Local impedance guides catheter ablation in patients with ventricular tachycardia

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Abstract
Aims: Catheter contact and local tissue characteristics are relevant information for successful radiofrequency current (RFC)-ablation. Local impedance (LI) has been shown to reflect tissue characteristics and lesion formation during RFC-ablation. Using a novel ablation catheter incorporating three mini-electrodes, we investigated LI in relation to generator impedance (GI) in patients with ventricular tachycardia (VT) and its applicability as an indicator of effective RFC-ablation.

Methods and Results: Baseline impedance, Δimpedance during ablation and drop rate (Δimpedance/time) were analyzed for 625 RFC-applications in 28 patients with recurrent VT undergoing RFC-ablation. LI was lower in scarred (87.0 Ω [79.0-95.0]) compared to healthy myocardium (97.5 Ω [82.75-111.50]; P = .03) while GI did not differ between scarred and healthy myocardium. ΔLI was higher (18 Ω [9.4-26.0]) for VT-terminating as compared to non-terminating RFC-ablation (ΔLI 13 Ω [8.85-18.0]; P = .03), but did not differ for ΔGI between terminating vs nonterminating RFC-ablation. Correspondingly, LI drop rate was higher for RFC-ablation terminating the VT compared with RFC-ablation not terminating the VT (0.63 Ω/s [0.52-0.76] vs 0.32 Ω [0.20-0.58]; P = .008) while there was no difference for GI drop rate. ΔLI was higher in patients with nonischemic cardiomyopathy vs patients with ischemic cardiomyopathy (16 Ω [11.0-20.0] vs 11.0 Ω [7.85-17.00]; P = .003).

Conclusion: Our findings suggest that LI is a sensitive parameter to guide RFC-ablation in patients with VT. LI indicates differences in tissue characteristics and generally is higher in patients with nonischemic cardiomyopathy. Hence, the etiology of the underlying cardiomyopathy needs to be considered when adopting LI for monitoring catheter ablation of VT.

KEYWORDS
catheter ablation, electrical impedance, high-density mapping, radiofrequency, ventricular tachycardia

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1 | INTRODUCTION

Myocardial electrical impedance has been employed to guide radio-frequency current (RFC)-ablation procedures for the treatment of cardiac arrhythmias for decades.\textsuperscript{1,2} Impedance is well-known to reflect tissue characteristics with scarred tissue exhibiting lower impedance.\textsuperscript{3-5} The impedance of the myocardial tissue during ablation is considered a sensible surrogate of lesion formation.\textsuperscript{6} Conventionally, a resistive load of the tissue is measured by the transthoracic impedance from the tip of the catheter to an indifferent electrode on the skin. Sufficiently high resistive load at the catheter-tissue interface reflects adequate catheter-tissue contact,\textsuperscript{7} but thoracic anatomical structures vary between individuals and influence generator impedance (GI). An early clinical study elegantly adopted a model measuring impedance using two body surface electrodes and successfully distinguished between contact and noncontact of catheter and tissue.\textsuperscript{8} However, impedance measurements in this model are influenced by the proximity of the body surface electrodes, limiting inter-individual comparability.

Recently, a novel ablation catheter incorporating three mini-electrodes in its tip measuring local impedance (LI) at the distal electrode of the catheter has been developed\textsuperscript{9} and introduced to clinical practice.\textsuperscript{10,11} Herein, we studied LI in comparison to GI during catheter ablation of ventricular tachycardia (VT) to assess its applicability as a feed-back-parameter of RFC-ablation. Our findings suggest that LI can be applied as a sensitive parameter to guide RFC-ablation.

2 | METHODS

2.1 | Study design

Consecutive patients with recurrent VT presenting for catheter ablation in our tertiary center were enrolled in this single-center study. LI and GI were analyzed for baseline impedance, \( \Delta \) impedance, and drop rate (\( \Delta \) impedance/time). The study was conducted in accordance with the provisions of the Declaration of Helsinki and its amendments and was approved by the institutional review board of the University Heart Center Hamburg. Written informed consent was obtained from all patients.

2.2 | Ablation procedures

In all cases, a steerable 6F decapolar diagnostic catheter (Inquiry, 5 mm spacing; St. Jude Medical, St. Paul, MN) was placed in the coronary sinus and served as a reference for the 3D electroanatomical mapping system. A 6-French quadripolar diagnostic catheter (Inquiry, 5 mm spacing; St. Jude Medical) was positioned in the right ventricular apex. High-density-3D mapping was performed in all patients (Rhythmia, Boston Scientific, Marlborough, MA) as previously described\textsuperscript{12} using a 64-electrode basket-catheter (Orion, Boston Scientific) during sinus rhythm, ventricular pacing and/or VT as appropriate. The left ventricle was accessed via a femoral retrograde transaortic approach (9 French, Terumo, Leuven, Belgium) or by transseptal access using a fixed curve long sheath (SL0, 8 French, St. Jude Medical). A steerable long sheath (Agilis large curl, 8.5 French, St. Jude Medical) was used for transseptal mapping and ablation.\textsuperscript{12} To maintain deep sedation, patients received propofol (2 mg/mL, B. Braun, Melsungen, Germany) combined with boluses of fentanyl (0.1 mg/mL, Rotexmedica, Trittau, Germany). The activated clotting time was maintained at more than 300 seconds by the adaptive administration of heparin. Programmed stimulation was performed from the right ventricular apex up to at least the coupling intervals required for the induction of VT.

2.3 | Impedance measurement

GI was measured from the RFC-generator (EP Shuttle, Stockert, Biosense Webster Inc, Diamond Bar, CA). LI was measured from the mapping and ablation catheter (IntellaNav MIFI OI, Boston Scientific) which incorporates three equally spaced mini-electrodes in the catheter tip. A nonstimulatory current (5.0 \( \mu \)A at 14.5 kHz) induces a local electrical field between the tip electrode and the proximal ring. Potential field distortions are divided by the injected current. Impedance is measured from the minielectrodes with a sampling rate of 20 Hz. The catheter has been described in detail previously.\textsuperscript{10,11}

RFC-ablation in a point-by-point method was analyzed for the complete duration of the RFC-application. Ablation points with instable catheter contact were excluded from the analysis. Dragged RFC-applications were analyzed until the catheter was moved from the initial position on the myocardium. Patients with inducible VT and successful termination by ablation were included in a subgroup analysis comparing impedance drops of RFC-applications terminating the VT to impedance drops for nonterminating RFC-applications. Only specific VT termination was included in the analysis, there was no VT termination by ventricular premature beats. Non-terminating RFC-ablations within a maximum distance of 20 mm from the terminating lesion were included in the subgroup analysis to avoid inclusion of RFC-ablation at sites irrelevant for VT mechanism or RFC-ablation at sites with various tissue characteristics (please see results of the subgroup analysis in paragraph 3.5 of the results section).

\( \Delta LI < 16 \ \Omega \) was defined as a "low drop" and \( \Delta LI \geq 16 \ \Omega \) was defined as a "high drop", as a \( \geq 16 \ \Omega \) drop was shown to be necessary to achieve a loss of capture in the ventricle.\textsuperscript{10} The impedance at the start of ablation was considered baseline impedance.\textsuperscript{10,11} The difference of baseline impedance and the minimum impedance during RFC-application was defined as \( \Delta LI \) and \( \Delta GI \) (\( \Omega \)), respectively. Relative \( \Delta LI \) and relative \( \Delta GI \) (%) were calculated as proportional impedance drop in relation to baseline impedance.\textsuperscript{10}

2.4 | Voltage measurement

Voltage measurements were acquired during mapping using the 64-electrode basket-catheter. Local bipolar voltage \( \leq 0.1 \ mV \) was defined as scar and local bipolar voltage \( \geq 1.0 \ mV \) as healthy myocardium, according to a previous study by Sacher et al.\textsuperscript{13} Local bipolar voltage
≥0.1 mV was defined as nonscarred myocardium. Bipolar voltage recorded from the mini-electrodes of the ablation catheter was analyzed as an additional parameter for substrate characterization with the same cut-off values as for the basket-catheter. Bipolar electrograms were filtered at 30 and 300 Hz. A notch filter was set at 50 Hz.

2.5 Catheter ablation

The irrigated radiofrequency current was delivered in temperature-controlled mode with a temperature limit of 43°C as previously described in detail.12 Initial energy was set to 30 W and titrated to a maximum of 40 W depending on the ablation site and expected myocardial thickness. For inducible and mappable VT, the critical isthmus of the VT was targeted. During the mapping of ongoing VT, we aimed at a maximum point density at the suspected critical site. Critical isthmus sites were defined a the part of the VT circuit which is delimited by conduction barriers showing the smallest activation region.14 Length of the isthmus was defined as the distance from the inward wavefront curvature to the outward wavefront curvature.15 Local signal characteristics were used as an additional parameter. Entrainment mapping was performed when appropriate. In the case of inducible but hemodynamically instable VT, areas with late potentials and local abnormal ventricular activity (LAVA) were targeted.12 Programmed stimulation was performed from the right ventricular apex adopting basic drive cycle lengths of 510, 440, and 370 ms with up to three extrastimuli. If VT was noninducible, substrate modification was performed in sinus rhythm. The procedural endpoint was defined as noninducibility and elimination of late potentials/LAVA.12,16,17

2.6 Data analysis

Full-length procedures were recorded by the 3D-mapping system and reviewed for analysis. Data analysis was performed with R version 3.4.4.18 Continuous data are reported as mean and standard deviation or median and interquartile range (IQR) if not normally distributed. As a measure of variability, we used the quartile coefficient of dispersion (Q3 – Q1/Q3 + Q1). For linear regression analysis of dependent values, we used a linear mixed model taking into account repeated measurements.19 To test homoscedasticity of non-normally distributed data, the Fligner-Killeen-test was used. For a comparison between more than two groups, Kruskall-Wallis-test was used given the non-normality of data distribution.

3 RESULTS

Twenty-eight consecutive patients undergoing catheter ablation for recurrent VT were included. Patient characteristics are presented in Table 1. In eight patients (28.6%), substrate mapping and modification only were performed. In 10 patients (35.7%), activation mapping and specific termination of 11 VT during ablation with additional substrate-based ablation was performed. In the other 10 patients (35.7%), VT was inducible, but was self-terminating, mechanically terminated or had to be terminated by rapid ventricular pacing or external electrical cardioversion due to hemodynamic compromise (Table 2).

3.1 LI but not GI discriminates between scarred and healthy tissue

Measuring bipolar voltage from the basket catheter, baseline LI was lower in areas of scarred myocardium (87.0 Ω [IQR, 79.0-95.0]) vs healthy myocardium 97.5 Ω ([IQR, 82.75-111.50]; P = .03). Baseline

| TABLE 1  Study population |
|---------------------------|
| Patient characteristics   | Patients |
| Sex, male, n (%)          | 26 (92.9) |
| Age, y (±SD)              | 63.2 (±11.4) |
| BMI, kg/m² (±SD)          | 28.6 (±3.1) |
| ICM, n (%)                | 18 (64.3) |
| DCM, n (%)                | 5 (17.9) |
| Other SHD, n (%)          | 2 (7.1) |
| No known SHD, n (%)       | 3 (10.7) |
| Arterial hypertension, n (%) | 15 (53.6) |
| CAD, n (%)                | 18 (64.3) |
| LVEF, % (±SD)             | 38.5 (±12.4) |
| Prior VT-ablation, n (%)  | 4 (14.3) |

Abbreviations: BMI, body mass index; CAD, coronary artery disease; DCM, dilative cardiomyopathy; ICM, ischemic cardiomyopathy; LVEF, left ventricular ejection fraction; SHD, structural heart disease; SD, standard deviation; VT, ventricular tachycardia.

| TABLE 2  Procedural data |
|--------------------------|
| Procedural and mapping parameters                   |
| Procedural time, min (±SD)                          | 241.2 (±88.5) |
| Fluoroscopy time, min (±SD)                         | 22.3 (±15.1) |
| Dose area product, cGy/cm² (±SD)                    | 1172.9 (±1002.6) |
| Number of RF-impulses, n (±SD)                      | 39.0 (±24.8) |
| LV mapping points, n (IQR)                          | 7308.5 (5546-12300) |
| RV mapping points, n (IQR)                          | 7638.0 (4980-9264) |
| LV mapping time, min (SD)                           | 40.9 (±25.9) |
| RV mapping time, min (SD)                           | 43.0 (±32.3) |
| LV volume, mL (SD)                                  | 167.3 (±91.7) |
| Complications                                       |
| Groin hematoma, no surgery required, n (%)         | 1 (3.6) |
| Arterio-venous fistula or arterial dissection       | 0 |
| Intraprocedural pericardial tamponade, pericardiocentesis, n (%) | 1 (3.6) |
| Stroke                                               | 0 |
| Death                                                | 0 |

Abbreviations: IQR, inter-quartile range; LV, left ventricular; RV, right ventricular; SD, standard deviation.
GI did not differ between scar (109 Ω [IQR, 100.0-115.0]) and healthy myocardium (107 Ω [IQR, 101.0-107.0]; P = .51; Figure 1A).

When bipolar voltage was determined via the mini-electrodes, baseline LI was lower in areas of scarred vs healthy myocardium (83.5 Ω [IQR, 76.0-93.5] vs 91.0 Ω; [IQR, 79.0-101.0]; P = .016). Equally, baseline GI did not differ between scar (103 Ω [IQR, 98.25-113.0]) and healthy myocardium, defined by voltage measurement of the mini-electrodes (106 Ω [IQR 99.5 to 113.0]; P = .26; Figure 1B).

Baseline LI is lower in scarred tissue even when comparing to healthy tissue in conjunction with borderzone (Figure S1). Exemplary voltage maps with corresponding LI are shown in Figure 2A, B and in Video S1. In a supplementary analysis including patients who underwent cardiac MRI previous to ablation (n = 4), baseline LI in the target area was lower in a patient with postinfarction myocardial scar compared to patients without detectable scar (n = 3), Figure S2.

Baseline LI positively correlated with baseline GI (R² = 0.85; [95% CI, 0.82-0.87]; P < .001). Moreover, baseline LI predicted ΔLI (R² = 0.44 [95% CI, 0.44-0.56]; P < .001). Similarly, baseline GI predicted ΔGI, albeit with a lower correlation coefficient (R² = 0.37; [95% CI, 0.30-0.44]; P < .001; Figure S3). ΔLI with our “ablation setting” with 30 to 40 W was neither dependent on ablation energy nor on temperature or ablation duration.

Overall baseline LI was lower (88 Ω [IQR, 80-97]) compared with baseline GI (107 Ω [IQR, 100-115]; P < .001) while ΔLI was higher compared with ΔGI (Figure 3). The higher drop rate of ΔLI compared to ΔGI (0.43 Ω/s [IQR, 0.26-0.72] vs 0.27 Ω/s [IQR, 0.16-0.47]; P < .001; Figure 3) suggests that impedance reduction is indicated instantaneously by ΔLI. Exemplary ΔLI during RFC-ablation as visualized intraprocedurally are shown in Figure 4.

3.2 | Baseline impedance predicts impedance drop during RFC-ablation

To assess the effect of cardiac rhythm on ΔLI we compared impedance values during SR, RV-pacing and VT: ΔLI was 12.0 Ω [IQR, 6.0 to 11.0]; 8.0 Ω [IQR, 6.5 to 10.5] and 7.0 Ω [IQR, 4.0 to 11.0] during SR, RV-pacing and VT, respectively (P = .23).

3.3 | ΔLI displays subtle ablation-induced impedance change with high resolution

In a subgroup analysis including patient data with VT termination (n = 11), ΔLI was higher for RFC-ablation terminating VT compared to ΔLI for nonterminating RFC-ablation in the immediate spatial proximity of terminating ablation site (18.50 Ω [IQR, 10.20-31.25] for terminating ablation vs 9.30 Ω [IQR, 7.25-15.00]; P = .03). There was no difference for ΔGI for terminating RFC-ablations compared to nonterminating RFC-ablations (Figure 5A). Drop rate was higher for LI (0.65 Ω/s [IQR, 0.52-0.76] vs 0.32 Ω/s [IQR, 0.20-0.58]; P = .008) but not for GI (0.34 Ω/s [IQR, 0.24-0.49] vs 0.24 Ω/s [IQR, 0.16-0.40]; P = .18) in RFC-ablations terminating VT (Figure 5B). Values for all individual terminations are reported in Table 3. An exemplary VT

**FIGURE 1** Local impedance identifies regions of the scar. A, Generator impedance (GI) and local impedance (LI) in scarred (<0.1 mV) vs healthy (≥1.0 mV) as defined by voltage measurement from the 64-electrode basket-catheter (Orion). B, GI and local impedance LI in scarred vs healthy myocardium as defined by voltage measurement from the mini-electrodes incorporated in the mapping and ablation catheter (IntellaNav MIFI OI). The ablation points are grouped into scar/healthy myocardium based on voltage measurements by the mapping and ablation catheter. Voltage, as measured by basket catheter (panel A and B), is indicated by color.
termination is shown in video 1 in the Supporting Information. From ablation start until termination of VT, median ΔLI was 11 Ω [IQR, 6.3 to 16.0] vs median ΔGI of 3.6 Ω [IQR, 0 to 5.75], data not shown). There was no difference for baseline LI between terminating (100 Ω [IQR, 92.8–100.3]) and nonterminating lesions (95 Ω [IQR, 83.0–101.0]; P = .30) and no difference for voltage between terminating (0.05 mV [IQR, 0.04–0.29]) and nonterminating lesions in the subgroup analysis (0.11 mV [IQR, 0.06–0.19]; P = .37; data not shown).

3.6 | High LI drop rate is associated with high ΔLI

Baseline LI for ΔLI≥ 16Ω (high drop) was higher than baseline LI for ΔLI<16Ω (low drop, 94.0 Ω [IQR 86.0–103.0] and 84.0 Ω [IQR, 79.0–92.0], respectively, P < .001; Figure S4A). LI drop rate was higher for RFC-ablations with high drop compared with RFC-ablations with low drop (LI drop rate: 0.58 Ω/s [IQR, 0.40–0.96] and 0.33 Ω/s [IQR, 0.20–0.58], respectively; P < .001). GI drop rate did not differ for RFC-ablations with high drop compared with low drop (GI drop rate: 0.33 Ω/s [IQR, 0.21–0.57] and 0.24 Ω/s [IQR, 0.14–0.42], respectively, P = .202; Figure S4B). Steam pop did not occur during any RFC-ablation.

3.7 | Absolute impedance drop is higher in patients with NICM compared to ICM

Baseline LI at the sites of RFC-ablations was higher for patients with nonischemic cardiomyopathy (NICM) compared to patients with ischemic cardiomyopathy (ICM). Correspondingly, local bipolar voltage at the sites of RFC-ablations was higher in patients with NICM (0.18 mV [IQR, 0.07–0.81]) compared to patients with ICM (0.06 mV [IQR, 0.04–0.14], P < .001). Absolute ΔLI as well as absolute ΔGI were higher for patients with NICM (ΔLI: 9.0 Ω [IQR, 7.0–12.0] for NICM vs 8.0 Ω [IQR, 5.0–10.0] for ICM; ΔGI: 16.0 Ω [IQR, 11.0–20.0] for NICM vs 11.0 Ω [IQR, 7.9–17.0] for ICM). Notably, relative ΔLI and relative ΔGI did not differ between NICM and ICM (Relative ΔLI: 16.7% [IQR, 11.6–22.5] for NICM vs 14.1% [IQR, 9.9–20.8] for ICM). LI drop rate was higher for NICM compared with ICM, whereas no difference for GI drop rate between NICM and ICM was observed (Figure S5).

4 | DISCUSSION

In this study, LI, measured from the tip of a novel ablation catheter with three mini-electrodes, was investigated in relation to the established GI during the ablation of VT. These are our major findings:

1. ΔLI comprises a wider range and has a higher variance compared with ΔGI.
2. For ablation during VT, ΔLI and LI drop rate but neither ΔGI nor GI drop rate are higher for RFC-ablations terminating VT compared with RFC-ablations not terminating VT.
3. LI drop rate is higher for RFC-ablations with a high drop ΔLI ≥ 16Ω compared to RFC-ablations with a low drop ΔLI < 16Ω.
4. In patients with NICM, absolute ΔLI and ΔGI are higher compared to patients with ICM, whereas there is no difference for relative ΔLI and ΔGI.
4.1 LI but not GI support substrate mapping

Impedance is well known to be dependent on tissue characteristics according to previous clinical and experimental studies. Discrimination of healthy and scarred tissue using LI was initially demonstrated in acute and chronic models of myocardial infarction. More than two decades later, translation of experimental findings to early clinical experience using an ablation catheter incorporating LI measurements has recently been reported. Here, we demonstrate that LI can identify areas of scar in patients with VT. However, it remains to be determined how robust the observed effect is with regard to ventricular anatomy with various potential niches and possibly varying catheter-tissue contact. Substrate characterization in current clinical practice largely relies on local bipolar voltage measurement, which can be impeded by its dependency on activating wavefronts and the interference of far-field electrograms. Therefore, catheter-based measurements of LI might serve as a complementary parameter for endocardial substrate mapping in patients with VT. Furthermore, we show that in addition to the bipolar voltage measured by the basket-catheter, the ablation catheter with mini-electrodes can provide valid near-field voltage measurements at the site of RFC-ablation.

4.2 LI is more sensitive to impedance reduction than GI as indicated by higher ΔLI drop and higher variance of ΔLI

Although baseline LI is in general lower than baseline GI, impedance drop during RFC-application is higher for LI than for GI. This finding is in line with initial experimental studies and early clinical data. We showed a correlation of ΔLI with baseline LI, albeit with a low correlation coefficient, which is most likely attributable to heterogeneities of ventricular myocardial tissue. We showed higher correlation coefficients for atrial myocardium, a divergence that has been shown previously. Presumably, higher ΔLI can be more easily assessed compared to the smaller and less sensitive ΔGI. Moreover, ΔLI comprised a wider range of values compared to ΔGI. This suggests that LI reflects more subtle changes of tissue characteristics which in turn might remain undetectable by GI.

4.3 Ablation terminating VT

Termination of the VT was used as a surrogate for immediate changes in tissue characteristics. Loss-of-local-capture as another measure to assess the change of tissue characteristics has been...
performed as a clinical control of ablation effectiveness, but not systematically after each RFC-application. While the assessment of loss of local capture (a) can be time consuming and (b) might be confounded by far-field capture we did not evaluate the loss of capture after each RFC application and therefore used VT termination as a parameter evaluating ablation effectiveness.

RFC-ablations at the critical isthmus leading to VT termination were characterized by a larger ΔLI compared to non-terminating RFC-ablations. In addition, the LI drop rate was higher for ablation terminating VT compared to ablation not-terminating VT, whereas the GI drop rate did not show a difference. This monitoring of impedance change over time might be useful to avoid excessive ablation. Therefore, ΔLI reflects differences in RFC-ablation in terminating vs nonterminating ablation which is not indicated by ΔGI, suggesting that LI is the more sensitive parameter.

4.4 | Target values for LI-guided ablation

Using VT termination as a surrogate for effective RF-ablation, we showed that median ΔLI was 18.5 Ω, corresponding to a change of 18.6% in relation to baseline LI. Martin et al. showed a median ΔLI of 16 Ω (17.1%) to achieve a loss of capture in the left ventricle. For nonterminating ablation (median 9.3 Ω and 10.6%) and unsuccessful ablation (9.4 Ω and 10.6%), LI values were likewise in a similar range. These two studies yield comparable values and provide an orienting target range of 16 to 18.5 Ω for LI in VT ablation. In our sample, terminating ablation was associated with a drop rate of 0.65 Ω/s which may serve as an initial reference value for LI-guided ablation. However, the required change in LI might depend on tissue characteristics and therefore baseline LI should be considered before start of ablation.

4.5 | LI as an additional parameter to guide RFC-ablation

Novel ablation indices adopting contact force are useful tools to guide catheter maneuvering and ablation. These ablation indices reflect extrinsic ablation parameters such as contact force, power and ablation time but do not reflect the immediate ablation effect on myocardial tissue. Monitoring the effect of RFC-ablation on myocardial tissue is especially relevant in VT ablation due to the heterogeneous structure of the ventricles and myocardial scar. Especially the variability of myocardial thickness poses a significant challenge, with the need to achieve sufficient lesion depth while avoiding complications due to excessive energy delivery (e.g. steam pops, charring, perforation). The use of LI as a feedback parameter is promising when the character of the myocardial tissue should be

FIGURE 4 | Visualization of ΔLI for VT-terminating RFC-ablations. A, Representation of Δlocal impedance (LI) as visualized to the operator during the procedure. The yellow graph indicates mean LI of 3 seconds, undulations are due to patient’s respiration (yellow arrowheads). White graphs indicate raw data of LI, undulations are due to systolic and diastolic movement of the heart (white arrowheads). B,C, ΔLI is prominent, few undulations in white graph indicate catheter stability. E,F, Undulations of the white graph represent varying catheter-tissue contact due to systolic-diastolic movements of the heart. I-K, Baseline LI is not stable, which may be due to catheter repositioning before the start of ablation.
assessed and for procedures in which more extensive ablation can be decisive.

5 | LIMITATIONS

RFC-applications preceding the terminating ablation possibly did have a relevant effect on the myocardium and the subsequent terminating ablation only provided some additional effect. It is possible that ablations preceding the terminating ablation relevantly affected tissue properties. Also, nonterminating RFC-application may have been effective but not applied at the correct site. Next, a catheter with LI measurement in conjunction with contact force is yet not available for clinical use. Therefore, catheter contact was verified by established indirect measures including fluoroscopy, tactile feedback, and signal amplitude. However, these parameters can be limited by anatomical and substrate characteristics.

This study reports the initial adoption of LI in a single-center with relatively small sample size and did not include randomization. Further studies including cardiac CT and MRI might additionally improve our understanding of ventricular substrate. In our study population, 25/28 patients were carrying either ICD or CRT-D, limiting eligibility for MRI.

6 | CONCLUSION

Our data suggest that (a) LI sensitively reflects RFC-ablation and (b) baseline LI and ΔLI are higher in NICM compared to ICM, requiring

| TABLE 3 ΔLI and ΔGI for all RFC-applications terminating the VT |
|---------------------------------------------------------------|
|                  | ΔLI until termination (Ω) | ΔGI until termination (Ω) | Maximum ΔLI (Ω) | Maximum ΔGI (Ω) |
| Patient 1        | 13                       | 5                         | 19               | 10               |
| Patient 2        | 11                       | 5                         | 11               | 6                |
| Patient 3        | 2.7                      | 1                         | 32               | 16               |
| Patient 3        | 12                       | 6                         | 21               | 17               |
| Patient 4        | 19                       | 8                         | 36               | 21               |
| Patient 5        | 21                       | 11                        | 21               | 21               |
| Patient 6        | 6.3                      | 2                         | 6.3              | 2                |
| Patient 7        | 3.2                      | 3                         | 4.6              | 3                |
| Patient 8        | 7.8                      | NA                        | 7.8              | 9                |
| Patient 9        | 6.3                      | 4                         | 14               | 9                |
| Patient 10       | 7.5                      | 3                         | 18               | 13               |

Abbreviations: GI, generator impedance; LI, local impedance; RFC, radiofrequency current; VT, ventricular tachycardia.
to consider the etiology of the underlying cardiomyopathy when adopting LI for the guidance of catheter ablation in patients with VT.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.