Circulation: Arrhythmia and Electrophysiology

ORIGINAL ARTICLE

How a Topological Mindset May Offer Extra Control During Mapping and Ablation of Left-Sided Reentrant Atrial Tachycardia

Mattias Duytschaever, MD, PhD; Maarten De Smet, MD, PhD; Jordi Martens, MS; Milad El Haddad, MS, PhD; Benjamin De Becker, MD, PhD; Clara Francois, MD; Rene Tavernier, MD, PhD; Robin Van den Abeele, MS; Sander Hendrickx, BS; Nele Vandersickel, PhD; Jean-Benoit Le Polain de Waroux, MD, PhD; Sebastien Knecht, MD, PhD

BACKGROUND: Reentry (macro or localized) is historically described as multiple pathways that are separated by barriers (either anatomic or functional) and involve active and passive loops (identified by electro-anatomic and entrainment mapping, EAM/ETM). Some reentrant atrial tachycardia (AT) cases are characterized by challenging activation patterns and unexpected ablation responses. A recent translational study, focusing on topology (TOP) and the role of boundaries, suggests that thinking topology within EAM/ETM might offer extra control during mapping and ablation of reentrant AT. We aimed to propose and prospectively validate a workflow (EAM/ETM+TOP) in which we integrate topological thinking within an EAM/ETM workflow for mapping and ablation of left-sided (left atrium) AT.

METHODS: The integrated workflow was performed in 88 left atrium reentrant AT cases. After EAM/ETM, the number of loops and potential ablation strategy were verified against the number of critical and noncritical boundaries (critical boundary [CB], non-CB). Linear radiofrequency lesions were deployed to connect both CBs, preferably by one direct CB-CB line.

RESULTS: EAM/ETM+TOP-based mapping was feasible in all cases and led to a diagnosis of a 2B topology with single-loop activation in 33 cases and a≥3B topology with dual-loop activation in 55 cases. In 87 out of 88 cases, subsequent ablation via a direct CB-CB approach (n=75), an indirect CB-non-CB-CB (n=9), or an indirect CB-non-CB-non-CB-CB approach (n=3) led to successful termination of AT. No unexpected changes in tachycardia cycle length occurred. After a median follow-up of 356 (inter-quartile range, 228–537) days, 16 patients experienced recurrence of AT (18%).

CONCLUSIONS: Thinking topology within an EAM/ETM workflow may offer extra control during mapping and ablation of left-sided reentrant AT.

GRAPHIC ABSTRACT: A graphic abstract is available for this article.

Key Words: arrhythmias, cardiac ■ heart atria ■ humans ■ tachycardia ■ workflow

Atrial tachycardia (AT) is a common arrhythmia, occurring in patients with and without prior ablation or cardiac surgery.[1,2] Reentry in the left atrium (LA) stands as the dominant mechanism. Reentry (macro or localized) is historically described as multiple pathways that are separated by barriers (either anatomic or functional) and involve active and passive loops that can be identified by electro-anatomic and entrainment mapping (EAM/ETM).[2–5] Some reentrant AT cases are characterized by complex activation patterns and entrainment responses.[4–8] Furthermore, unexpected ablation-induced responses, like no change in tachycardia cycle length

Correspondence to: Mattias Duytschaever, MD, PhD, Department of Cardiology, AZ Sint-Jan Brugge, Ruddershove 10, 8000 Brugge, Belgium. Email mattias.duytschaever@azsintjan.be

Supplemental Material is available at https://www.ahajournals.org/doi/suppl/10.1161/CIRCEP.125.013780.
For Sources of Funding and Disclosures, see page 538.

Circulation: Arrhythmia and Electrophysiology is available at www.ahajournals.org/journal/circep

WHAT IS KNOWN?

- Reentrant atrial tachycardia involves circuits defined by anatomic or functional boundaries, which can be mapped using electro-anatomic and entrainment techniques.
- Some reentrant atrial tachycardia cases present with complex activation patterns and unpredictable responses to standard ablation strategies.
- Prior studies suggest that incorporating topological thinking into mapping may enhance understanding of arrhythmia mechanisms.

WHAT THE STUDY ADDS

- This study introduces and prospectively validates a novel workflow (electro-anatomic and entrainment mapping+topology) that integrates topological analysis into conventional mapping for reentrant atrial tachycardia.
- In 88 left atrial atrial tachycardia cases, topological mapping allowed classification into distinct activation loop patterns and guided targeted ablation using boundary-based strategies.
- The approach enabled successful arrhythmia termination in 99% of cases without unexpected tachycardia cycle length changes and was associated with a relatively low recurrence rate (18%) over 1 year.

Nonstandard Abbreviations and Acronyms

AT	atrial tachycardia
CB	critical boundary
EAM/ETM	electro-anatomic and entrainment mapping
dPPI	postpacing interval minus tachycardia cycle length
LA	left atrium
LAT	local activation time
LOB	line of block
LPV	left pulmonary veins
MV	mitral valve
NCB	noncritical boundary
PVI	pulmonary vein isolation
RA	right atrium
RPV	right pulmonary vein
SR	sinus rhythm
TCL	tachycardia cycle length

(TCL) or a switch to a sequential AT with longer TCL (up to 43%),[2] may occur throughout the ablation process. This may lead to time-consuming remapping and deployment of unnecessary lines.

Recent studies by Vandersickel,[9] Duytschaever,[10] and Santucci et al,[11] focusing on topology and the role of critical boundaries (CBs) and noncritical boundaries (NCBs) during reentry, suggest that thinking topology on top of EAM/ETM might offer extra control during mapping and ablation of reentrant AT.

In the present article, we propose and prospectively validate an EAM/ETM+topology (TOP) workflow in which we apply topological thinking in an effort to provide extra control during EAM/ETM-guided mapping and ablation. We provide procedural outcomes and 1-year freedom from recurrence.

METHODS

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

Topology Construct

The topology construct, rooted in mathematical principles and validated in computational spheric modeling,[9,10] entails 6 key principles (Figure 1): (1) Each reentrant AT (macro or localized) is based upon paired rotation around 2 CBs. (2) In atria featuring 2 boundaries only (left panel), paired rotation manifests as a single loop with counterclockwise rotation around 1 CB and clockwise rotation around the other. (3) In atria with ≥ 3 boundaries (right panel), paired rotation manifests as dual-loop activation around 2 CBs, with parallel activation around >1 NCBs. Due to differences in boundary cycle length of the CBs, dual-loop activation is asymmetrical, with an active loop around CB1 (being characterized by boundary cycle length=TCL) and a passive loop around CB2 (boundary cycle length>TCL). In clinical AT, asymmetry is often underappreciated because visual interpretation cannot differentiate between complete and near-complete rotation and because the definition of asymmetrical entrainment (a postpacing interval minus TCL, ie, postpacing interval minus TCL [dPPI], being smaller or >30 ms) lacks resolution. Irrespective of the boundary cycle length or dPPI at CB2, however the passive loop is relevant because it will invariably become active whenever the first loop is selectively ablated outside the common isthmus. (4) Any ablation strategy that connects both CBs will terminate AT. CB-CB ablation can be performed either directly (implying a single line) or indirectly (2 lines connecting CB-to-NCB-to-CB or 3 lines connecting CB-to-NCB-to-NCB-to-CB). (5) In ≥3B topology, the ablation response to CB-NCB ablation, is contingent on symmetry, with no change in TCL if symmetrical dual-loop activation, and either no change in TCL (if CB2-to-NCB) or a transition to slower TCL (if CB1-to-NCB) in asymmetrical cases. (6) In asymmetrical dual-loop activation, the dPPI value at the edge of CB2 predicts the degree of TCL prolongation if a CB1-NCB strategy is chosen.

In addition to the 6 key elements, the following topological observations were made in the clinical AT data set (see lower box in Figure 1).[10] A 3B or more topology, implying inherent dual-loop activation, is not the exception but the rule in clinical reentrant AT (62.5%). Moreover, whenever a patient presents with AT without prior ablation, or with a history of pulmonary vein isolation (PVI) only, or when a map shows localized reentry, a dual-loop mechanism is universal. In ≥3B atria, we never observed single-loop reentry around 1 CB with parallel activation around 2 NCBs, or

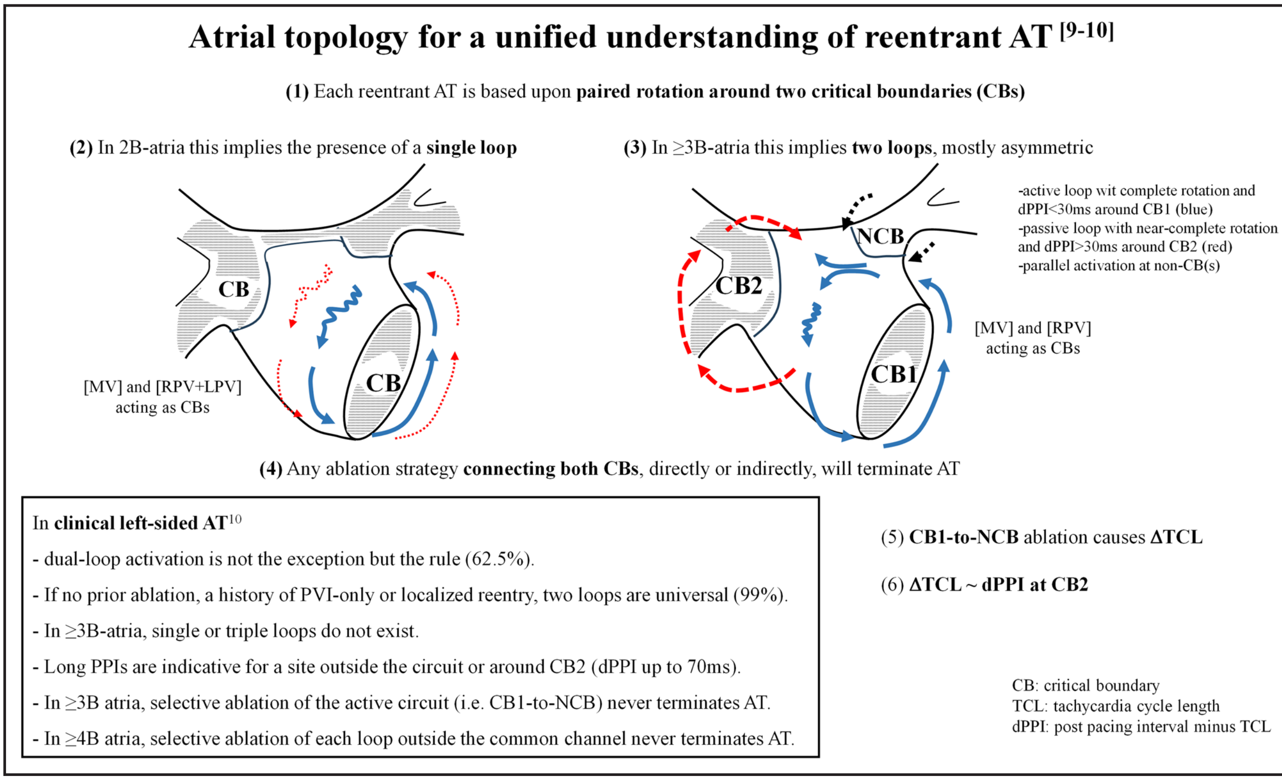

Figure 1. Atrial topology for a unified understanding of reentrant AT.
The 6 key elements of the topology construct, rooted in mathematical principles and validated in computational AT are shown. The clinical data set provided additional elements (see box). Triple loops using 3CBs do not exist. AT indicates atrial tachycardia; MV, mitral valve; NCB, noncritical boundary; RPV, right pulmonary veins; and TCL, tachycardia cycle length.

triple loops using 3CBs. Long PPIs were found to be indicative of sites outside the circuit, but also around CB2 (up to dPPI of 70 ms). Selective ablation of the active circuit (ie, outside the common channel) never terminated AT. In other words, the passive loop will always become active if not involved in the ablation process. In ≥4B atria, selective ablation of both circuits outside the common channel never terminated AT.

Of note, from a modeling standpoint, each atrium operates independently, with the interatrial connections representing 1 link between both spheres and with a net topological charge of zero per atrium.[9,10]

Database

All patients undergoing ablation for AF/AT at the Sint Jan Hospital Bruges gave written informed consent to be followed in a prospective database approved by the local institutional review committee. Beginning in October 2021, 88 cases of LA reentrant AT were prospectively mapped and ablated according to the topology-integrated workflow. Cases were excluded if reentry occurred in the right atrium (RA), if focal or breakthrough activation was observed in the LA, or if LA activation maps were incomplete. All procedures were performed under general anesthesia with double transseptal access.

EAM/ETM+TOP Workflow to Map and Ablate Reentrant AT

The workflow sequence for EAM/ETM+TOP is depicted in Figure 2. The aim of the central EAM/ETM framework together with analysis of propagation movies, was to identify single-loop or dual-loop patterns with active and passive loops.[2–5]

Electro-Anatomic Mapping

EAM of the LA was conducted using multielectrode catheters (PENTARAY, OCTARAY) with the CARTO system for automatic annotation of local activation time (LAT). A bipolar electrogram on the decapolar CS catheter served as the fiducial point for mapping and TCL measurement. Reentry was confirmed by mapping activation over the entire TCL around an anatomic (eg, mitral valve [MV], right pulmonary vein [RPV], or left pulmonary vein [LPV]) or nonanatomic boundary (eg, isolated line of block [LOB]), avoiding terms like macro and localized reentry due to their overlap.[12] On the activation map, LATs are color-coded with red and purple representing the earliest and latest LAT within the window of interest. Key anatomic structures such as MV, RPV, and LPV were almost invariably encircled as gray areas regardless of PV reconnection. Double potentials, defined as split electrograms with an isoelectrical segment, were annotated as blue tags. Visualization of loops was enhanced by analysis of propagation movies. Mapping of the RA was not consistently performed.

Entrainment Mapping

After interpreting wavefront propagation, entrainment pacing (10–15 ms shorter than TCL) was applied at multiple locations (except if TCL <200 ms). PPI values were collected and annotated as color-coded tags (green if the resulting dPPI was ≤30 ms, orange if dPPI 30–50 ms, black if dPPI >50 ms). In the

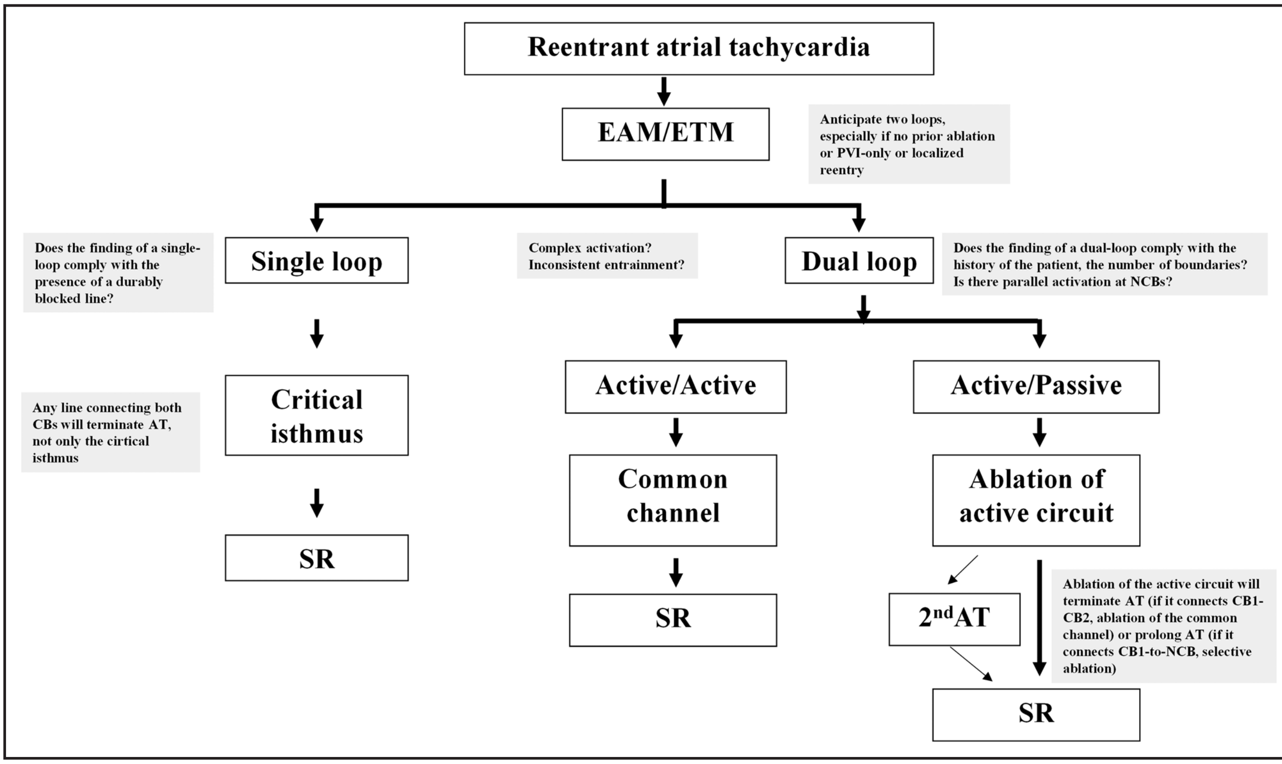

Figure 2. The EAM/ETM+TOP workflow.

The aim of the central EAM/ETM framework together with analysis of propagation movies was to identify single-loop or dual-loop patterns with active and passive loops. A topological mindset within EAM/ETM can enhance control at various stages of mapping and ablation phase (gray annotations). AT indicates atrial tachycardia; CB, critical boundary; EAM, electro-anatomical mapping; ETM, entrainment mapping; NCB, noncritical boundary; PVI, pulmonary vein isolation; SR, sinus rhythm; and TOP, topology.

case of 2 loops, loops with dPPI ≤30 ms and >30 ms were labeled as active and passive.[2–6]

Topological Thinking

Figure 2 illustrates at which stages topological thinking within EAM/ETM may enhance control. (1) In general, the topology construct encourages the operator to search for 2 loops in all cases (because 3B topology and dual-loop is the rule and not the exception and even universal if the patient had no prior ablation or a history of PVI-only or whenever localized reentry is evident). (2) Whenever EAM/ETM reveals 2 loops, this diagnosis can be verified by demonstrating roof and mitral conduction, by annotating minimally 3 boundaries, or by recognizing embracing activation around ≥1 NCBs. (3) In case EAM/ETM identifies an active and passive loop (which is the rule), thinking topology may enhance control during ablation. Ablation of the active circuit will stop AT if the line connects CB1 to CB2, whereas it will prolong AT (with a ΔTCL equal to dPPI at CB2) if the line connects CB1 to NCB. Indirect ablation (CB1-to-NCB-to-CB2) may be preferred whenever CB1-CB2 ablation is considered unsafe (phrenic nerve, esophagus) or challenging (Bachmann bundle). (4) When EAM/ETM suggests single-loop reentry, this diagnosis can be confirmed by identifying 2 boundaries only (implying either roof of mitral line block). (5) When faced with a single loop, thinking topology may enhance control during ablation. Whereas ablation is often applied at the narrowest isthmus with slow or mid-diastolic conduction, that region may be challenging (Bachmann bundle) or unsafe (phrenic nerve, esophagus) to ablate. Topology adds that any single line connecting both CBs is effective. (6) Whenever EAM/ETM leads to uncertainty, because of complex activation patterns, doubt on true versus pseudo-reentry,[12] triple loops or inconsistent dPPI values, annotation and differentiation of boundaries may solve the puzzle.

Ablation Protocol Aiming for AT Termination

Following EAM/ETM+TOP, an ablation strategy was outlined, prioritizing direct CB-CB ablation via 1 line. In some cases, indirect routes such as CB-NCB-CB (2 lines) or CB-NCB-NCB-CB (3 lines) were chosen. Predictions regarding dTCL were made based on topology, with anticipated slowing of TCL after CB1-NCB ablation and no TCL change after CB-NCB or CB2-NCB block.

Lines were deployed using contiguous/optimized radiofrequency lesions with the Thermocool SmartTouch ablation catheter (Biosense Webster, Inc). In line with prior work, we applied 45 W in a power-controlled mode at most sites, reducing power to 25 to 30 W near the esophagus (to prevent inadvertent thermal injury) and within the coronary sinus (to avoid steam pops).[13,14] The duration of each application was determined by achieving the target ablation index value: 400 for the posterior wall and coronary sinus, and 550 for the anterior wall, roof, and lateral mitral line.[13,14]

Epicardial radiofrequency and ethanol injection into the vein of Marshall were performed when endocardial radiofrequency did not lead to block over the lateral mitral line.[14] In some cases though vein of Marshall was performed before radiofrequency delivery. If AT unexpectedly continued despite proof of line block (double potentials, CS reversal, and changed entrainment), we remapped the second AT and repeated the workflow.

Ablation Protocol After Restoration of SR

Upon restoring sinus rhythm (SR), PVs and all previously ablated lines were re-assessed and re-ablated if necessary. In rare cases where roof and lateral mitral lines had not been previously ablated—or were not required for AT termination—these lines were ablated at the discretion of the operator. The guiding philosophy was to reduce the LA to a single-boundary sphere incapable of sustaining reentry.[9,10] However, systematic inducibility testing was not performed in a systematic way. Clinical evaluation, ECG and Holter-ECG were performed at 3, 6, and 12 months.

RESULTS

Overall

Median age was 72 (IQR, 67–77) years, TCL 270 (IQR, 240–300) ms, LA volume 168 (IQR, 134–195) mL. Prior AF ablation was performed in 82 (93%) patients (PVI-only 24; PVI-plus 58). One patient had undergone prior valve surgery. Number of mapping points was 4952 (IQR, 3251–7331). Entrainment was performed in 82 cases at 5 (IQR, 3–8) sites. Vein of Marshall was performed in 25 out of 55 deployed lateral mitral lines (45%).

Added Value of a Topological Mindset Within EAM/ETM: Case-Based Description

In the first case (TCL 304 ms; Figure 3), EAM/ETM together with analysis of the propagation movie revealed an evident counterclockwise loop with dPPI ≤30 ms around the mitral valve (MV) and clockwise rotational activity at the anterior wall. It was unclear though whether the anterior rotational activity reflected a true reentrant passive loop (with dPPI 41 ms) or pseudo-reentry near a LOB.[12] Because the patient was never ablated before and because embracing activation was observed both at the RPV and LPV, thinking topology helped to withhold the diagnosis of dual-loop activation with an active and passive loop with certainty. Topology also added extra control during ablation: a line connecting the MV to the LOB would (and did) terminate AT (because of CB1-CB2 connection). Without topology in mind, one could wrongly assume that a lateral mitral line would terminate the active loop with ensuing restoration of SR. A lateral mitral line, however, would always have led to a second AT with a TCL of ≈350 ms upon achieving block (because of CB1-NCB connection).[9] That information would also add extra control when an operator prefers to treat each reentrant AT with standard anatomic lesion sets (without mapping).

The second case (TCL 220 ms; Figure 4) illustrates how thinking topology offers control when deliberately opting for an indirect ablation strategy. EAM/ETM

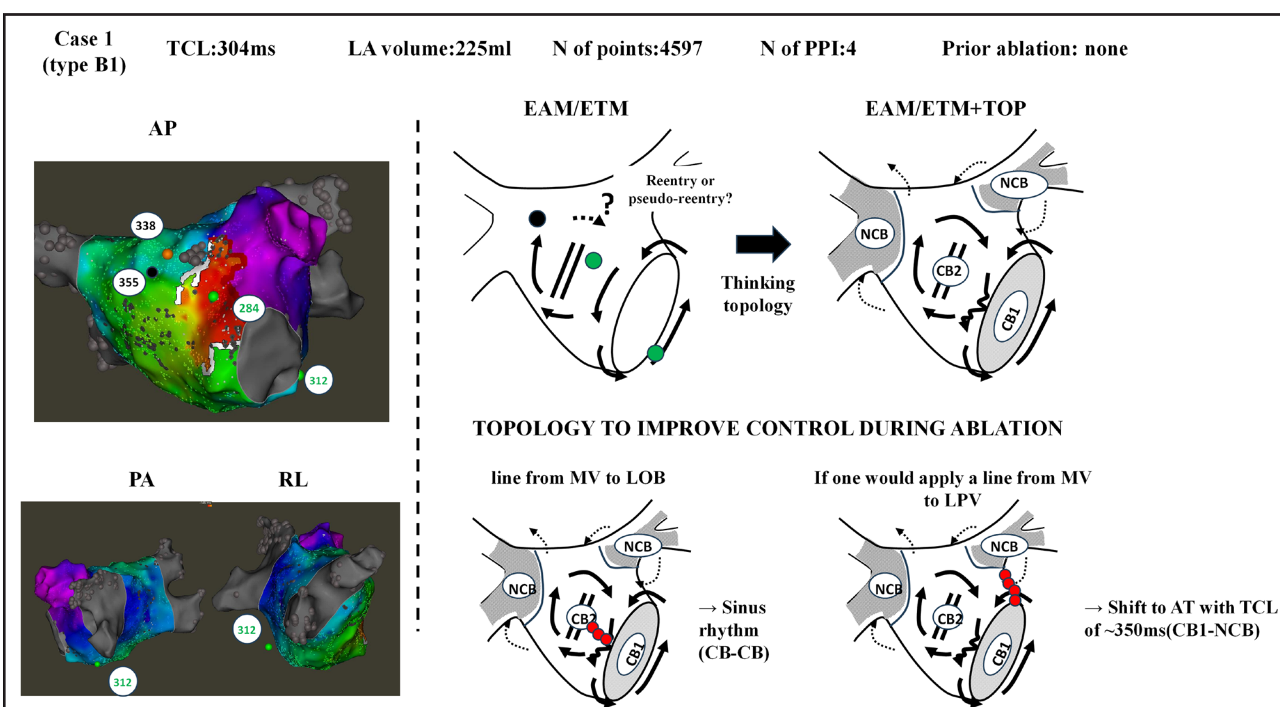

Figure 3. EAM/ETM+TOP in complex activation patterns.
AP indicates antero-posterior; AT, atrial tachycardia; EAM, electro-anatomical mapping; ETM, entrainment mapping; LA, left atrium; LOB, isolated line of block; LPV, left pulmonary veins; MV, mitral valve; NCB, noncritical boundary; PA, postero-anterior; PPI, post pacing interval; TCL, tachycardia cycle length; and TOP, topology.

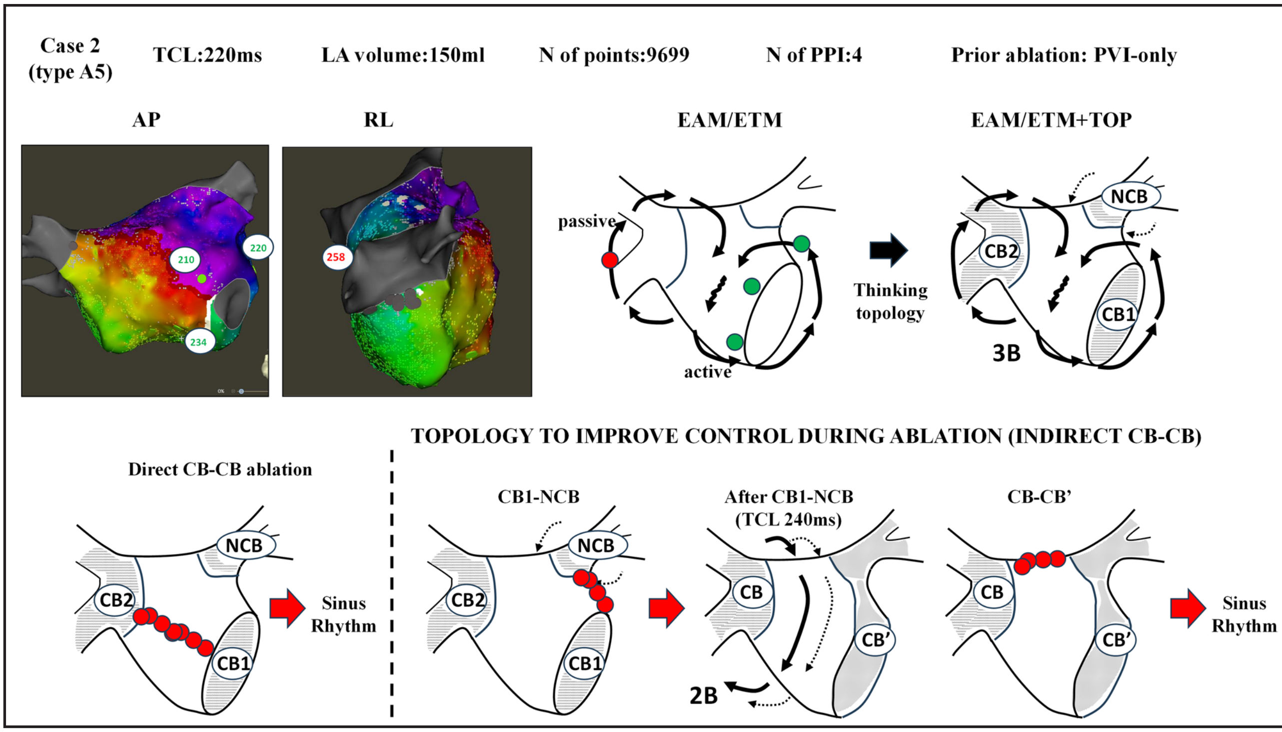

Figure 4. How adopting a topological mindset enhances control during ablation.
AP indicates antero-posterior; CB, critical boundary; EAM, electro-anatomical mapping; ETM, entrainment mapping; LA, left atrium; NCB, noncritical boundary; PPI, post pacing interval; PVI, pulmonary vein isolation; RL, right-lateral; TCL, tachycardia cycle length; and TOP, topology.

mapping was compatible with an active loop peri-MV and passive loop peri-RPV. A history of PVI-only implying conduction over the roof and the mitral isthmus together with embracing activation at the LPV confirmed this diagnosis from a topological perspective. To avoid a long linear ablation (5.9 cm) over the Bachmann bundle (direct CB-CB),

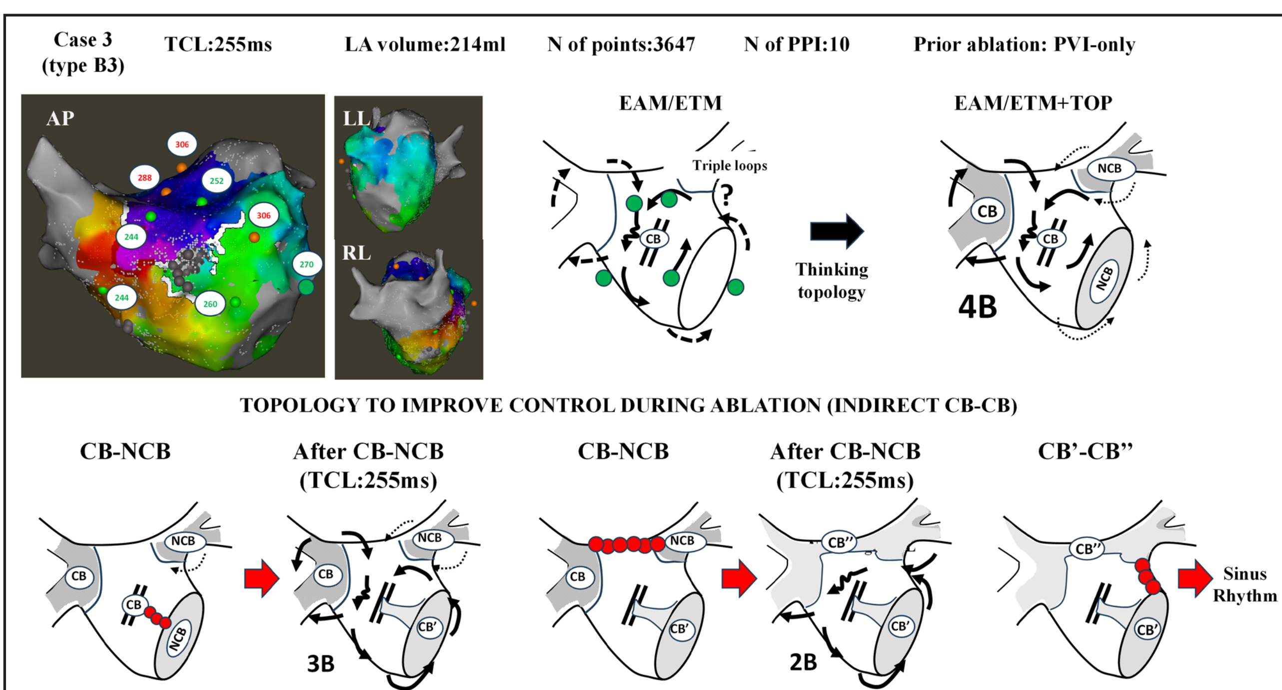

Figure 5. EAM/ETM+TOP in a complex case with multiple loops and boundaries.
AP indicates antero-posterior; CB, critical boundary; EAM, electro-anatomical mapping; ETM, entrainment mapping; LA, left atrium; LL, left lateral; NCB, noncritical boundary; PPI, post pacing interval; PVI, pulmonary vein isolation; RL, right lateral; TCL, tachycardia cycle length; and TOP, topology.

we performed an indirect CB-NCB-CB-strategy starting with a lateral mitral line (CB1-NCB) followed by a roof line. As anticipated by topology, the first line converted the AT into a single-loop AT in a 2B topology at a prolonged TCL of 240 ms. The a priori knowledge of an expected dTCL of 20 ms (≈dPPI at CB2 was 38 ms) helps to identify conduction block during ongoing AT and prevents unnecessary remapping. Finally, as expected, the roof line (connecting CB to the newly formed CB') restored SR.

The third case (TCL 255 ms; Figure 5) illustrates how a topological mindset may offer extra control during both mapping and ablation in a patient with localized reentry, multiple loops and boundaries. EAM/ETM together with analysis of the propagation movie showed an evident counterclockwise loop with short dPPI values at the anterior wall. However, extra loops with similar short PPI values were observed around the MV and RPV. Thinking topology (dual-loop must be present because of a history of PVI-only and triple loops using 3CBs do not exist) led to the diagnosis of dual-loop reentry with a second loop traced around the RPV. Despite the presence of a visual wider loop rotating en bloc around the MV and LOB (referred to as the outer loop in the topology construct),[10] the MV was activated by a parallel wavefront. Because a direct line connecting the RPV to LOB was perceived as challenging to block (thick tissue of the Bachmann bundle), we used topology to design and control an ablation strategy using 3 lines (see lower panels): a 9 o'clock line, roof line, and lateral mitral line. As expected, the first line converted the AT into a dual-loop tachycardia with the same TCL in a 3B topology (RPV and MV+LOB acting as CBs). The second line at the roof converted this AT into a single-loop reentry in a 2B topology (RPV+LPV and MV+LOB as CBs). The final step, being a lateral mitral line connected both CBs directly and terminated this AT (leaving the atrium with a single boundary). Although the sequence of lines does not matter, in this case, the chosen sequence illustrated how (against the intuition of some operators) selective ablation of each circuit (MV-to-LOB line and RPV-to-LPV line) cannot terminate dual-loop AT in a 4B atrium.

The fourth case (TCL 230 ms; Figure 6) finally illustrates how topology integration may also offer control in apparently straightforward single-loop cases. EAM/ETM was compatible with a single loop around the RPV (short dPPI). The diagnosis of a single loop was topologically confirmed by the presence of lateral line block (resulting in 2 boundaries only being the RPV and the MV+LPV). From a topological perspective any line connecting RPV to either MV or LPV will terminate this AT. In this case, we preferred to deploy a roof line (easy to block, previously ablated, easy to assess block) rather than to ablate the narrowest, slow-conducting channel on the anterior wall (which showed missing LATs compatible with epicardial conduction).

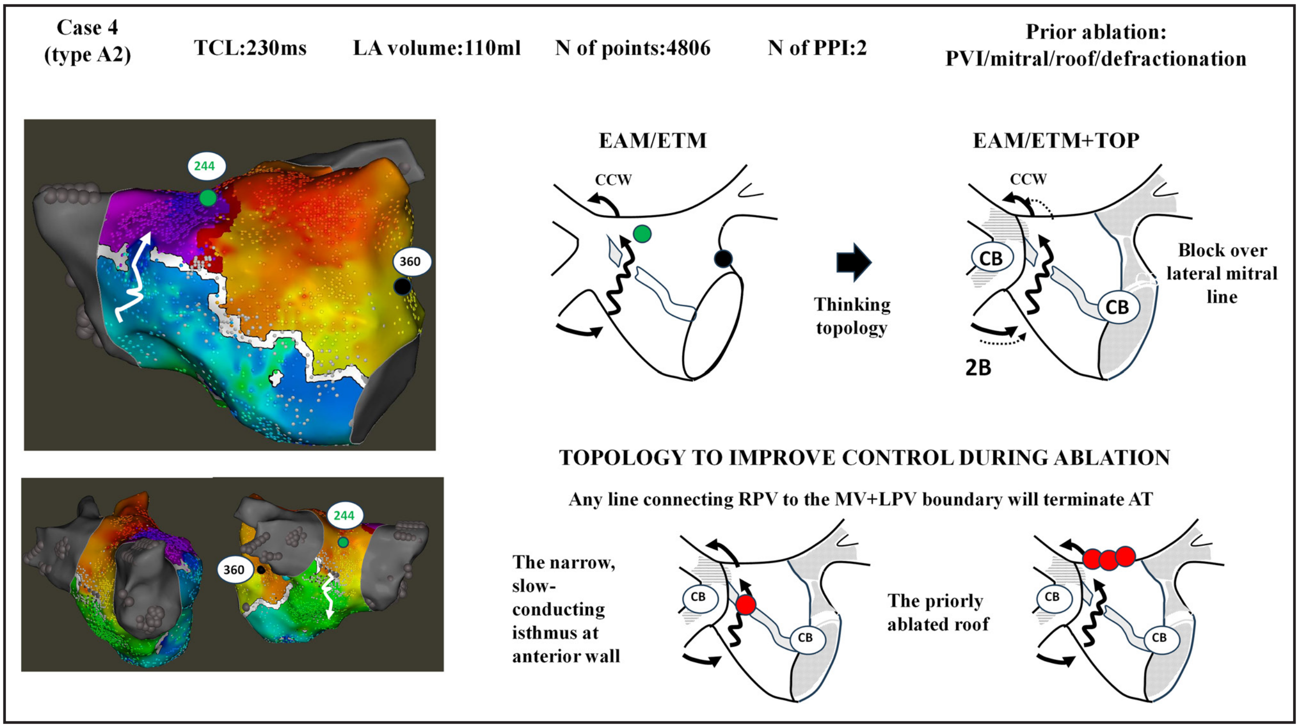

Figure 6. EAM/ETM+TOP in a single-loop reentrant case.
AT indicates atrial tachycardia; CB, critical boundary; EAM, electro-anatomical mapping; ETM, entrainment mapping; LA, left atrium; LPV, left pulmonary veins; MV, mitral valve; PPI, post pacing interval; PVI, pulmonary vein isolation; RPV, right pulmonary veins; TCL, tachycardia cycle length; and TOP, topology.

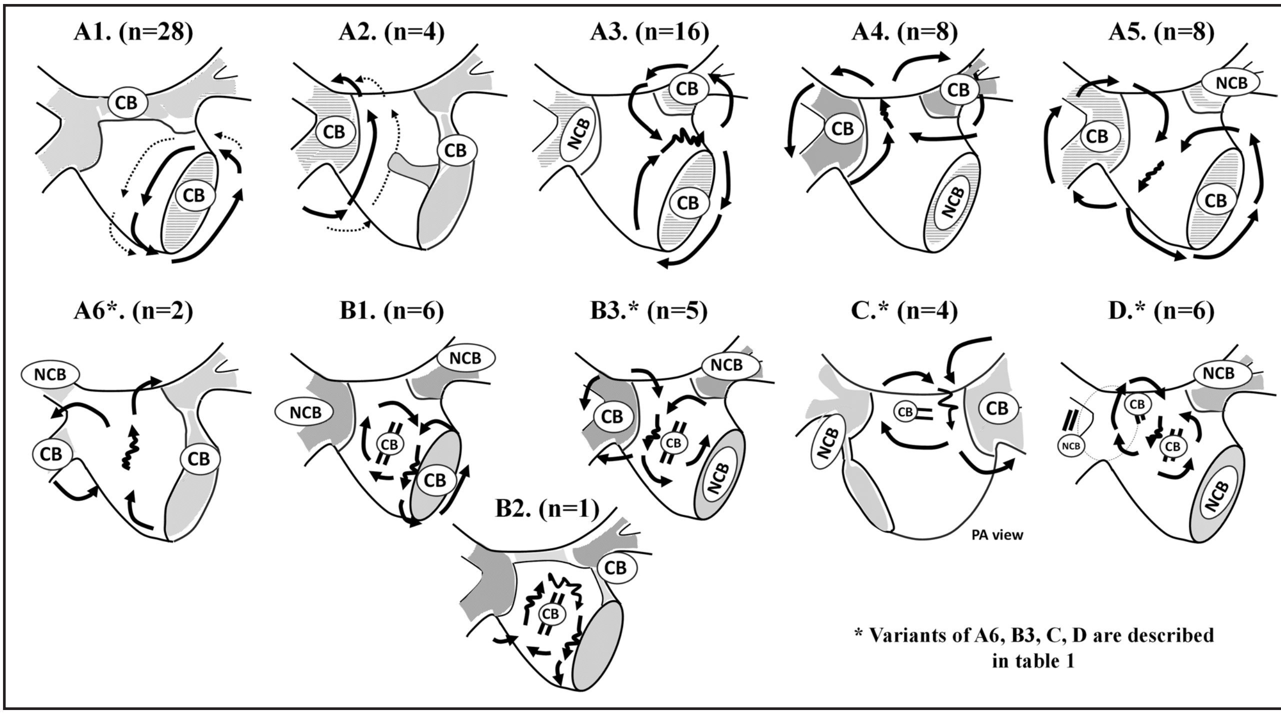

Figure 7. Spatial distribution of loops and boundaries.
See text for explanation. CB indicates crictial boundary; and NCB, noncritical boundary.

EAM/ETM+TOP Mapping in 88 Cases

The workflow of EAM/ETM+TOP was successfully applied in 87 out of 88 cases. The observed spatial distribution of loops is given in Figure 7. Overall, a single-loop reentry was identified in 33 (38%) cases, a dual-loop reentry in 55 (62%) cases. In patients with no prior ablation (n=6) or PVI-only (n=24), dual-loop reentry occurred in 100% of cases.

A detailed description of the spatial distribution of loop(s), CBs/NCBs is given in the Table.

Age and sex were not different between cases with anatomic loops only (A1–A6) versus cases involving nonanatomic (B-C-D) reentry (respectively 71±8 versus 70±10 years, 2-tailed Student *t* test *P*=0.593 and 83% versus 91% males, Fisher exact test *P*=0.504).

Direct CB-CB Ablation

Direct CB-CB ablation, performed in 75 cases, successfully terminated LA-AT in all, either into SR (n=69) or RA-AT (n=6; Table).

Topology-Controlled Indirect CB-CB Ablation

A CB-NCB-CB approach via 2 lines, performed in 9 cases, led to SR in all. Indirect CB-NCB-NCB-CB ablation via 3 lines, performed in 3 cases, successfully restored SR after completion of the lesion set in all.

In all 12 deliberately chosen indirect CB-CB ablations, the topology construct correctly predicted the TCL response and degree of TCL prolongation upon block of an intermediary line. In 5 symmetrical cases, CB-to-NCB ablation did not change TCL as expected. In 7 asymmetrical cases, connecting CB1-to-NCB prolonged TCL with a dTCL of 31±17 ms, in the same order of magnitude as dPPI at CB2 (47±15 ms).[10]

One Case of Failed Ablation

In 1 out of 88 cases (see case 5; Figure 8), apparent CB-CB ablation did not terminate AT. Post hoc, this was due to incorrect EAM/ETM+TOP mapping which initially suggested the diagnosis of a single clockwise peri-mitral loop (dPPI <30 ms) in the presence of 2 boundaries (MV and RPV/LPV; type A1) with an anterior LOB connected to the MV (associated with pseudo-reentry on the anterior wall). The correct diagnosis (B3), however, was true reentry at the anterior wall, with a second loop around the RPV+LPV (merged by a LOB) and a misleading outer loop around the MV and LOB. This diagnosis only became apparent by failed CB-CB ablation, as AT did not terminate but prolonged at the instant of lateral mitral line block (as evidenced by CS reversal). This ΔTCL response pointed to the presence of a CB1 and NCB at the edges of the lateral line. Finally, the AT was successfully terminated by ablation of the continuous fractionated electrograms at the conducting rim of tissue near the MV 9 o'clock.

Coexisting Right-Sided AT

In 7 cases, LA-AT coexisted, with RA-AT. In 6 cases, LA ablation led to conversion to RA-AT (Figure S1). In 1 out

Table. Results of Mapping and Ablation Guided by EAM/ETM+TOP

Type*	CB	CB	(n)	Direct	Indirect	Termination of LA
Anatomic loops only (n=66)						
A1	MV	RPV+LPV	28	28 (mitral)	…	26 SR, 2 RA
A2	RPV	MV+LPV	4	4 (roof)	…	3 SR, 1 RA
A3	MV	LPV	16	16 (mitral)	…	15 SR, 1 RA
A4	LPV	RPV	8	8 (roof)	…	8 SR
A5	MV	RPV	8	1 (anterior)	7 (roof/mitral)[4]	8 SR
A6	RIPV	MV+LPV	1	…	1 (carina/roof)[1]	1 SR
	LSPV	RPV+LIPV	1	1 (carina)		1 SR
Anterior LOB+Anatomy (n=12)						
B1	Ant LOB	MV	6	6 (9 o'clock)	…	5 SR, 1 RA
B2	Ant LOB	MV+RPV+LPV	1	1 (9 o'clock)		1 SR
B3	Ant LOB	RPV+LPV	3	2 (roof→LOB)	1 (by error)[1]	1 SR, 1 RA, 1 failed
	Ant LOB	RPV	2	…	2 (roof/mitral//9 o'c)	2 SR
Posterior LOB+Anatomy (n=4)						
C	Post-LOB	LPV	1	1 (roof)	…	1 SR
	Post-LOB	LSPV	1	1 (roof)	…	1 SR
	Post-LOB	MV	1	1 (mitral)	…	1 SR
	Post-LOB	RPV	1	1 (roof)	…	1 SR
LOB-LOB (n=6)						
D	LOB	LOB	6	4	2[2]	6 SR
Overall			88	75	13	81 SR, 6 RA, 1 failed

(n)=number of cases with TCL prolongation.
*ATs were grouped in 4 categories; (A) AT using anatomic-only CBs; (B) AT using a nonanatomic CB at the anterior wall and 1 anatomic CB; (C) LA-AT using a nonanatomic CB at the posterior wall and 1 anatomic CB; and (D) LA-AT using 2 nonanatomic CBs. AT indicates atrial tachycardia; CB, critical boundary; EAM, electro-anatomical mapping; ETM, entrainment mapping; LA, left atrium; LOB, isolated line of block; LPV, left pulmonary veins; LSPV, left superior pulmonary vein; MV, mitral valve; RA, right atrium; RIPV, right inferior pulmonary vein; RPV, right pulmonary veins; SR, sinus rhythm; TCL, tachycardia cycle length; and TOP, topology.

of 7 cases, we did upfront suspect a coexisting RA-AT (Figure S2). Ablating the CTI prolonged TCL by 100 ms upon block (unveiling the slower intrinsic TCL of LA-AT). The residual LA-AT was readily terminated by CB-CB ablation.

What Was Not Observed

We did not observe reentry using 1 CB or 3 CBs (confirming the topology theorem), presence of 2 independent loops coexisting without a common channel, triple loops using 3CBs, biatrial AT,[15] AT using LPV and MV+RPV as CBs, or AT using the LA appendage as one of the CBs. We did not observe that selective ablation of the active circuit (around CB1), outside the common channel, terminated AT (Figure 5).

Ablation Beyond Termination

At the end of the procedure, PVs were blocked in 88 cases, whereas roof and lateral lines were blocked in 80 cases. The atrium was reduced to a single-B topology in 79 cases. In select cases where inducibility was tested, our findings supported the hypothesis that reentrant AT remains inducible as long as 2 boundaries exist and ceases to be inducible when only one boundary remains (Figure S3).

Freedom From AT During Follow-Up

After a median follow-up of 356 (IQR, 228–537) days, 16 patients experienced AT recurrence (18%). Out of 13 undergoing repeat ablation, in 9 (69%) patients recurrence was due to reconduction over a CB-CB line, whereas in 4 (31%) patients, the mechanism of AT was focal in the presence of blocked lines.

Expected Termination Rates of Blind Ablation

A strategy of a blind mitral lateral line, roof line, or line connecting the MV 9 o'clock to an isolated LOB on the anterior wall, would terminate 45 (51%), 15 (17%), and 8 (9%) cases. Combing a lateral and roof line in all, would terminate 68 out of 88 (77%) cases. Combining a lateral, roof, and line connecting the MV 9 o'clock to an isolated LOB on the anterior wall would terminate 82 out of 88 (93%) cases.

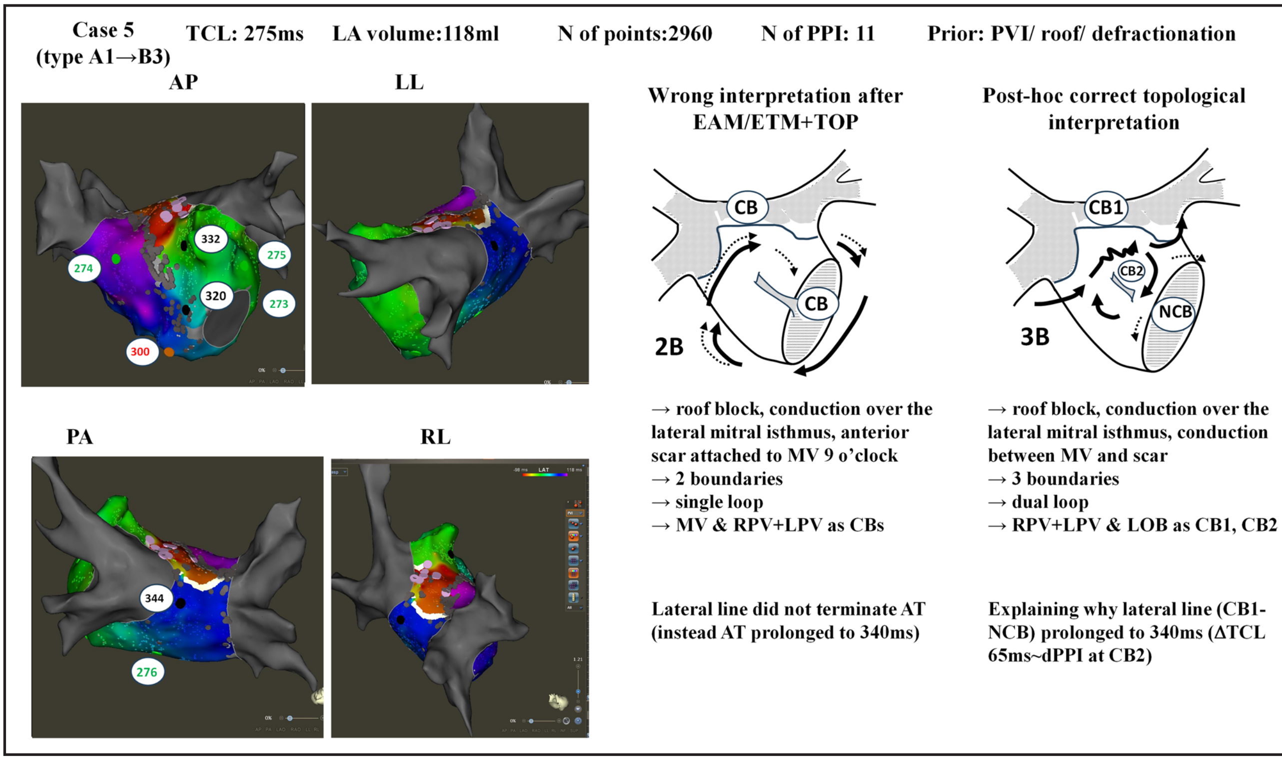

Figure 8. Failed EAM/ETM+TOP.
AP indicates antero-posterior; AT, atrial tachycardia; CB, critical boundary; EAM, electro-anatomical mapping; ETM, entrainment mapping; LA, left atrium; LL, left-lateral; LOB, isolated line of block; LPV, left pulmonary veins; MV, mitral valve; NCB, noncritical boundary; PA, postero-anterior; PPI, post pacing interval; PVI, pulmonary vein isolation; RL, right-lateral; RPV, right pulmonary veins; TCL, tachycardia cycle length; and TOP, topology.

DISCUSSION

Main Findings

(1) This study demonstrates how integrating topological thinking within EAM/ETM may enhance control during LA reentrant AT mapping and ablation; (2) The EAM/ETM+TOP workflow reliably identified reentrant loops in all but 1 case, with dual-loop activation observed in 62% of cases. In patients with no prior ablation, PVI-only history or localized reentry, dual-loop activation was universal (100%). (3) Direct or indirect CB-CB ablation lines consistently terminated LA reentrant AT. (4) The topology construct reliably anticipated TCL changes. (5) In ≈10% of cases a coexisting RA reentrant AT was present.

Advantages of Topological Thinking as an Adjunct to EAM/ETM

Our data suggest that integrating topology enhances but not replace well-established EAM/ETM. Together with analysis of propagation movies, EAM/ETM is highly effective, with AT termination rates of 90% to 100% and 1-year outcome of ≈65%.[2–5]

Some reentrant AT cases, however, are characterized by complex activation patterns (with multiple loops or pseudo-reentry) and inconsistent entrainment responses.[4–8,12,16] In addition, unexpected ablation-induced responses like no termination or switch to a sequential AT with longer TCL (up to 43%),[2] may occur throughout the ablation process. This may lead to time-consuming remapping and deployment of unnecessary, potentially harmful, lines.

The current study suggests that a topological perspective within EAM/ETM may enhance control at various timepoints during the mapping and ablation phases (Figure 2). An approach that enhances control without incurring additional costs or requiring extra maneuvers should be seen as a valuable advancement. While experienced operators may see benefit in complex cases, topology will readily help mapping and ablation for less-experienced operators holding common misconceptions about reentry mechanisms. These include beliefs such as: dual-loop is the exception rather than the rule (20–29%), 2 loops may coexist without a common channel; ablation should always target the slow conduction zone; selective ablation of the active circuit (ie, outside the common channel) will terminate AT; dual-loop ablation may shorten the TCL; selective ablation of both loops outside the common channel can terminate AT; and atria with multiple boundaries may still contain a single circuit with radial spread.

Thinking topology may prevent incorrect annotation of the critical isthmus and its aids in designing and executing indirect ablation strategies, whenever a direct strategy is considered challenging or unsafe. During indirect ablation itself, topology-driven TCL predictions help prevent unexpected response changes, facilitate block identification during ongoing tachycardia, allowing the operator to adhere to the initial strategy without remapping and with confidence until block is achieved. Vice versa, if an unexpected ΔTCL occurs upon ablation, reapplying topology may clarify the correct mechanism (Figure 5). Even in single-loop reentry, topology may expand ablation options beyond the narrowest slow-conducting channel, which is beneficial when this area is considered unsafe to ablate (near the esophagus, AV node, phrenic nerve, or LAA).

For EAM/ETM+TOP to claim superiority, a comparator (like an EAM/ETM-only approach or ablation using standard lesion sets) would be ideal. However, it is challenging to blind for topology (EAM/ETM-only) in mapping and ablation, once it is part of the thinking. On the other hand, we can state that in the present cohort, a strategy of blind anatomic lesion sets would have terminated 93% of AT cases.

Its challenging to determine if EAM/ETM+TOP also contributed to the excellent 1-year AT freedom of 82%, as outcomes depend on the extra lines deployed after termination and the durability of all ablation lines more than on the termination workflow itself. A critical unknown remains whether a strategy targeting all boundaries (theoretically eliminating reentry) is necessary to provide optimal freedom from recurrent AT.

Tips and Tricks for Optimally Using EAM/ETM+TOP

When used correctly (stable cycle length, accurate reference electrogram), EAM and propagation movies allow rapid, accurate identification of reentrant loop(s). However, verifying color-coded maps with electrogram review (eg, checking for double or fractionated potentials) is essential to overcome incorrect LAT annotation and interpolation errors falsely suggesting reentry.[12] At the anterior or posterior wall, however, it is challenging to differentiate between true rotation around an isolated LOB or passive curvature in the presence of a a LOB connected to an anatomic boundary (Figure 5). To facilitate EAM interpretation, one can easily annotate the anatomic boundaries as silent areas and typically, as shown by our work, the superior and inferior PVs can be annotated as 1 single boundary as well. Entrainment is not mandatory but may differentiate active from passive loops. A long PPI interval, however, can be indicative both for a location outside the reentrant circuit(s) as well as for a location around the second CB. In case of a passive loop, the PPI value at CB2 can help to predict TCL prolongation and assess block in indirect ablation strategies. However, PPI accuracy may be compromised by TCL variation, inaccurate tagging, far-field capture, or local conduction delay.

Throughout the article we have underscored how to optimally implement topology within EAM/ETM. The following tips and tricks may be of added value;

- The primary goal of a topologic mindset is to anticipate or verify the number of loops that will be or were detected. Only in the presence of roof or lateral mitral line block together with absence of a LOB, one can safely retain a 2B topology. Vice versa, if a patient only underwent no prior ablation or PV isolation only, there is always a ≥3B topology.
- Although boundary detection might be feasible by mapping during SR or differential pacing, only during AT one can differentiate CB from NCB.
- Being aware of the phenomenon of septal flash or an outer loop might prevent unexpected responses. In ≥3B topology, an outer loop encircles a CB and its neighboring NCB.[10] While this loop is not readily visible in most cases, in others, an outer loop might be mistaken as the active loop (see the failed case). Searching for a loop within a given loop can avoid this error.
- After EAM/ETM+TOP mapping, it is sensible to take the time to reflect on the potential ablation strategies. This time invest may offset later time-consuming remapping and switch in strategy. In case of an indirect ablation in an asymmetrical ≥3B-topology, it is wise to start with a CB1-NCB line because a shift in TCL (if in the order of magnitude of the PPI at CB2) can be used to recognize block.
- A shift to a second AT with prolonged TCL can be topologically attributed to either CB1-NCB ablation or ablation of the coexisting faster atrium. Other mechanisms for ablation-induced AT slowing are the presence of a tributarized isthmus,[17] ablation-induced conduction slowing, or endocardial but not epicardial block.[7,18] Shortening of the TCL upon ablation was not observed.

Limitations

This study requires updates by future studies from other centers. It is plausible that pulsed field ablation with creation of wider lesions might alter the spatial distribution of loops and boundaries. We did not study the role of reentry and topology in focal activation patterns because these cases were excluded. Descriptions of cases referred to the atrial wall as myocardium with 2-dimensional properties only. In rare cases, dissociated epicardial connections (at Bachmann's bundle, vein of Marshall, coronary sinus, or simply thicker tissue) may contribute to reentry.

Finally, we did not test systematically (re-)inducibility for AT at various timepoints during the procedure.

ARTICLE INFORMATION

Received January 24, 2025; accepted May 22, 2025.

Affiliations

Department of Electrophysiology, AZ Sint-Jan Hospital, Bruges, Belgium (M.D., M.D.S., J.M., M.E.H., B.D.B., C.F., R.T., J.-B.L.P.d.W., S.K.). Department of Physics and Astronomy, Ghent University, Belgium (R.V.d.A., S.H., N.V.).

Sources of Funding

None.

Disclosures

None.

Supplemental Material

Figures S1–S3

REFERENCES

1. Joglar JA, Chung MK, Armbruster AL, Benjamin EJ, Chyou JY, Cronin EM, Deswal A, Eckhardt LL, Goldberger ZD, Gopinathannair R, et al; Peer Review Committee Members. 2023 ACC/AHA/ACCP/HRS guideline for the diagnosis and management of atrial fibrillation: a report of the American College of Cardiology/American Heart Association Joint Committee on Clinical Practice Guidelines. *Circulation*. 2024;149:e1–e156. doi: 10.1161/CIR.0000000000001193
2. Derval N, Takigawa M, Frontera A, Mahida S, Konstantinos V, Denis A, Duchateau J, Pillois X, Yamashita S, Berte B, et al. Characterization of complex atrial tachycardia in patients with previous atrial interventions using high-resolution mapping. *JACC Clin Electrophysiol*. 2020;6:815–826. doi: 10.1016/j.jacep.2020.03.004
3. Takigawa M, Derval N, Frontera A, Martin R, Yamashita S, Cheniti G, Vlachos K, Thompson N, Kitamura T, Wolf M, et al. Revisiting anatomic macroreentrant tachycardia after atrial fibrillation ablation using ultrahigh-resolution mapping: implications for ablation. *Heart Rhythm*. 2018;15:326–333. doi: 10.1016/j.hrthm.2017.10.029
4. Takigawa M, Derval N, Maury P, Martin R, Denis A, Miyazaki S, Yamashita S, Frontera A, Vlachos K, Kitamura T, et al. Comprehensive multicenter study of the common isthmus in post-atrial fibrillation ablation multiple-loop atrial tachycardia. *Circ Arrhythm Electrophysiol*. 2018;11:e006019. doi: 10.1161/CIRCEP.117.006019
5. Patel AM, d'Avila A, Neuzil P, Kim SJ, Mela T, Singh JP, Ruskin JN, Reddy VY. Atrial tachycardia after ablation of persistent atrial fibrillation: identification of the critical isthmus with a combination of multielectrode activation mapping and targeted entrainment mapping. *Circ Arrhythm Electrophysiol*. 2008;1:14–22. doi: 10.1161/CIRCEP.107.748160
6. Pathik B, Lee G, Sacher F, Jaïs P, Massoullié G, Derval N, Bates MG, Lipton J, Joseph S, Morton J, et al. New insights into an old arrhythmia: high-resolution mapping demonstrates conduction and substrate variability in right atrial macro-re-entrant tachycardia. *JACC Clin Electrophysiol*. 2017;3:971–986. doi: 10.1016/j.jacep.2017.01.019
7. Takigawa M, Derval N, Martin CA, Vlachos K, Denis A, Kitamura T, Cheniti G, Bourier F, Lam A, Martin R, et al. A simple mechanism underlying the behavior of reentrant atrial tachycardia during ablation. *Heart Rhythm*. 2019;16:553–561. doi: 10.1016/j.hrthm.2018.10.031
8. Strisciuglio T, Vandersickel N, Lorenzo G, Van Nieuwenhuyse E, El Haddad M, De Pooter J, Kyriakopoulou M, Almorad A, Lycke M, Vandekerckhove Y, et al. Prospective evaluation of entrainment mapping as an adjunct to new-generation high-density activation mapping systems of left atrial tachycardias. *Heart Rhythm*. 2020;17:211–219. doi: 10.1016/j.hrthm.2019.09.014
9. Vandersickel N, Hendrickx S, Van den Abeele R, Verstraeten B. Impact of topology on the number of loops during macro-re-entrant atrial tachycardia. *Eur Heart J*. 2024;45:1586–1588. doi: 10.1093/eurheartj/ehae032
10. Duytschaever M, Van den Abeele R, Carlier N, Bezerra AS, Verstraeten B, Lootens S, Desplenter K, Okenov A, Nezlobinsky T, Shah D, et al. Atrial topology for a unified understanding of typical and atypical flutter. *Circ Arrhythm Electrophysiol*. 2024;17:e013102. doi: 10.1161/CIRCEP.124.013102
11. Santucci PA, Bhirud A, Vasaiwala SC, Wilber DJ, Green A. Identification of 2 distinct boundaries distinguishes critical from noncritical isthmuses in ablating atypical atrial flutter. *JACC Clin Electrophysiol*. 2024;10:251–261. doi: 10.1016/j.jacep.2023.09.024
12. Pathik B, Lee G, Nalliah C, Joseph S, Morton JB, Sparks PB, Sanders P, Kistler PM, Kalman JM. Entrainment and high-density three-dimensional mapping in right atrial macroreentry provide critical complementary information: entrainment may unmask "visual reentry" as passive. *Heart Rhythm*. 2017;14:1541–1549. doi: 10.1016/j.hrthm.2017.06.021
13. Wolf M, El Haddad M, Fedida J, Taghji P, Van Beeumen K, Strisciuglio T, De Pooter J, Lepièce C, Vandekerckhove Y, Tavernier R, et al. Evaluation of left atrial linear ablation using contiguous and optimized radiofrequency lesions: the ALINE study. *Europace*. 2018;20:f401–f409. doi: 10.1093/europace/eux350
14. Gillis K, O'Neill L, Wielandts JY, Hilfiker G, Almorad A, Lycke M, El Haddad M, le Polain de Waroux JB, Tavernier R, Duytschaever M, et al. Vein of marshall ethanol infusion as first step for mitral isthmus linear ablation. *JACC Clin Electrophysiol*. 2022;8:367–376. doi: 10.1016/j.jacep.2021.11.019
15. Zhang J, Cheng G, Deng C, Zhao A. Electrophysiologic mechanism and ablation strategy for macroreentrant biatrial tachycardias after Cox-maze procedures. *Heart Rhythm*. 2024;21:1853–1866. doi: 10.1016/j.hrthm.2024.03.1819
16. Shah D, Jaïs P, Takahashi A, Hocini M, Peng JT, Clementy J, Haïssaguerre M. Dual-loop intra-atrial reentry in humans. *Circulation*. 2000;101:631–639. doi: 10.1161/01.cir.101.6.631
17. Asirvatham SJ, Stevenson WG. Editor's perspective: the Isthmus of uncertainty. *Circ Arrhythm Electrophysiol*. 2014;7:175–177. doi: 10.1161/CIRCEP.114.001425
18. Rostock T, Drewitz I, Steven D, Hoffmann BA, Salukhe TV, Bock K, Servatius H, Aydin MA, Meinertz T, Willems S. Characterization, mapping, and catheter ablation of recurrent atrial tachycardias after stepwise ablation of long-lasting persistent atrial fibrillation. *Circ Arrhythm Electrophysiol*. 2010;3:160–169. doi: 10.1161/CIRCEP.109.899021