lesion volume (P=0.84). The tendency was preserved in the correlation between the catheter-tissue angle vs AE*%LID (lesion depth, P<0.0001; lesion surface, P<0.0001; lesion volume, P=0.71)

For FTI, surface area was more strongly correlated with a parallel catheter orientation (P=0.047), while lesion volume was more strongly correlated with a perpendicular catheter orientation (P=0.03). This tendency was preserved in the correlation between the catheter-tissue angle vs FTI*%LID (lesion depth, P=0.06; lesion surface, P=0.0001; lesion volume, P=0.04)

Steam-pops

Of 402 RF applications, 27 steam-pops were observed as shown in Table 2. Although neither catheter orientation nor CF affected the occurrence of steam-pops, power and duration of RF application, AE, FTI,

%LID, AE*%LID, and FTI*%LID were all significantly larger in RF applications in the steam-pop group, and these were all predictors of steam-pops in univariate analysis. To avoid interaction between several parameters, multivariate analysis was performed with AE, FTI, and %LID, showing that AE (P=0.02) and %LID (P=0.002) remained as significant predictors of steam-pops (Table 2B).

Sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of major parameters, in addition to the optimal cutoff values to predict the occurrence of steam-pops, are described in Table 3A. AE ≥ 1800 W*s predicted steam-pops with a sensitivity of 81.5%, specificity of 79.5%, PPV of 22.2%, and NPV of 98.3%, providing an AUC of 0.822, which proved the best parameter to predict the occurrence of steam-pops. FTI ≥ 528g*s predicted steam-pops with a sensitivity of 81.5%, specificity of 58.4%, PPV of 12.4%, and NPV of 97.8%, which provided an AUC of 0.731. %LID ≥ 34.6% predicted steam-pops with a sensitivity of 59.3%, specificity of 90.4%, PPV of 30.8%, and NPV of 96.9%, which provided an AUC of 0.741. No significant differences in AUC were seen between power, duration, FTI, and %LID, but AE showed significantly larger AUC values compared to any of these parameters. Additionally, no significant differences in AUC were seen between AE and AE*%LID (P=0.390), or between FTI and FTI* %LID (P=0.550) (Supplemental Figure). Each cut-off value of power, duration, AE, FTI, %LID, AE*%LID, and FTI*%LID to maintain the sensitivity of 90% in predicting the occurrence of steam-pops, is described in Table 3B.

DISCUSSION

Major findings

This study demonstrates that:

(1) Adding %LID, as a factor representing a passive tissue reaction from RF applications, to conventional active parameters such as AE or FTI may predict lesion characteristics more precisely.

(2) Lesion depth tends to be larger with perpendicular catheter orientation, but lesion surface and volume are significantly larger with parallel catheter orientation. AE was similarly correlated to the lesion volume regardless of catheter orientation, but FTI with perpendicular catheter orientation is more strongly

correlated with lesion volume.

(3) Although both AE and %LID was individually associated with the occurrence of steam-pop, the simple formula of AE*%LID did not provide a higher predictive value compared to the AE alone.

Factors in lesion prediction

Lesion size has been reported to be associated with multiple factors; controllable factors include power, ablation electrode temperature, duration of energy delivery, catheter-tissue CF, CF direction, ablation circuit impedance, electrode diameter, direction of ablation placement, and irrigation flow rate; and uncontrollable factors include tissue thickness and architecture and myocardial blood flow[4]. Recently, a combined index of several controllable factors such as power, duration of energy delivery, and CF has been reported to be more useful than each individual factor alone, in predicting lesion characteristics. FTI calculated from the duration of energy delivery and CF[123], and Ablation index[13133] and LSI calculated from the power and duration of RF application and CF, are correlated with lesion dimensions[14151617]. However, these indices are generally composed of only actively controllable factors, and factors reflecting the tissue reaction from RF applications such as impedance drop and electrogram attenuation are not included. Bourier F et al, have shown that impedance significantly influences current delivery and varies considerably between patients[18]. Previous animal experiments demonstrate that the magnitude of impedance drop after the onset of RF ablation strongly correlated with lesion depth (R^2=0.68)[8], diameter (R^2=0.66)[8] and volume (R^2=0.72)[81920721]. This impedance does not represent the LI at the tip of the catheter but the GI through the entire circuit. Recent reports have demonstrated that LI is more sensitively associated with lesion size than GI.[1110]

We have demonstrated in the present study that a combination of controllable active factors and parameters reflecting the passive tissue reaction during RF application is more valuable in predicting lesion size.

Effect of catheter orientation

Lesion depth tended to be larger with perpendicular catheter orientation, but lesion surface and volume were significantly larger with parallel catheter orientation.

The correlation between the AE and lesion volume was similar regardless of catheter orientation. In contrast, the correlation between the FTI and lesion volume was stronger with a perpendicular orientation. As these two parameters share time as one of the components, this discrepancy between the AE and the FTI may be due to the difference in power in AE and CF in FTI. Contact area between the electrode and catheter may increase more as the CF increases with a perpendicular catheter orientation, resulting in a stronger correlation to the lesion volume in FTI, but not in AE.

Steam-pops

The occurrence of steam-pops may cause superficial craters or deep tears, leading to cardiac perforation or tamponade. Similar to previous reports[314221023], the present study demonstrates that longer and high-power RF application, as well as larger impedance drops, independently increase the risk of steam-pop.

Furthermore, the combined parameters of AE and FTI were both associated with the occurrence of steam-pops. AE ≥ 1800 W*s showed the best prediction of steam-pops with the largest AUC of 0.822. However, FTI did not provide a better AUC compared to the single parameters. This may be because RF applications with different CFs of 30W, 40W, and 50W are all included.

New indices which include %LID, such as AE*%LID, and FTI*%LID, are superior to AE alone and FTI alone in predicting lesion size as mentioned above. However, in predicting steam-pops, no additional impact of %LID is observed despite the result that %LID remained as a significant predictor of steam-pops by multivariate analysis. A pop occurs when tissue temperature exceeds 100 °C resulting in a sudden release of steam.[24] To mitigate against this, cutoffs for RF parameters such as power, catheter tip temperatures, CF,[19] and impedance drop[25] have been proposed. However, these parameters have inherent limitations and none can completely be a substitute for tissue temperature, which is the ultimate determinant of steam formation. LI may be one of the most sensitive parameters available currently to reflect tissue temperature. However, it is still an indirect and multifactorial parameter and sensitively affected by other environments around the tissue-catheter interface area as well as the during the tissue temperature during RF application. This may partially explain the reason that the simple formula multiplying AE and %LID does not increase the predictive value of predicting steam-pops. A new formula using these parameters may be considered for improved prediction.

Clinical implication

Several papers have reported that active factors such as power, time, and CF of RF applications are important in predicting lesion characteristics. Conversely, local impedance reflects a passive tissue reaction to RF applications, which has also been reported as a determinant of lesion size. As far as we are aware, this is the first study to report that the combined use of both active and passive factors provides a stronger correlation with lesion volume than individual factors alone.

Limitations

Firstly, since our study is conducted in an ex-vivo model, the results may not be the same as in an in-vivo model and human heart. However, a precisely controlled model is required to achieve the purpose of this study, so an ex-vivo model was more suitable for the purpose of this study. For the same reasons, the absolute value of each parameter and lesion size may be affected by this experimental model. However, the main message of the present study showing the additional impact of %LI drop to the AE and FTI data, to increase the correlation with lesion size may be preserved. CF was measured using a submersible load cell and not a catheter incorporating a CF sensor because this new catheter was unavailable for use.[5] However, the reliability of catheter-tissue contact force in this model has been confirmed under the same condition as this study, using the TactiCath™ ablation catheter capable of CF measurement (INTELLANAV STABLEPOINT™ catheter, Boston Scientific, Marlborough, MA, USA).

CONCLUSION

Addition of LI to conventional parameters (AE and FTI), may provide a stronger correlation with lesion characteristics. Active factors (AE and FTI) and passive tissue reaction (%LI-drop) should be combined to predict lesion size more effectively.

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DISCLOSURE

Dr. Martin has received consulting fees from Boston Scientific.

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TABLE

Table 1. Correlation between lesion characteristics varying ablation parameters and catheter orientations

		Correlation coefficient		P
		Perpendicular	Parallel	
AE	Lesion depth, mm	$\rho=0.783$	$\rho=0.874$	0.004
	Lesion surface, mm^2	$\rho=0.385$	$\rho=0.730$	<0.0001
	Lesion volume, mm^3	$\rho=0.810$	$\rho=0.817$	0.84
AE*%LID	Lesion depth, mm	$\rho=0.794$	$\rho=0.903$	<0.0001
	Lesion surface, mm^2	$\rho=0.428$	$\rho=0.760$	<0.0001
	Lesion volume, mm^3	$\rho=0.858$	$\rho=0.868$	0.71
FTI	Lesion depth, mm	$\rho=0.705$	$\rho=0.705$	1
	Lesion surface, mm^2	$\rho=0.543$	$\rho=0.672$	0.047
	Lesion volume, mm^3	$\rho=0.744$	$\rho=0.628$	0.03
FTI*%LID	Lesion depth, mm	$\rho=0.794$	$\rho=0.857$	0.06
	Lesion surface, mm^2	$\rho=0.578$	$\rho=0.786$	0.0001
	Lesion volume, mm^3	$\rho=0.864$	$\rho=0.800$	0.04

Table 2A. Association of LI between scar and gap in lesions for 3 types of catheter orientation and for various lengths of gap.

	Non-Pop (N=375)	Pop (N=27)	P-values
30/40/50W	146 (38.9%)/104 (27.7%)/ 125 (33.3%)	1 (3.7%)/4 (14.8%)/ 22 (81.5%)	<0.0001
parallel/perpendicular	185(49.3%)/190(50.7%)	16(59.3%)/11(40.7%)	0.426
8/15/25/35g	93 (24.8%)/93(24.8%)/121(32.3%)/68(18.1%)	4 (14.8%)/7(25.9%)/8(29.6%)/8(29.6%)	0.412
Absolute duration	30 [15-45]	61 [41-72]	<0.0001
AE	1000 [600-1500]	2880 [1800-3450]	<0.0001
FTI	450 [250-960]	1025 [528-2415]	<0.0001
%LID	0.228 [0.165-0.292]	0.356 [0.239-0.414]	<0.0001
AE*%LID	232.6 [101.5-432.2]	953.8 [543.3-1356.2]	<0.0001
FTI*%LID	102.6 [43.6-230.3]	419.9 [152.6-648.1]	<0.0001

Table 2B. Univariate and multivariate analysis for the prediction of steam-pops

	Univariate	Multivariate	95%CI
Conventional indices			
Power	<0.0001		
Duration	<0.0001		
AE	<0.0001	0.02	1.04 [1.01-1.08] per 100w*s
FTI	0.0017	0.73	1.0 [0.99-1.00] per 10 g*s
%LID	<0.0001	0.002	1.07 [1.02-1.12] per 0.01

AE, ablation energy; FTI, force-time-integral; %LID, %local impedance drop (absolute local impedance drop divided by initial local impedance)

Table 3A. Optimal cut-off values for the prediction of steam-pops

	AUC	Cutoff	Sensitivity	Specificity	PPV	NPV
Conventional indices						
Power	0.764	50	81.5	66.7	15.0	98.0
Duration	0.770	49	66.7	52.4	25.4	97.3
AE	0.822	1800	81.5	79.5	22.2	98.3
FTI	0.731	528	81.5	58.4	12.4	97.8
%LID	0.741	0.346	59.3	90.4	30.8	96.9
New indices						
AE*%LID	0.790	622.6	74.1	85.6	27.0	97.9
FTI*%LID	0.751	146.5	81.5	61.9	13.3	97.9

Table 3B. Cut-off values to maintain 90% sensitivity for the prediction of steam-pops

	Cutoff	Sensitivity	Specificity	PPV	NPV
Conventional indices					
Power	40	96.3	38.9	10.2	99.3
Duration	20	92.6	28.8	8.6	98.2
AE	1000	92.6	45.1	10.8	98.8
FTI	392	92.6	43.5	10.5	98.8
%LID	0.102	92.6	11.7	7.0	95.7
New indices					
AE*%LID	93.8	92.6	22.1	7.9	97.6
FTI*%LID	46.9	92.6	27.7	8.4	98.1

AE, ablation energy; FTI, force-time-integral; %LID, %local impedance drop (absolute local impedance drop divided by initial local impedance); NPV, negative predictive value; PPV, positive predictive value

FIGURE LEGENDS

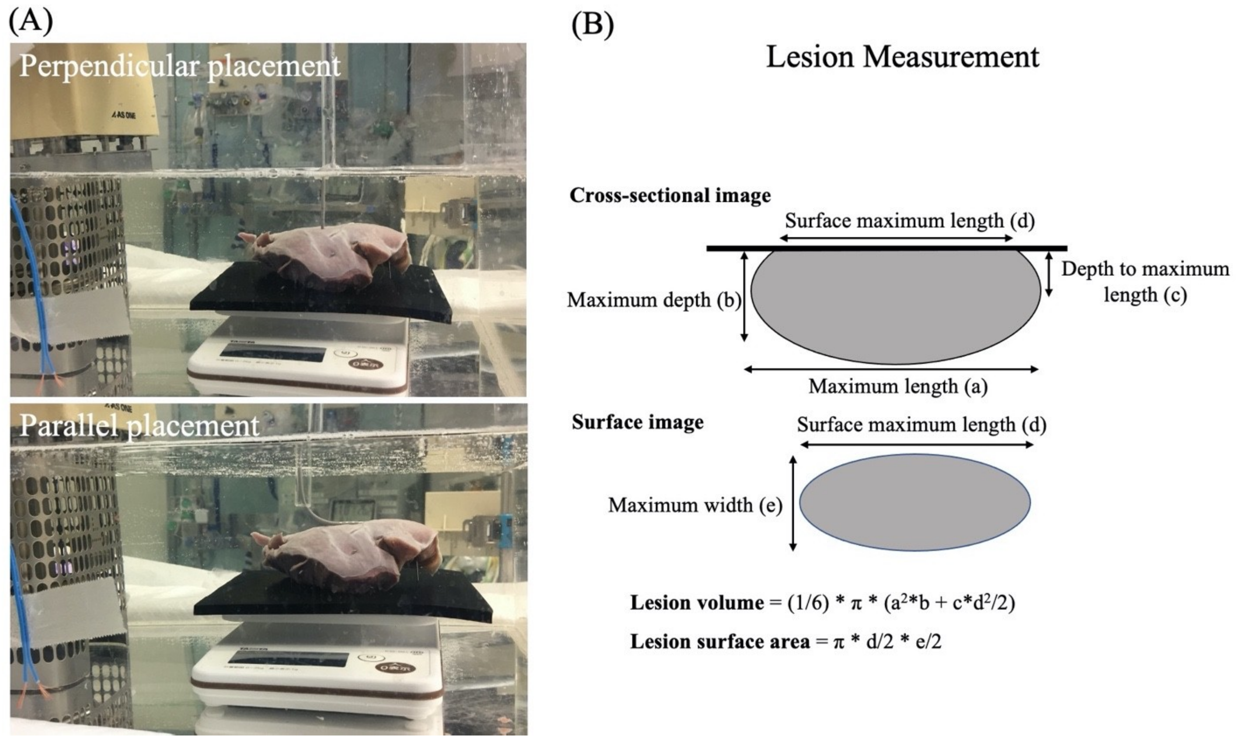


Figure 1: Ex-vivo experimental model

Lesion characteristics are measured in different catheter orientations (perpendicular and parallel) (A). Scheme of lesion measurements (B).

Figure 2A.

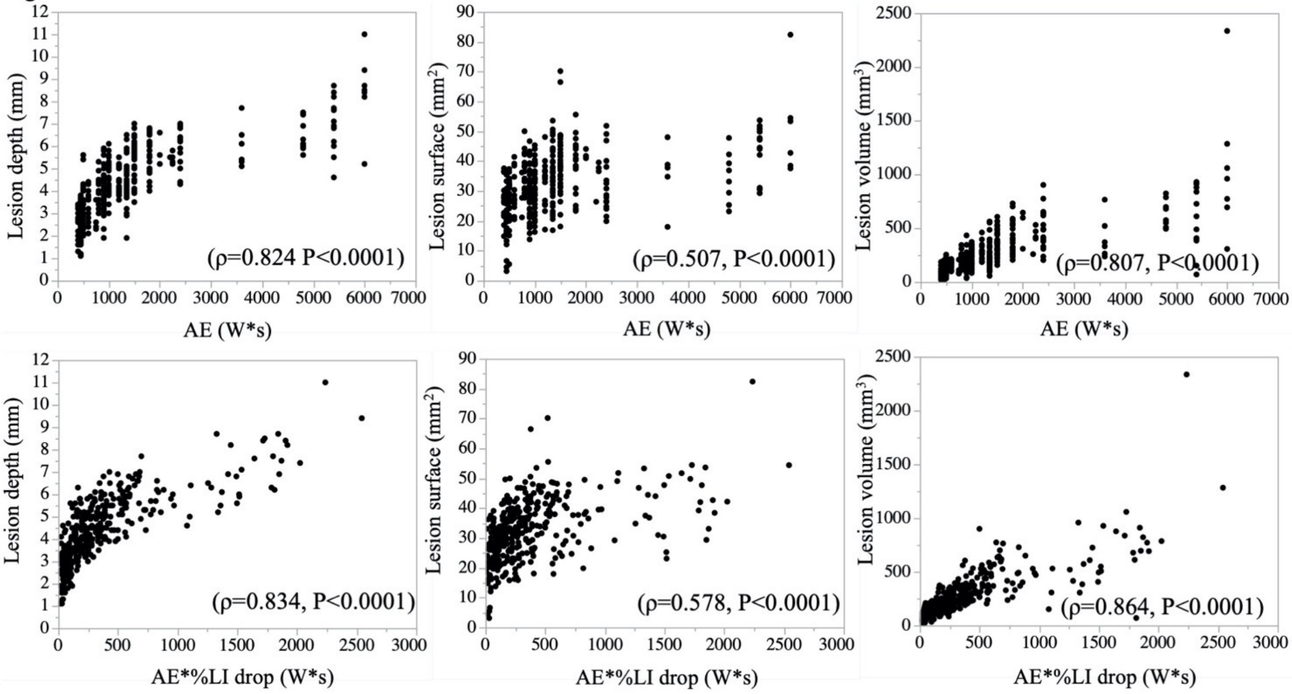
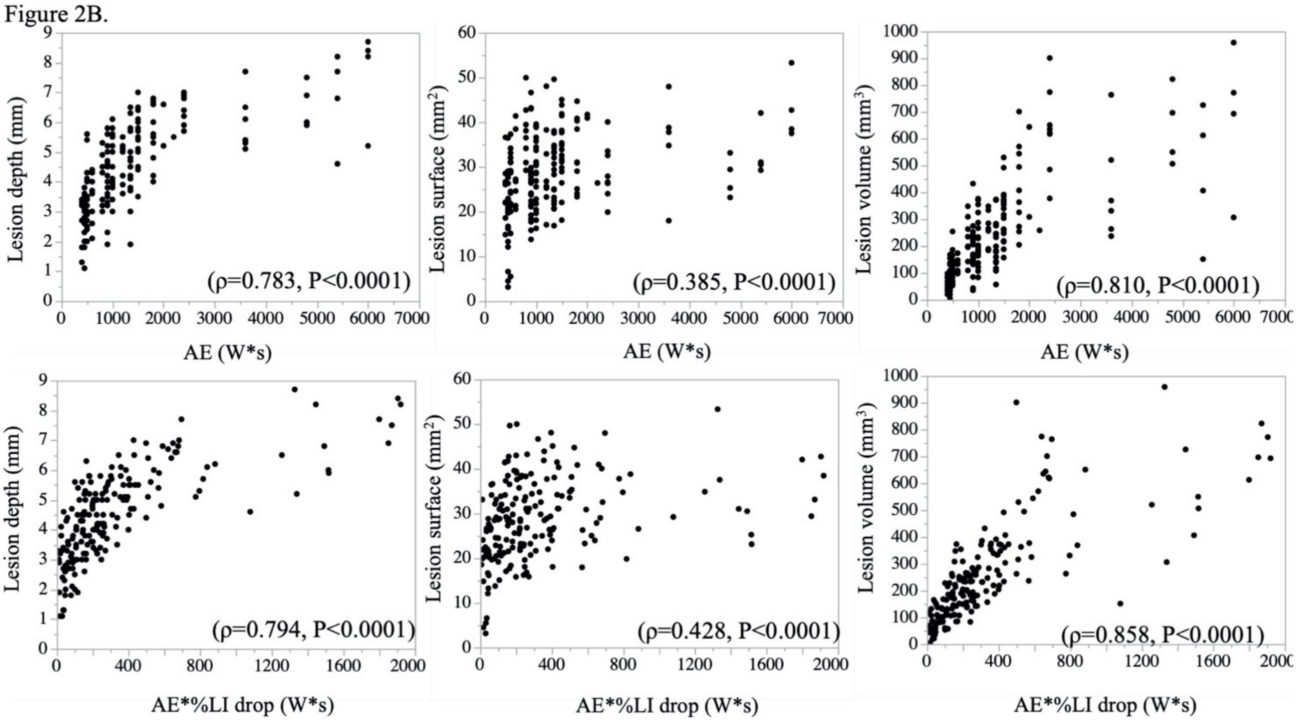

Lesion depth (mm)
(ρ=0.824 P<0.0001)
AE (W*s)
Lesion surface (mm²)
(ρ=0.507, P<0.0001)
AE (W*s)
Lesion volume (mm³)
(ρ=0.807, P<0.0001)
AE (W*s)
Lesion depth (mm)
(ρ=0.834, P<0.0001)
AE*%LI drop (W*s)
Lesion surface (mm²)
(ρ=0.578, P<0.0001)
AE*%LI drop (W*s)
Lesion volume (mm³)
(ρ=0.864, P<0.0001)
AE*%LI drop (W*s)

Figure 2B.



Lesion depth (mm)
AE (W*s)
(ρ=0.783, P<0.0001)
Lesion surface (mm²)
AE (W*s)
(ρ=0.385, P<0.0001)
Lesion volume (mm³)
AE (W*s)
(ρ=0.810, P<0.0001)
Lesion depth (mm)
AE*%LI drop (W*s)
(ρ=0.794, P<0.0001)
Lesion surface (mm²)
AE*%LI drop (W*s)
(ρ=0.428, P<0.0001)
Lesion volume (mm³)
AE*%LI drop (W*s)
(ρ=0.858, P<0.0001)

Figure 2C.

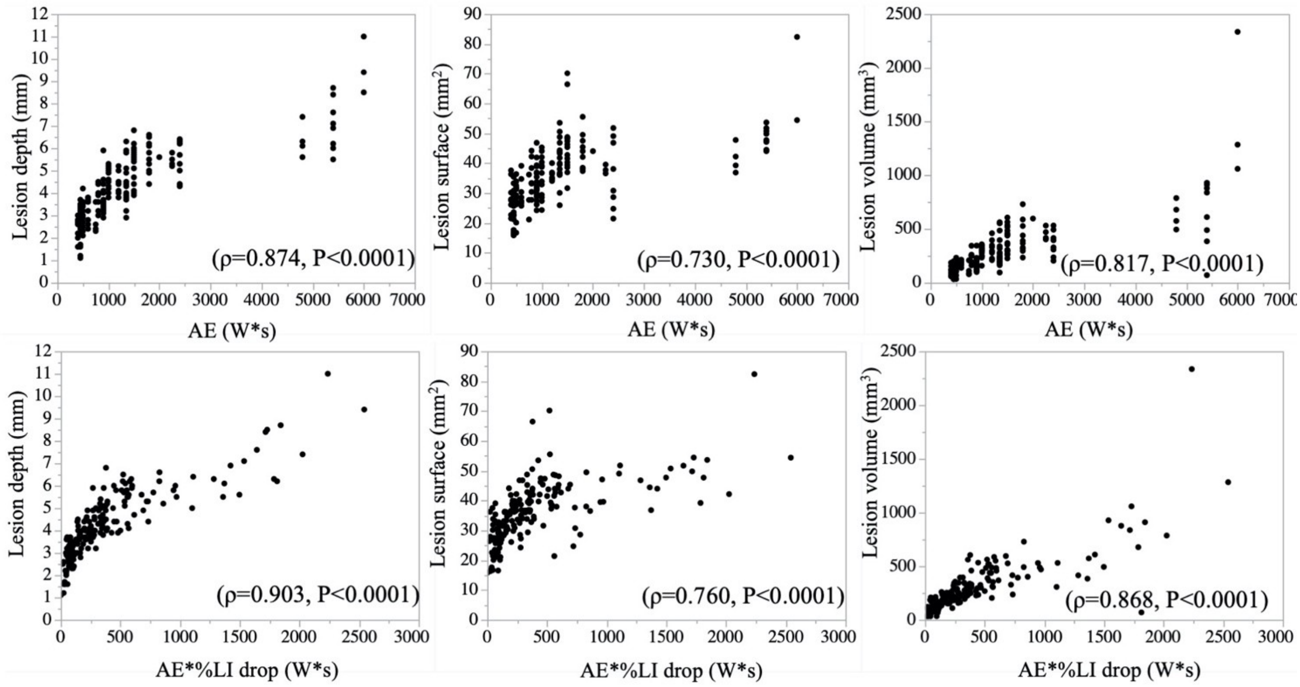


Figure 2: Lesion characteristics vs AE and AE-%LID

Data from both catheter orientation (parallel and perpendicular) (A), perpendicular catheter orientation only (B), parallel catheter orientation only (C).

Figure 3A.

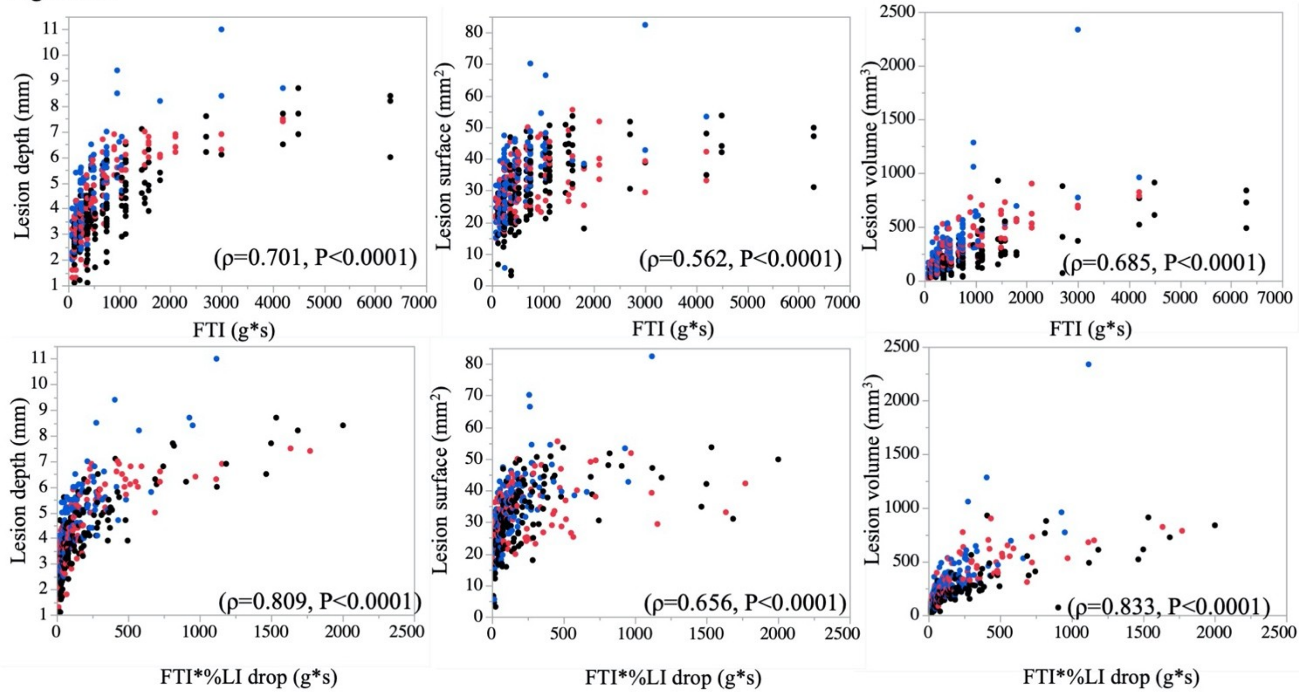
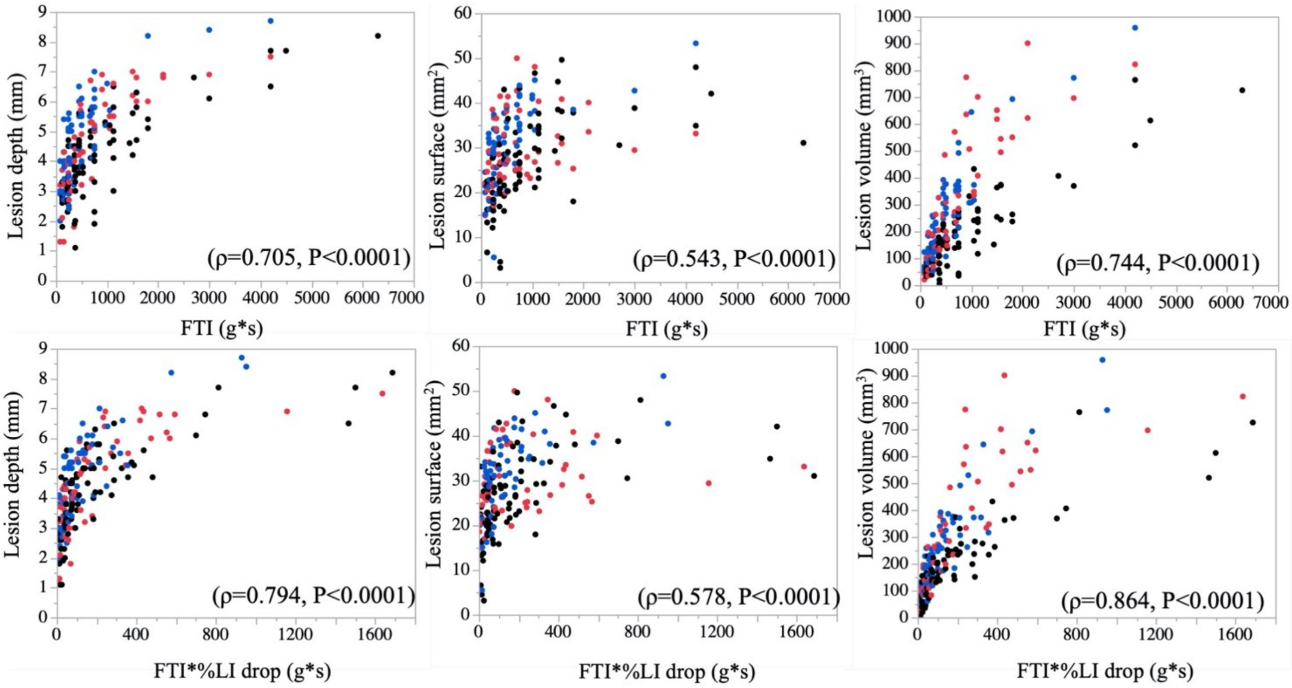

Lesion depth (mm)
(ρ=0.701, P<0.0001)
FTI (g*s)
Lesion surface (mm²)
(ρ=0.562, P<0.0001)
FTI (g*s)
Lesion volume (mm³)
(ρ=0.685, P<0.0001)
FTI (g*s)
Lesion depth (mm)
(ρ=0.809, P<0.0001)
FTI*%LI drop (g*s)
Lesion surface (mm²)
(ρ=0.656, P<0.0001)
FTI*%LI drop (g*s)
Lesion volume (mm³)
(ρ=0.833, P<0.0001)
FTI*%LI drop (g*s)

Figure 3B.



Lesion depth (mm)
(ρ=0.705, P<0.0001)
FTI (g*s)
Lesion surface (mm2)
(ρ=0.543, P<0.0001)
FTI (g*s)
Lesion volume (mm3)
(ρ=0.744, P<0.0001)
FTI (g*s)
Lesion depth (mm)
(ρ=0.794, P<0.0001)
FTI*%LI drop (g*s)
Lesion surface (mm2)
(ρ=0.578, P<0.0001)
FTI*%LI drop (g*s)
Lesion volume (mm3)
(ρ=0.864, P<0.0001)
FTI*%LI drop (g*s)

Figure 3C.

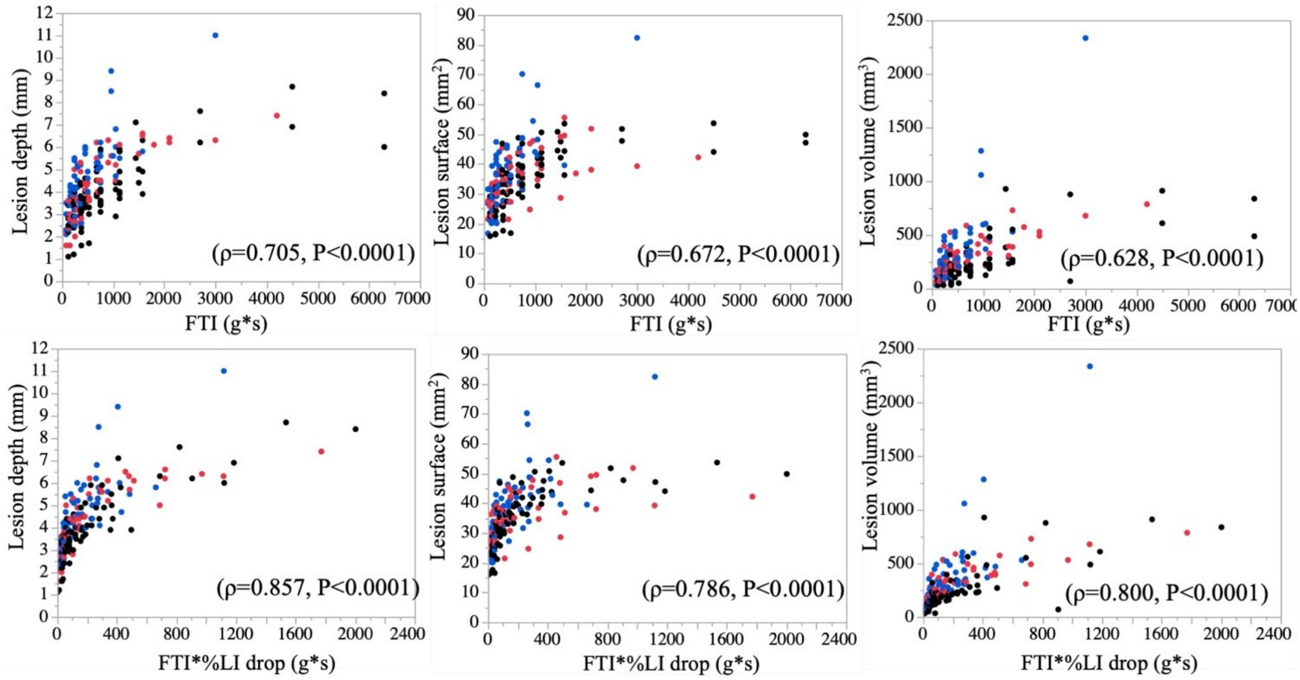
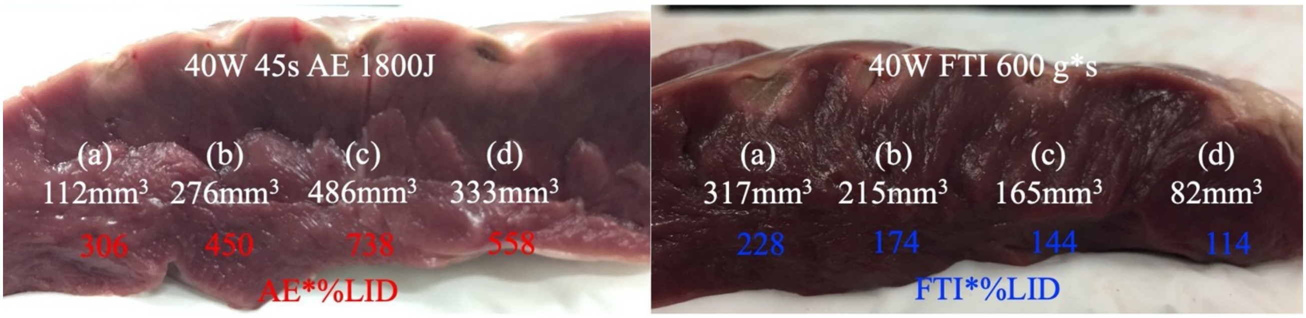


Figure 3: Lesion characteristics vs FTI and FTI-%LID

Including both catheter directions (parallel and perpendicular) (A) perpendicular catheter placement (B) parallel catheter placement (C). Black, red, and blue dots represent 30W, 40W, and 50E RF applications, respectively.

Figure 4



(a) 5g : %LID (17%), AE*%LID (306)

(b) 15g: %LID (25%), AE*%LID (450)

(c) 25g: %LID (41%), AE*%LID (738)

(d) 35g: %LID (31%), AE*%LID (558)

(a) 10g 60s: %LID (38%), FTI*%LID (228)

(b) 20g 30s: %LID (29%), FTI*%LID (174)

(c) 20g 30s: %LID (24%), FTI*%LID (144)

(d) 20g 30s: %LID (19%), FTI:%LID (114)

Figure 4: Example of Lesion characteristics

Left panel demonstrates that lesion characteristics are different regardless of the RF application with the same AE of 1800watt*sec. AE*%LID values are more correlated to the lesion size. Right panel demonstrates that lesion characteristics are different regardless of the RF application with the same FTI of 600g*sec. FIT*%LID values are more correlated to the lesion size.

Supplemental figure