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**CLINICAL RESEARCH**
*Ablation for atrial fibrillation*

# Reliability of luminal oesophageal temperature monitoring during radiofrequency ablation of atrial fibrillation: insights from probe visualization and oesophageal reconstruction using magnetic resonance imaging

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**Aims** A current concept to prevent atrio-oesophageal fistula during radiofrequency (RF) catheter ablation of atrial fibrillation is to monitor luminal oesophageal temperature (LET). The objective of this study was to describe the temporal course of LET and to assess the reliability of monitoring the maximal LET during pulmonary vein isolation (PVI) using irrigated multi-electrode (IMEA, nMARQ$^{TM}$) and focal ablation catheters.

**Methods and results** We studied 40 patients with LET monitoring during PVI (20 patients using the IMEA and 20 patients using the focal catheter). A linear probe was used and visualized in the 3D mapping system. Left atrial and oesophageal reconstructions from delayed enhanced magnetic resonance imaging were integrated. Analysing 745 temperature profiles, LET $>38^{\circ}C$ was observed in 48 of 296 (17%) and 44 of 449 (10%) ablations for the IMEA and the focal catheter, respectively ($P = 0.012$). Temporal latency after interruption of RF energy delivery was observed for both catheters. Time until LET baseline temperature was restored after an increase of $>1^{\circ}C$ was 100 and 86 s for the IMEA and the focal catheter, respectively ($P = 0.183$). Imprecise representation of the maximal LET was observed in 24 (60%) and 28 patients (70%) for the left and right PVs, respectively.

**Conclusion** Due to the unknown exact lateral position of the LET probe within the oesophagus, the measured temperature does not necessarily reflect the maximal LET. The absence of LET increase does not rule out significant temperature increase within the oesophagus. Consequently, the temperature information of the linear multipolar probe should be used with caution.

**Keywords** Luminal oesophageal temperature monitoring • Radiofrequency ablation • Atrial fibrillation • nMARQ



## Introduction

Despite the very low incidence of atrio-oesophageal fistula associated with catheter ablation of atrial fibrillation (AF),[1,2] this dramatic complication is feared due to its high mortality. With standard point-by-point radiofrequency (RF) ablation, the reported rate of atrio-oesophageal fistula ranges between 0.03 and 0.2%.[1,2] After focal RF ablation of AF, mostly asymptomatic oesophageal lesions have been described in 2–20% of patients.[3] This rate of these oesophageal lesions is too high to serve as predictors of atrio-oesophageal fistula. Applying the standard power settings used for focal ablation to the irrigated multi-electrode ablation (IMEA) catheter (nMARQ) resulted in an early report of atrio-oesophageal fistula.[4] This led to adaptations of the procedural protocols, mainly in

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## What's new?

- Luminal oesophageal temperature (LET) increases (>38°C) occur in 10% of all posterior LA wall ablations during PVI using a focal RF ablation catheter.
- Luminal oesophageal temperature increases (>38°C) are more frequent (17%) when using a multi-electrode ablation catheter.
- Luminal oesophageal temperature measurements using the linear multipolar probe do not necessarily reflect maximal oesophageal temperature for focal and multi-electrode ablation.
- Delayed oesophageal temperature increases may occur after the interruption of RF energy delivery.
- Cumulative heating of the tissue may occur if energy delivery is restarted before reaching baseline LET.
- A waiting period of up to 90 s could prevent the problem of cumulative and delayed heating of the tissue.

reduction of power for ablation at the posterior wall.[5–7] However, oesophageal lesions were also detected after implementing these procedural changes.[5,6] When using oesophageal temperature monitoring to prevent oesophageal injury, the current concept is to keep the maximal luminal oesophageal temperature (LET) below a predefined cut-off value during ablation. These temperatures were deduced from studies investigating the correlation between LET and incidence of any oesophageal lesions.[3,5,6] However, only the incidence of the lesion but not its position related to the position of the LET probe during temperature measurement is documented. Furthermore, the reliability of the LET measurement using linear temperature probes to detect maximal oesophageal temperature is still unclear. To address this, we analysed the LET measurements using a commonly used linear multipolar temperature probe during focal and IMEA pulmonary vein isolation (PVI) and integrated oesophageal reconstructions from pre-procedural delayed enhanced magnetic resonance imaging (MRI).

The aim of the current study was (i) to assess the reliability of LET monitoring to reflect maximal LET during PVI and (ii) to compare the observations of the continuously recorded LET during PVI using the established standard focal irrigated catheter ablation with the IMEA ablation catheter.

# Methods

In this non-randomized comparison, a total of 40 patients with paroxysmal or persistent AF undergoing PVI and no additional left atrial ablation were included. The study was approved by the local ethics committee on human research and written informed consent was obtained from all patients. In the IMEA group, PVI in 20 consecutive patients was performed using the IMEA catheter (nMARQ, Biosense Webster, Diamond Bar, CA, USA). In the focal group, point-by-point PVI was performed in 20 consecutive patients using a focal contact force-sensing catheter (Thermocool SmartTouch, Biosense Webster). All patients received a proton-pump inhibitor for 6 weeks after the procedure.

For each energy application at the posterior wall, the biophysical parameters were analysed and the closest distance between the ablation electrode and the sensor of the oesophageal temperature probe with the highest detected temperature was measured in 3D on the electroanatomic mapping system (Carto3, Biosense Webster, Diamond Bar, CA, USA). With the assumption of homogeneous heat conduction properties of the tissues, maximal LET within the oesophagus must be expected at the closest position to the ablation catheter. Consequently, the reliability of LET monitoring to detect maximal temperature was assessed on the basis of the position of the probe within the oesophagus (left, middle, right). Left-sided probe position was considered to accurately reflect the closest position for ablation at the left PV and right-sided position for ablation at the right PV. Probes located in the middle of the oesophagus (*Figure 1C*) do not represent the closest position either for ablations around the left or the right PVs.

## Cardiac imaging

All patients underwent MRI the day before the procedure on a 1.5 Tesla scanner (Magnetom Avanto/Espree, Siemens, Erlangen, Germany). A respiratory- and ECG-gated three-dimensional balanced steady-state free precession sequence was acquired in axial orientation. Three-dimensional delayed enhanced MRI (3D-dMRI) was acquired 15 min after the injection of contrast agent (Multihance, 0.1 mmol/kg, Bracco, Milan, Italy). We used a three-dimensional inversion recovery prepared, respiration navigated, ECG-gated, segmented fast low-angle shot pulse sequence with fat saturation (navigator gating, voxel size 1.25 mm × 1.25 mm × 2.5 mm, flip angle 22°, TR/TE 451/1.8 ms, inversion time 250–320 ms).

## Electrophysiological procedure

All PVI procedures were performed under conscious sedation using midazolam, fentanyl, and propofol. Trans-septal puncture was performed under fluoroscopic guidance. After trans-septal puncture, intravenous heparin was administered to maintain an activated clotting time of 350 s. The endpoint was the elimination of all PV potentials on a circular mapping catheter.

## Oesophageal temperature acquisition

Before sedating the patient, the linear five-pole temperature probe with three temperature sensors (Sensitherm, St Jude Medical, St Paul, MN, USA) was introduced into the oesophagus under fluoroscopic guidance to ensure proper position behind the posterior wall of the LA. The five electrodes of the LET probe were connected to the Carto3 system for visualization. Cut-off temperature to terminate energy application was set to 38°C for the IMEA group and, based on previous studies, to 41°C for the focal group.[3] Temperature readings of the three thermocouples were exported in real time from the Sensitherm oesophageal monitoring system for post-procedural analysis.

Temperature acquisition was started with the beginning of the energy delivery of the ablation and stopped 10 s after the end of the ablation if no obvious temperature increase (>0.5°C) was observed or when temperature returned to baseline. After the procedure, the temperature profile of every ablation was analysed and baseline temperature, temperature at the end of energy application, maximal temperature, and time at maximal temperature were recorded. On the basis of these data, thermal latency was calculated for ablations with an increase of >2°C as the time difference between the end of energy application and maximal temperature reached. Time to recovery to baseline temperature was assessed for all patients with a LET increase of at least 1°C.

## Multipolar irrigated-tip ablation

Multipolar irrigated-tip ablation using the nMARQ catheter was performed as published elsewhere.[7] Briefly, a single trans-septal puncture

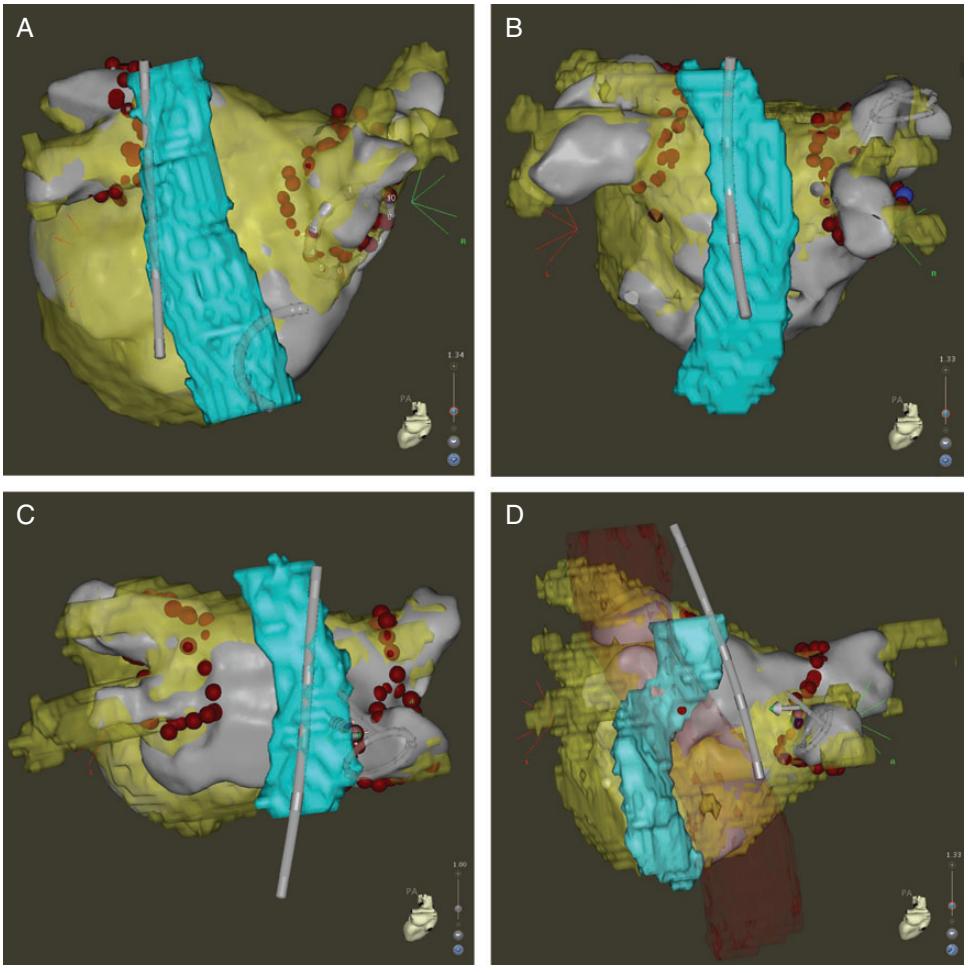


**Figure 1** Exemplary posterior views with the FAM (grey), the MR reconstruction of the LA (yellow), the 3D-dMRI reconstruction of the oesophagus (cyan), and the LET probe: (*A*) left oesophageal position with LET probe on the left side within the oesophagus, (*B*) middle oesophageal position, and (*C*) right oesophageal position with LET probe in the middle of the oesophagus. (*D*) Shows patient with mobile oesophagus, perhaps due to the oblique course of the descending aorta (semi-transparent red).

was performed and a steerable sheath (Agilis Nxt, St Jude Medical) was advanced into the left atrium. A 20-pole circular mapping catheter (Lasso 2515, Biosense Webster) was used to create the 3D-electroanatomic map of the left atrium using the 'fast anatomical mapping' (FAM) feature. Unipolar ablation at the antrum was performed for 30–40 s and a starting power of 15 W (flow rate 60 mL/min.) per lesion on all electrodes with presumed tissue contact. Power was titrated up to a maximum of 18 W at the posterior wall and 20 W at the anterior wall if needed. Ablation was stopped if one of the three temperature sensors of the LET probe reached the pre-defined cut-off of 38°C. Pulmonary vein isolation was confirmed using the 20-pole circular mapping catheter.

## Focal irrigated-tip radiofrequency ablation

Double trans-septal puncture was performed, and a 20-pole circular mapping catheter (Lasso 2515, Biosense Webster) and a 3.5 mm open irrigated-tip contact force-sensing catheter (Thermocool SmartTouch, Biosense Webster) were advanced into the left atrium. The FAM of the left atrium was used to guide the continuous circumferential point-by-point antral ablation around the ipsilateral PVs. Radiofrequency energy was delivered with a power of 25 W using the EP Shuttle RF generator (Biosense Webster) and an irrigation fluid flow rate of 17 mL/min. Target contact force range was 10–40 g for a maximal duration of 30 s at the posterior wall. No catheter dragging during RF energy application was performed.

## Anatomical relationship

The reconstructed left atrium from the cardiac MRI was registered to the FAM of the left atrium. Measurements of the closest distance between the ablation electrodes of the IMEA catheter or the focal catheter and the LET probe were conducted post-procedurally using the distance measurement tool of the software. The course and width of the oesophagus and its relationship to the LET probe and the LA were quantified using the reconstruction of the oesophagus obtained from the 3D-dMRI.

## Statistical analysis

Continuous variables are presented as mean ± standard deviation or as median and interquartile range (IQR). For continuous variables,

comparisons were made using Student's *t*-test or Mann–Whitney *U* test, as appropriate. Discrete variables were compared using Fisher's exact test.

Univariate predictors for LET with *P*-value of <0.1 were included into a stepwise multivariate logistic regression model to determine independent predictors for LET temperature increase of ≥1°C. A *P*-value <0.05 was considered to indicate statistical significance. Analysis was performed using SPSS (IBM SPSS Statistics, Version 22.0. Armonk, NY, USA).

# Results

We analysed 745 ablations performed at the posterior wall of the LA (296 in the IMEA group and 449 in the focal group). Patients had a mean age of 62 ± 8 years and 75% were men. Left atrial size in the parasternal long axis was 42 ± 6 mm and left ventricular ejection fraction was 56 ± 11%. Pulmonary vein isolation could be reached in all patients. No complications occurred. In particular, no clinical oesophageal symptoms were observed. Biophysical results on a per-vein analysis are shown in *Table 1* for the IMEA group and in *Table 2* for the focal group.

## Anatomical analysis

The median closest distance between the temperature probe and the ablation electrode are summarized in *Tables 1* and *2*. The mean width of the oesophagus in contact with the posterior wall was 21 ± 3 mm. The location of the oesophagus was behind the left PVs in 16 patients (40%), in the middle of the LA in 21 patients (52.5%), and behind the right PVs in 3 patients (7.5%). In the Carto3 system, the LET probe was identified behind the left PVs in 17 (43%), in the middle of the LA in 17 (43%), and behind the right PVs in 6 patients (14%). The lateral extension and course of the oesophagus obtained from the pre-procedural 3D-dMRI was congruent with the real-time position of the LET probe in the Carto3 system in 30 of 40 patients (75%). But due to the oesophageal width, the LET probe position does not inevitably reflect the closest distance between the ablation electrode and the oesophagus. The LET probe position represented the closest position of the oesophagus to the ablation catheter in 16 patients (40%) for the left PVs and in 12 patients (30%) for the right PVs. In 12 patients (30%) with the LET probe in the middle of the oesophagus, LET probe position within the oesophagus did reflect neither its right nor its left extension. In 2 of 40 patients (5%), the real-time LET probe position during the procedure was completely outside the pre-procedural 3D-dMRI reconstruction of the oesophagus, suggesting significant movement of the oesophagus between the time of pre-procedural imaging and the procedure (*Figure 1D*).

## Analysis of the steady-state temperature behaviour

The median of the maximal temperatures of all RF energy applications at the posterior wall was 36.5°C (36.2–37.3°C) in the IMEA group and 36.5°C (36.3–36.9°C) in the focal group. Maximal temperature reached was 40.7°C in the IMEA group and 43.7°C in the focal group.

Temperature increase above 38°C during ablation leading to the termination of energy delivery was observed in 11 patients (55%) of the IMEA group. In the focal group, temperatures above 38°C were observed in 14 patients (70%) ($P = 0.515$). Cut-off temperature was reached during 30 energy applications (10%) in the IMEA group (*Table 3*). In the focal group, 38°C was reached during 45 energy applications (10%). The higher cut-off temperature of 41°C used in this group was reached in 2 of 20 patients (10%) and during five energy applications (1%) (*Table 4*). On a per-vein analysis, cut-off temperature was reached during 5 ablations at the left superior PV (LSPV) (8%), 16 at the left inferior PV (LIPV) (17%), 0 at the right superior PV (RSPV) (0%), and 9 at the right inferior PV (RIPV) (10%) in the

**Table 1 Results of the ablations using the IMEA catheter per pulmonary vein**

| | All | LSPV | LIPV | RSPV | RIPV | *P*-value |
|---|---|---|---|---|---|---|
| Ablations | 296 | 64 | 96 | 50 | 86 | |
| Mean power (W) | 14 (13–17) | 14 (13–16) | 14 (12–16) | 15 (14–17) | 14 (13–17) | 0.68 |
| Mean temperature (°C) | 38.3 (36.3–40.6) | 39.0 (37.4–40.3) | 38.8 (35.8–40.8) | 37.8 (36.3–40.5) | 37.7 (35.9–40.8) | 0.71 |
| Baseline impedance (Ω) | 112 (105–118) | 114 (108–118) | 113 (104–118) | 110 (106–120) | 110 (105–116) | 0.38 |
| Energy (J) | 1222 (756–1812) | 1035 (616–1581) | 1076 (523–1632) | 1384 (1008–1882) | 1320 (767–1997) | 0.02 |
| Maximal LET (°C) | 36.5 (36.2–37.3) | 36.4 (36.2–37.3) | 36.8 (36.3–37.9) | 36.4 (36.2–36.8) | 36.4 (36.2–37.3) | 0.03 |
| Stop due to LET > 38°C | 30 (10%) | 5 (9%) | 16 (17%) | 0 (0%) | 9 (10%) | 0.02 |
| ΔLET > 2°C | 32 (11%) | 5 (8%) | 17 (18%) | 0 (0%) | 10 (12%) | 0.01 |
| LET > 38°C | 48 (17%) | 6 (9%) | 23 (24%) | 2 (4%) | 17 (20%) | <0.01 |
| ΔLET after stop (°C) | 0.6 (0.4–0.9) | 0.5 (0.1–0.9) | 0.6 (0.4–0.9) | n.a. | 0.8 (0.4–1.0) | 0.55 |
| Time at stop (s) | 25 (16–30) | 27 (17–30) | 20 (16–30) | n.a. | 26 (21–39) | 0.34 |
| Latency after stop (s) | 8 (3–14) | 9 (3–13) | 8 (3–13) | n.a. | 11 (6–16) | 0.57 |
| Distance (mm) | 22 (15–21) | 22 (15–32) | 18 (10–25) | 32 (24–44) | 22 (15–31) | <0.001 |

Values are *n* (%) for categorical and median (interquartile range) for continuous variables.
LET, luminal oesophageal temperature; n.a., not available.

**Table 2 Results of the ablations using the focal catheter per pulmonary vein**

| | All | LSPV | LIPV | RSPV | RIPV | *P*-value |
|---|---|---|---|---|---|---|
| Ablations | 449 | 76 | 139 | 102 | 132 | |
| Mean power (W) | 25 (25–25) | 25 (25–25) | 25 (25–25) | 25 (25–25) | 25 (25–25) | 0.93 |
| Mean temperature (°C) | 39.0 (38.0–41.0) | 37.2 (36.2–38.2) | 38.1 (37.0–39.4) | 37.6 (36.8–38.1) | 37.8 (37.1–38.9) | <0.001 |
| Baseline impedance (Ω) | 132 (124–138) | 131 (125–138) | 132 (125–138) | 133 (124–138) | 133 (124–139) | 0.98 |
| Mean force (N) | 14 (10–20) | 14.5 (10.8–21.0) | 14.0 (9.5–18.0) | 17.0 (12.3–24.0) | 12.0 (9.0–18.0) | <0.001 |
| Delivered energy (J) | 700 (525–850) | 700 (525–900) | 690 (529–825) | 723 (550–825) | 650 (502–850) | 0.79 |
| Maximal LET (°C) | 36.5 (36.3–36.9) | 36.5 (36.3–36.9) | 36.8 (36.4–37.4) | 36.4 (36.3–36.5) | 36.5 (36.2–37.0) | <0.001 |
| Stop due to LET > 41°C | 5 (1%) | 0 | 4 (3%) | 0 (0%) | 1 (0.8%) | 0.11 |
| ΔLET > 2°C | 31 (7%) | 4 (5%) | 17 (12%) | 1 (1%) | 9 (7%) | 0.18 |
| LET > 38°C | 44 (10%) | 5 (7%) | 24 (17%) | 1 (1%) | 14 (11%) | |
| ΔLET after stop (K) | 0.1 (0.1–0.2) | 0.1 (0.00–0.2) | 0.2 (0.1–0.3) | n.a. | 0.1 (0.1–0.2) | 0.31 |
| Time at stop (s) | 26 (21–30) | 23 (17–29) | 26 (20–31) | n.a. | 25 (21–30) | 0.66 |
| Latency after stop (s) | 2 (0–6) | 0 (0–5) | 2 (0–5) | n.a. | 4 (1–7) | 0.14 |
| Distance (mm) | 21 (14–30) | 17 (13–25) | 15 (11–22) | 28 (22–32) | 25 (17–33) | <0.001 |

Values are *n* (%) for categorical and median (interquartile range) for continuous variables.
LET, luminal oesophageal temperature; n.a., not available.

**Table 3 Summary of all ablations with a temperature increase above 38°C in the oesophagus resulting in interruption of energy application for the IMEA group**

| | RF interrupted (*n* = 30) | RF not interrupted (*n* = 266) | *P*-value |
|---|---|---|---|
| Pre-procedural parameters | | | |
| Impedance at start (Ω) | 113 (101–119) | 112 (106–118) | 0.38 |
| Baseline temperature (°C) | 36.3 (35.9–36.6) | 36.2 (35.9–36.5) | 0.24 |
| Electrodes in contact | 4 (2–4.8) | 3 (2–4) | 0.12 |
| Oesophagus position | | | 0.07 |
| Left | 25 (83%) | 87 (33%) | |
| Middle | 17 (57%) | 130 (49%) | |
| Right | 6 (20%) | 31 (12%) | |
| Probe position | | | 0.94 |
| Left | 18 (60%) | 89 (33%) | |
| Middle | 20 (67%) | 110 (41%) | |
| Right | 10 (33%) | 49 (18%) | |
| Distance (mm) | 9 (6.5–10) | 24 (17–32) | <0.001 |
| Duration of energy application (s) | 19 (15–26) | 30 (29–34) | <0.001 |
| Cumulative power over all electrodes in contact (W) | 40 (28–52) | 42 (28–56) | 0.68 |
| Post-procedural | | | |
| Cumulative energy over all electrodes in contact (J) | 760 (421–1143) | 1299 (810–1855) | <0.001 |
| ΔImpedance (Ω) | 12 (8–19) | 13 (9–17) | 0.87 |
| Max. catheter temperature (°C) | 43.5 (38.1–46.2) | 41.9 (38.8–46.0) | 0.70 |
| Max. LET (°C) | 38.8 (38.6–39.3) | 36.4 (36.2–36.9) | <0.001 |

Values are *n* (%) for categorical and median (interquartile range) for continuous variables.
LET, luminal oesophageal temperature; max., maximal.

IMEA group (*Table 1*). In the focal group, cut-off temperature of 41°C was reached during 4 ablations at the LIPV (3%) and 1 at the RIPV (1%) (*Table 2*). Temperatures increases above 1°C were only observed if the closest distance between the ablation electrode and the LET probe was below 19 mm in the IMEA group and below 16 mm in the focal group (*Figure 2*).

**Table 4 Summary of all ablations with a temperature increase above 41°C in the oesophagus resulting in interruption of energy application for the IMEA group**

| | RF interrupted ($n = 5$) | RF not interrupted ($n = 444$) | *P*-value |
|---|---|---|---|
| Pre-procedural parameters | | | |
| Impedance at start (Ω) | 123 (122–128) | 133 (125–139) | 0.06 |
| Baseline temperature (°C) | 36.9 (36.4–37.4) | 36.2 (36.0–36.5) | 0.01 |
| Mean force (N) | 9 (6–12) | 14 (10–20) | 0.03 |
| Oesophagus position | | | 0.12 |
| Left | 4 (80%) | 87 (33%) | |
| Middle | 1 (20%) | 130 (49%) | |
| Right | 0 | 31 (12%) | |
| Probe position | | | 0.95 |
| Left | 0 | 89 (33%) | |
| Middle | 4 (80%) | 110 (41%) | |
| Right | 11 (20%) | 49 (18%) | |
| Distance (mm) | 10 (7.5–11) | 22 (15–31) | <0.001 |
| Duration of energy application (s) | 11 (10–12) | 28 (22–34) | <0.001 |
| Cumulative power (W) | 25 (28–25) | 25 (25–25) | 0.50 |
| Post-procedural | | | |
| Energy (J) | 275 (250–300) | 700 (550–850) | <0.001 |
| ΔImpedance (Ω) | 5 (4–8) | 11 (6–15) | 0.03 |
| Max. catheter temperature (°C) | 37.0 (37.0–38.0) | 39.0 (38.0–41.0) | 0.01 |
| Max. LET (°C) | 43.0 (42.5–43.7) | 36.5 (36.3–36.9) | <0.001 |

Values are *n* (%) for categorical and median (interquartile range) for continuous variables.
LET, luminal oesophageal temperature; Max., maximal.

## Analysis of the dynamic temperature behaviour

In the 64 energy applications in the IMEA group with a temperature increase of >1°C, the median time after stopping energy delivery until reaching maximal temperature was 10 s (4–14 s). Within this latency period, LET increased by 0.5°C (0.2–0.8°C). An increase between 1 and 1.8°C was observed during nine energy applications (six LIPV, two RIPV, and one LSPV) after a median of 11 s (5–15 s). Time until baseline temperature was restored after an increase of at least 1°C was 100 s (70–110 s).

In the 49 energy applications in the focal group with a temperature increase of >1°C, the median time after stopping energy delivery until reaching maximal temperature was 3 s (0–6 s) ($P < 0.001$ compared with IMEA group). Within this latency, LET increased by 0.1°C (0.05–0.25°C) ($P < 0.001$ compared with IMEA group). An increase of >1°C after stopping energy application was observed for one ablation at RIPV after 7 s. Time until baseline temperature was restored was 86 s (66–104) ($P = 0.183$ compared with IMEA group).

## Predictors for temperature increase

In a multivariate logistic regression, including baseline impedance, baseline temperature, distance, ablation at the inferior PVs, and position of the oesophagus, the shortest distance between the LET probe and the ablation electrode [OR 0.651 (95% CI: 0.577–0.735), $P < 0.001$] and the number of electrodes delivering energy to the posterior wall [OR 1.787 (95% CI: 1.246–2.563), $P < 0.01$] were the only independent predictors for an LET increase of >1°C in the IMEA group. In the focal group, the baseline temperature [OR 3.014 (95% CI: 1.132–8.022), $P = 0.03$], the shortest distance between the LET probe and the ablation electrode [OR 0.582 (95% CI: 0.492–0.689), $P < 0.001$], and a right-sided position of the oesophagus compared with a middle position [OR 15.479 (95% CI: 3.396–70.547), $P < 0.001$] were independent predictors for an LET increase of >1°C.

# Discussion

To the best of our knowledge, this is the first human study combining continuous LET assessment with probe visualization in an electroanatomic mapping system and oesophageal reconstruction on 3D-dMRI to interpret the reliability of LET measurements associated with PVI. The main findings of our study are the following: (i) The LET probe position is variable within the oesophagus (mean oesophageal width of 21 mm) and the oesophagus position itself is variable behind the LA. (ii) LET position only reflects the closest distance between the ablation electrode and the oesophagus in 40% of the ablations at the left PVs and in 30% of the ablations in right PVs. (iii) We observed latency of the temperature increase after stopping RF energy delivery and this latency was greater for the IMEA catheter than for the focal catheter. (iv) The time until LET returned to the baseline temperature was ~90 s for both groups.

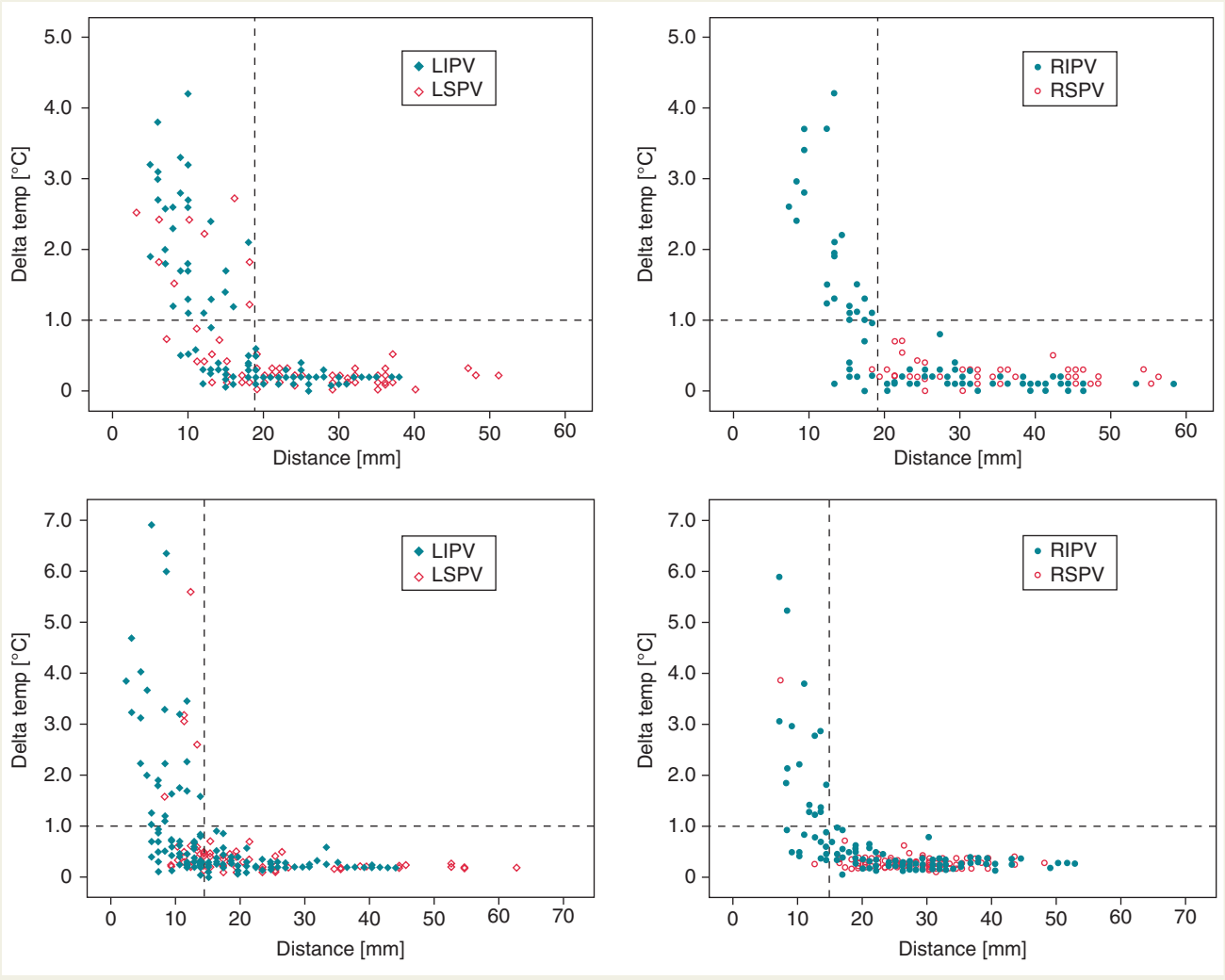


**Figure 2** Plot of the LET increase and the closest distance between the ablation electrode and the LET probe in the IMEA group (top row) and the focal group (lower row). The horizontal dashed line highlights an increase of 1°C; the vertical dashed line represents the distance cut-off for which an increase of >1°C should be expected. For greater distances, no relevant increase was observed.

## Anatomical relationship

The value and safety of LET monitoring with a dedicated probe is controversial.[8–11] A previously underestimated aspect of the reliability of LET monitoring addressed in our study may be the variability of the LET probe position within the oesophagus due to a mean lateral extension of the oesophagus of >2 cm. Whereas the position in cranial–caudal position can easily be adjusted by advancing or retracting the probe as performed in this study if needed, specific lateral positioning is impossible to control with the probe used in our study and consequently the closest distance to the ablation electrode cannot be granted. This may, at least in part, explain the different results of previously published studies. Even when visualizing the LET probe in real-time in the electroanatomic mapping system, the oesophageal tissue can be in fact be several millimetres closer the ablation electrode and consequently the 'true' maximal tissue temperature in the oesophagus could be markedly higher than the detected increase. According to a numerical simulation by Perez *et al.*, the maximal LET for an ablation with 35 W can be 10°C warmer than the measured LET when the probe is only 3 mm away from the spot with the maximal temperature.[12] Such local deviations must be expected in an oesophagus with a mean with of 21 mm. Furthermore, Perez *et al.* showed that no temperature increase above body temperature must be expected in a distance greater than ~10 mm, which is comparable to our observations for the focal ablation catheter (*Figure 2*). Consequently, if no temperature increase is detected, this does not necessarily mean that there is no heating of the oesophagus and the maximal oesophageal temperature increases might be much higher than the increases observed by the LET probe. The S-shaped 12-pole LET probe (Circa Scientific, Park City, UT, USA) is wider and may potentially be positioned more reliably in the middle of the oesophagus and may cover the area of interest better.[13] An alternative option to address this problem is an oesophageal infra-red thermography catheter.[14] As the oesophageal position was more often the behind the left compared

with the right PVs among lesions for which RF application was stopped for both technologies (focal: 2% vs. 0.5%; IMEA: 13% vs. 7%), attention should be taken specifically at the left-sided inferior location. No LET increase was observed with ablation at the RSPV.

## Luminal oesophageal temperature monitoring

For both irrigated catheter technologies, our observations are consistent with the dynamic temperature behaviour reported with PVI using an 8 mm catheter and a single sensor temperature probe.[15] Especially for the IMEA catheter, we observed latency in temperature increase after stopping RF energy delivery. This temperature latency implies that the thermal equilibrium is not reached and maximal temperature within the oesophagus is higher than the measured LET. Dependent on the distance between probe and catheter, this resulted in an LET increase of up to 1.8°C after stopping of the ablation.

With the IMEA catheter, energy is transferred over up to four electrodes simultaneously to the tissue of the posterior wall. This higher transferred energy explains the greater possible distance between the ablation electrode and the LET probe for an increase of >1°C to be observed and also the greater temperature latency for the IMEA catheter compared with the focal catheter (*Figure 2*). To prevent overheating of the tissue by cumulative energy transfer with ablation, a waiting period between the lesions is warranted to address the temperature latency and to allow cooling down of the tissue.

## Limitations

This observational study is too small to correlate the findings with the occurrence of atrio-oesophageal fistula with an incidence below 0.5%. This is a relatively small study; however, a total of 296 and 449 ablation lesions were analysed in the two groups. Oesophageal endoscopy after PVI to determine the incidence of oesophageal injury was not performed in our study. However, endoscopically detected oesophageal lesions also represent a mere surrogate marker for atrio-oesopheageal fistula and occur in up to 45% of patients,[13,16] whereas atrio-oesopheageal fistula is exceedingly rare.[1,2] On the other hand, the relationship between LET measurement location and oesophageal lesion is not unambiguous, as described above. Finally from a biophysical standpoint, the distance between the ablation electrode and the temperature probe was measured as a straight line (closest distance), which might not reflect heat transfer *in vivo* because of its dependency on tissue heat conductive properties.

## Clinical implications

Cumulative heating and temperature latency have been identified in both groups, requiring a waiting period of ~90 s between RF applications to allow full recovery to baseline temperature in the oesophagus. Furthermore, if the linear, multipolar LET probe displays temperature increase mainly at the inferior PVs, the duration of the energy duration can be adapted accordingly. However, due to the lateral extension of the oesophagus and the unclear lateral intra-oesophageal position of the linear LET probe, the measured temperature does not necessarily reflect the highest temperature in the oesophagus. The true LET can be much higher, and no increase of LET does not mean that there is no temperature increase within the oesophagus. With a probe distance of >20 mm from the ablation electrode, no LET increase (>1°C) might be recognized for the herein described ablation settings and the value of the probe to detect LET increase is negligible. LET probe visualization in a 3D mapping system in combination with the reconstruction of oesophagus from 3D-dMRI might overcome this limitation, but movement of the oesophagus between the time of the MRI and PVI remains a reality. The above-mentioned 90 s waiting period between lesions is impractical for focal ablation, but might be feasible for multi-electrode ablation where fewer energy applications are necessary to achieve PVI. Furthermore, if a linear LET probe is used, a more conservative cut-off temperature than the 41°C used for focal ablation is indicated to at least in part address the inherent inaccuracy of LET probes in detecting the maximal LET.

# Conclusions

Due to the unknown exact lateral position of the LET probe within the oesophagus, the measured temperature does not necessarily reflect the highest LET. Therefore, on the basis of the absence of LET increase, one cannot rule out significant temperature increase within the oesophagus. Consequently, the temperature information of the linear multipolar probe during PVI should be used with caution.

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## EP CASE EXPRESS

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# Migration of femoral vein thrombus to the right ventricle: an undesiderable complication in patients undergoing electrophysiological procedures

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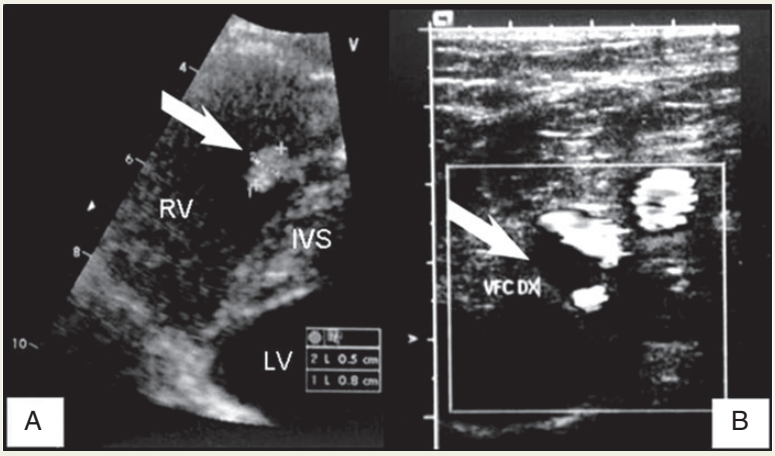
A 44-year-old obese man with a history of type 2 diabetes underwent electrophysiological study due to recurrent episodes of palpitations with documented paroxysmal supraventricular tachycardia. After introduction of two venous sheaths into both common femoral veins a typical slow–fast atrioventricular nodal re-entrant tachycardia (AVNRT) was induced, and the slow pathway was ablated uneventfully. Routine echocardiographic pre-discharge control showed a grape-like mobile mass entrapped in the right ventricular moderator band, compatible with a thrombus (*Panel A*, see Supplementary material online, *Video S1*). A Doppler ultrasound scan showed a dilated and not compressible distal tract of the right common femoral vein whose lumen was partially occupied by the isoechoic formation compatible with a recent deep venous thrombosis (DVT) (*Panel B*). Unfractionated heparin was immediately started at therapeutic doses. Clinical and instrumental workup for acute pulmonary embolism was negative (D-Dimer = 0.6 mg/L), and no echocardiographic signs of RV dilation or dysfunction were detected. Over the following days the patient remained asymptomatic, and bridge therapy with warfarin was commenced until INR reached the therapeutic range (2–3). Serial echocardiographic controls revealed a complete resolution of the thrombus after 12 days. The patient was discharged asymptomatic and in good haemodynamic state. After a few months, once obtained the entire thrombophilic screening (including homocysteine levels, antinuclear antibodies, antithrombin-III, MTHFR, lupus anticoagulant, protein S and protein C) which did not show any relevant alteration, anticoagulation therapy was interrupted.

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