Robotic-enhanced hybrid ablation for persistent and long-standing atrial fibrillation: early assessment of feasibility, safety and efficacy

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Robotic-Enhanced Hybrid Ablation for Persistent and Long-Standing Atrial Fibrillation

METHODS
- 64 patients with persistent and long-standing AF
- Hybrid ablation (robotic epicardial → catheter endocardial
- January 2021 – June 2023, single-center, retrospective, study
- Rhythm follow-up at 3 and 12 months
- Feasibility, safety and efficacy

RESULTS
- Mean AF duration: 85 months
- Mean LAVI: 47.5 ml/m²
- CHA-DS2-Vasc: 2.7 ± 1.6
- BMI: 34.1 ± 6.3 kg/m²
- No thoracotomy/CPBP
- No deaths/CVA/esophageal injury
- 100% lesion set completion
- No blood products
- Average LOS 1.7 days
- No readmissions
- Freedom from AF at 3 months: 73.4%
- Freedom from AF at 12 months: 71.9%
- LAAO: 98.4% (OAC discontinuation: 89.8%)

IMPLICATIONS
A robotic approach to hybrid ablation of persistent and long-standing AF is feasible, safe and effective. It improves exposure of the intended anatomic targets, and favors short hospital stay and return to activity.
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ABBREVIATIONS AND ACRONYMS

AF= Atrial Fibrillation

AAD= Anti Arrhythmic Drugs

CHA2DS2-VASc= Congestive heart failure, Hypertension, Age, Diabetes, Stroke, Vascular Disease Score

HA= Hybrid Ablation

HAS-BLED= Hypertension, Abnormal renal/liver function, Stroke, Bleeding history or predisposition, Labile INR, Elderly, Drugs/alcohol concomitantly

ICS= Intercostal space

LAA= Left Atrial Appendage

LAAO= Left Atrial Appendage Occlusion

LAPW= Left Atrial Posterior Wall

LAVI= Left Atrial Volume Index

LSPV= Left Superior Pulmonary Vein

LSAF= Long-Standing Atrial Fibrillation

OAC= Oral Anticoagulation

PAF= Paroxysmal Atrial Fibrillation

PsAF= Persistent Atrial Fibrillation

PM= Pacemaker
58   PR= Pericardial Reflection
59   PVs= Pulmonary Veins
60   RSPV= Right Superior Pulmonary Vein
61   RE-HA= Robotic Enhanced Hybrid Ablation
62   SVC= Superior Vena Cava
63   TEE= Trans-Esophageal Echocardiography
CENTRAL MESSAGE

A robotic, epicardial, approach to hybrid ablation of persistent atrial fibrillation safely and effectively improves visualization and treatment of the target anatomy while promoting faster recovery.

PERSPECTIVE

Hybrid ablation, combining surgical epicardial and catheter endocardial approach to AF, has developed with remarkable results impacting the need for lifelong oral anticoagulation and anti-arrhythmic therapy with higher quality of life. Robotic technology may further decrease invasiveness and facilitate ablation of the intended anatomic targets, while accelerating recovery and improving outcomes.
Objectives: To assess feasibility, safety and early efficacy of robotic-enhanced epicardial ablation (RE-EA) as first stage of a hybrid approach to patients with persistent (PsAF) and long-standing atrial fibrillation (LSAF).

Methods: Single center, retrospective, analysis of patients with documented PsAF and LSAF who underwent RE-EA followed by catheter-guided endocardial ablation. Postoperatively, patients were monitored for major adverse events and underwent rhythm follow-up at 3 and 12 months.

Results: Between January 2021 and June 2023, we performed RE-EA in 64 patients (73.5% male, CHA2-Ds2-Vasc 2.7±1.6, BMI 34.1±6.3 kg/m²). Mean AF preoperative duration and left atrial volume index were, respectively, 85 months and 47.5 ml/m². Through robotic approach, the intended lesion set was completed in all patients without cardiopulmonary bypass support, conversion to thoracotomy/sternotomy, blood transfusions or perioperative mortality. The average LOS was 1.7 days, with only one patient requiring ICU admission and ≥65% of patients discharged within 24 hours. At follow-up, 2 (3.1%) patients experienced new left pleural effusion or hemidiaphragm paralysis requiring treatment. There were no readmissions related to AF, stroke, thromboembolic events or deaths. The mean interval between the epicardial and endocardial stages of the procedure was 5.9 months. Rhythm follow-up showed AF resolution in 73.4% and 71.9% of patients at 3 and 12 months, respectively.

Conclusions: RE-EA is a feasible and safe, first stage, approach for treatment of patients with PsAF and LSAF. It improves exposure of the intended targets, favors short hospital stay and return to activity with satisfactory AF treatment in the short-term.
Keywords: atrial fibrillation; hybrid ablation; left atrial posterior wall; robotic; rhythm follow-up
Atrial fibrillation (AF) is the most prevalent arrhythmia worldwide with a projected impact on 15137 million individuals, in the US alone, by 2050.\textsuperscript{1} The effects of paroxysmal AF (PAF), progressing into persistent (PsAF) or long-standing (LSAF), are particularly evident in the elderly where increased risk of congestive heart failure,\textsuperscript{2} cognitive dysfunction,\textsuperscript{3} stroke\textsuperscript{4} and premature death\textsuperscript{5} are known. Rhythm or rate control medical therapy, combined with lifelong oral anticoagulation (OAC) has showed no benefit in terms of mortality in large randomized trials.\textsuperscript{6,7} While catheter ablation of non-PAF is characterized by marginal results, surgical ablation (Cox-maze procedure) remains the treatment with the most favorable outcomes.\textsuperscript{8} Surgical treatment of AF, however, remains underperformed.

In an effort to replicate the success of the Cox-maze while further minimizing invasiveness, hybrid ablation (HA) techniques combining surgical epicardial ablation and catheter-based endocardial ablation have evolved. The most popular of these is the Convergent procedure\textsuperscript{9}, a two-stage multidisciplinary approach taking advantage of:

(a) surgical, closed-chest, epicardial access to the left atrial posterior wall (LAPW), typically via a sub-xiphoid window;

(b) percutaneous, catheter-based, mapping and endocardial completion of the intended epicardial lesion set.

The introduction of a robotic surgical platform consistently facilitates cardiothoracic surgical procedures and has already proved its efficacy for LAA occlusion.\textsuperscript{10} Aim of this study is to demonstrate safety, feasibility and efficacy of a robotic-enhanced approach to hybrid ablation (RE-HA) of PsAF and LSAF.
MATERIALS AND METHODS

Clinical Protocol and Patients

This study was reviewed by the Medical College of Wisconsin Institutional Review Board who approved the protocol (PRO00039130, approved December 30th, 2020, Supplemental Figure 1). Given the observational and retrospective nature of the study, the need for informed consent was waived.

This is a retrospective, single-center, analysis of safety and efficacy outcome data of 64 consecutive patients who underwent RE-HA at our institution between January 2021 and June 2023 (Figure 1). Indication for the procedure was based on the most recent HRS/EHRA/ECAS guidelines,\textsuperscript{11} where persistent AF is defined as continuous AF that is sustained beyond 7 days and either less (“early”) or more (“true”) than 3 months in duration, while long-standing AF is defined as continuous AF greater than 12 months in duration.

All surgical, epicardial, stages of the procedure were performed by the same two surgeons (MG and SS). The endocardial catheter stage was performed by one of 6 referring EP cardiologists. All intraoperative transesophageal echocardiography (TEE) was performed by the same TEE-credentialed cardiac anesthesiology team, while postoperative TEE follow-up was completed by the EP cardiologists involved in the hybrid procedures.

The endocardial ablation portion of the procedure was completed within 12 to 24 weeks.
Robotic epicardial ablation was performed with the Da Vinci Xi system. Intra-operative signal and impedance-guided tissue coagulation was achieved with a 3-cm, irrigated, Epi-sense unipolar probe (CDDP-4330, AtriCure, Inc., Mason, OH). A complete epicardial lesion set (Figure 2) was defined as:

a) Bilateral, semi-circumferential PVs ablation;
b) Complete box lesion set (connecting lesions between all PVs);
c) LAPW ablation (except for the area underneath the pericardial reflection);
d) Division of the ligament of Marshall;
e) Ablation of the left atrial ridge (extending from the LAA to the LSPV);
f) Exclusion of the LAA, via epicardial clip (AtriClip PRO2 or PROV devices).

Each epicardial lesion was completed with as many applications as needed to reach adequate drop in tissue conductance. Confirmation of LAPW and PVs isolation was obtained in patients who were successfully electrically cardioverted to restore sinus rhythm. This was performed intraoperatively through testing of bidirectional block with the use of an isolator, long, TT transpolar pen™ (AtriCure, Inc., Mason, OH) set on pacing/mapping mode. Conduction block was also inspected, confirmed or achieved during the endocardial, catheter-based, stage performed in the electrophysiology lab. Following the first 9 cases combining unilateral robotic with sub-xiphoid epicardial access, we modified the surgical approach to a total robotic procedure without sub-xiphoid incision.

Finally, the LAA was considered excluded if intra-operative TEE demonstrated no persistent intraluminal flow and a residual stump of <10 mm, as previously described. Findings would then be confirmed by TEE re-assessment at the time of the endocardial, catheter-based, stage and/or by gated cardiac CT-angiography (CTA).
Pre-operative Evaluation and Data Collection

All patients with PsAF and LSAF received full pre-operative assessment and underwent transthoracic echocardiography as well as CTA at Froedtert Hospital/Medical College of Wisconsin. Relevant demographics, baseline characteristics and risk-stratification data were collected in an Excel (Microsoft Corp., Redmond, WA) institutional protected database. Aside from the conduct of the procedure (robotic vs subxiphoid), all patients who underwent RE-HA were otherwise selected, managed and followed as per our institutional standard for patients treated with a hybrid epicardial/endocardial approach.

Outcome and follow-up data were obtained from longitudinal outpatient follow-up visits, electronic medical record review, phone interviews, rhythm data transmission from previously implanted devices (ICD, pacemakers or loop recorders), and reports of wearable heart rhythm monitors (7-day Holter) scheduled per protocol.

Surgical Technique (Video)

All procedures were performed via unilateral, left-sided, approach under general anesthesia with double-lumen endotracheal intubation for selective right lung ventilation, and placement of an esophageal temperature probe to constantly monitor for possible retrocardiac thermal spreading. Thorough TEE evaluation was performed in every patient to confirm the absence of intracardiac thrombi.
The patient is placed, supine, and the left chest slightly elevated with a roll placed cephalad-to-caudal, just below the shoulder. The left arm is slightly flexed at the elbow and padded on an armboard, below the left posterior axillary line. The left lung is deflated and four robotic ports are inserted in “hockey-stick” fashion (Figure 3). The camera is inserted through an 8-mm port placed first in the mid-to-anterior axillary line midway between the xiphoid and the sternal notch. Carbon dioxide insufflation at 8 mmHg pressure is used. The remaining ports are then placed under camera visualization with manual use of the 0-degree robotic scope. The use of long trocars with maximized clearance on the robotic arms is critical as this allows best separation of these arms and avoids collisions. The upper port is placed in correspondence of the LSPV, in the anterior axillary line, which usually corresponds to the 3rd or 4th intercostal space (ICS). Two more, long, 8-mm ports are then placed respectively at the level of the cardiophrenic angle, in the midclavicular line and anterior axillary line, usually at the 7th or 8th ICS. Finally, a 12-mm AirSeal port (ConMed Corp., Largo, FL) is placed in the 6th ICS at the level of the midaxillary line and serves as the bedside assistant port through which the LAA clip is ultimately placed. The robotic platform is docked and the left pleural cavity is inspected. Any adhesions are taken down and the lung allowed to retract posteriorly. The procedure is performed on a beating heart and does not require systemic heparinization or cardiopulmonary bypass. The left lateral aspect of the pericardium is then visualized, the phrenic nerve identified and the pericardium entered 1 cm posteriorly (supplemental figure 2). A longitudinal pericardiotomy is created in order fully expose the LAA, left PVs, pulmonary artery and obtuse margin. The anterior edge of the pericardiotomy is retracted superiorly with a braided suture externalized through the chest wall. The ligament of Marshall is identified and divided. The transverse sinus is then entered and the roof of the left atrium visualized all the way to the RSPV. The superior
vena cava and right atrial appendage are also identified (supplemental figure 3). The pericardial reflection (PR) around left and right PVs is developed with blunt dissection. The 3-cm Epi-sense unipolar probe is then inserted through the 12-mm AirSeal port and advanced within the transverse sinus to the confluence of the RSPV and left atrium. A “roof” ablation line is initiated at this level and extended proximally to the origin of the LSPV. Each targeted area is ablated at least twice based on measured tissue impedance and probe-detected electrical silence. The probe is then positioned on the antrum of the left PVs and an ablation line connecting the two vessels anteriorly is performed. The posterior pericardial space is then dissected and the unipolar probe positioned accordingly in order to perform circumferential isolation of both the left PVs. The heart is then retracted anteriorly and the LAPW inspected identifying both the right and left PVs, as well as the PR. The probe is then used to achieve semi-circumferential ablation of the right PVs. An ablation line is then created by connecting the inferior aspect of the RIPV to the inferior aspect of the LIPV (“floor line”) and the entire LAPW is ablated proceeding, in a parallel fashion, from the right towards the left PVs and from floor line to the PR (supplemental figure 4). Although we continuously monitor the esophageal temperature throughout the procedure, esophageal heating is rarely an issue as the heart is elevated, which minimizes thermal spreading. Once the LAPW is completed, we allow the heart to fall back to its normal anatomic position and return our attention to the LAA. One last ablation is performed to address the left atrial ridge. Next the LAA is sized at its base and occluded using an AtriClip, as previously described. We then undock the robot and remove all instruments, insert a 19 French Blake drain through one of the port sites and close all incisions. All patients are awakened from general anesthesia and extubated in the OR prior to be transferred to the recovery room.
Endocardial Ablation

At the time of endocardial ablation, patients underwent 3D CARTO endocardial mapping (Figure 4, insert A) followed by a standard ablation set including a roof line, LAPW between LSPV and RSPV, completion wide-area circumferential ablation for PVs isolation and, although rarely required following the epicardial stage, touch-up ablation of the inferior border of the LAPW between the inferior PVs (Figure 4, insert C). If typical or atypical flutter was also identified, patients had ablation lines to the mitral valve isthmus, between LIPV and the mitral valve annulus, or at the cavo-tricuspid isthmus at approximately 6 o’clock position between the tricuspid valve and the IVC.

Follow-up Protocol

Patients underwent telemetry monitoring after completion of each stage of the procedure. They also underwent both outpatient follow-up within 14 days of discharge as well as rhythm surveillance. The latter was performed at 3 and 12 months from the completion of the endocardial stage through: 1) intermittent 12-lead electrocardiograms obtained at each visit; 2) wearable 7-day Holter monitor; 3) rhythm analysis of pre-existing automated implantable cardioverted-defibrillator, pacemakers or loop recorders. Additionally, rhythm data were also retrospectively harvested for all readmissions and emergency department visits related to a diagnosis of “arrhythmia”.

Statistical Analysis

Continuous variables were expressed as mean with standard deviation while categorical variables were calculated as percentages of absolute numbers, using a standard Excel (Microsoft 365, Microsoft Corp) statistical package. Values were rounded to the first decimal.

A failure of the HA procedure was defined as any episode of AF, flutter, or atrial tachycardia longer than 30 seconds detected after a 3-month blanking period and at 12-month follow-up during continuous heartbeat rhythm monitoring tests obtained after discontinuation of class I/III anti-arrhythmic drugs (AAD). A failed epicardial LAA exclusion was defined as any appendage with either a stump >10 mm or residual flow (detected by TEE) or contrast enhancement (by CTA) at follow-up.

RESULTS

Between January 2021 and June 2023, a total of 64 RE-HA procedures were completed. All patients were treated according to protocol and each procedure was considered completed when both the robotic epicardial and the transcatheter endocardial ablations were performed in sequential fashion. Of the 64 patients treated, 37 underwent synchronized cardioversion of their pre-existing AF following anesthesia induction. Only the first 9 patients in the series underwent access to the LAPW through a sub-xiphoid pericardial incision.
Patient Characteristics

Preoperative baseline characteristics and clinical data are summarized in Table 1. More than 67% of patients was obese (BMI $\geq 30$ kg/m$^2$), with 21 (48.8%) and 9 (20.9%) being respectively class II (BMI 35-39) and class III (BMI $\geq 40$) obese. Approximately 65% of patients were symptomatic with mild exertion (NYHA Class II). None of the patients presented with significant, concurrent mitral, tricuspid or aortic valvular disease. Mean AF duration prior to surgery was 85 months and, in 70.3% of cases, this was persistent in nature. Fourth-eight patients (75%) had one or more failed cardioversion as part of their AF history. Medical management consisted of class I/III anti-arrhythmic in 65.6% and oral anticoagulation in 93.7% of cases.

At pre-operative echocardiographic evaluation, the mean EF was 54.6%. Not unexpectedly, the patients in this cohort presented with large left atria (mean LAVI 47.5 ml/m$^2$) with 24 (37.5%) of them being considered severely enlarged (>48 ml/m$^2$) per previously delineated criteria.$^{13}$ The mean CHA$_2$DS$_2$-Vasc was 2.7 and HASBLED was 3. Finally, 12 (18.7%) patients had a previously implanted rhythm-control device while 3 (4.7%) patients had previous cardiac surgery through sternotomy.

Observed intra-operative features are described in Table 2. Of the 3 patients with pre-existing sternotomy, two had prior CABG and one had septal myectomy. In addition, unexpected pericardial adhesions were identified in 4 other cases and successfully managed with the robotic approach. The epicardial ablation set could be successfully completed in all patients. One patient did not undergo LAAO due to very dense adhesions that did not allow for safe definition of its
margins. The patient subsequently underwent successful, percutaneous, placement of a
Watchman™ device. No adverse events occurred intraoperatively that lead to conversion of the
robotic approach to either thoracotomy or sternotomy, blood products transfusion, emergent
institution of cardiopulmonary bypass or abandonment of the procedure. All patients were
successfully extubated in the OR and admitted to a regular surgical floor. In one case, temporary
ICU admission was indicated due to patient’s known history of chronic congestive heart failure
and need for weaning of intravenous inotropic support.

The mean length of stay was 1.7 days while the mean interval between the two stages of
the HA procedure was 5.9 months.

Operative Morbidity and Mortality (≤ 30 days)

Post-operative complications are listed in Table 3. There were no operative deaths, stroke
or esophageal injuries. No patient required temporary or permanent pacemaker (PM) insertion
postoperatively. Three patients (4.7%) developed new pleural effusions and required
thoracentesis. In two cases (3.1%), we observed left hemidiaphragm paralysis. The first resolved
spontaneously with observation while the second required thoroscopic diaphragmatic plication.
Lastly, during the early stages of our experience, we observed 2 (3.1%) subxiphoid incisional
hernias that required repair.

Follow-Up
Imaging and clinical aspects observed during follow-up are reported in Table 4. To date, no deaths have been observed during follow-up. Four (6.4%) patients have been readmitted for reasons related to AF and all during the 90-days blanking period. Four (7.7%) patients, among those who didn’t already have one, required postoperative PM or ICD implantation for indications unrelated to AF (progression of pre-existing sick sinus syndrome and non-ischemic cardiomyopathy). No cerebral or peripheral thromboembolic events have occurred.

Proper exclusion of the LAA was appreciated at TEE performed during the endocardial catheter ablation stage. This was also confirmed in all but 1 (1.6%) patient through CTA obtained at 3 months.

Per intention to treat protocol, all patients were also scheduled for rhythm follow-up respectively at 3 and 12 months. In more than 80% of cases, rhythm surveillance was obtained through wearable continuous ambulatory or interrogation of previously implanted devices. Thirty-two (50%) patients have reached the 12 months follow-up timepoint thus far. At completion of the estimated blanking period, 47 (73.4%) patients were free from any supraventricular tachyarrhythmia lasting more than 30 seconds. Of those 32 patients that reached the 12-month follow-up, 23 (71.9%) were free from any supraventricular tachyarrhythmias per HRS guidelines. Within this subgroup, 17 (73.4%) already had class I/III AAD discontinued at the time of rhythm monitoring.

**DISCUSSION**

This study describes a single-institution experience focused on feasibility, safety and efficacy of RE-HA as part of a two-staged hybrid treatment of PsAF and LSAF. To our
knowledge, this is the first report of such technique and the largest series with short-term follow-up.

Although the Cox-maze procedure stands as the surgical gold standard with nearly 3 decades of excellent outcomes, its utilization requires cardiopulmonary bypass and cardiac arrest even when performed in a minimally invasive fashion. Moreover, despite defined practice guidelines for surgical treatment of AF, concomitant ablation is performed in <25% of AF patients undergoing surgery for other indications. In the meantime, the past decade has witnessed the introduction and growing popularity of combined, minimally invasive surgical/epicardial and percutaneous catheter/endocardial, hybrid approaches to PsAF. The minimally invasive nature of the surgical stage aims at enhancing patient recovery, while the endocardial catheter stage offers the possibility to achieve and confirm a transmural lesion set, as well as ablating structures not accessible epicardially (i.e. cavo-tricuspid or mitral isthmus lines).

This approach, supported by the results of the randomized controlled CONVERGE trial, raised interest in both the cardiology and surgical communities with increasing adoption even through slightly different iterations, including LAA and PVs management, in most centers. These last two features have been accomplished by combining either uni- or bilateral video-assisted thoracoscopy (VATS) to a subxiphoid pericardial access for the LAPW.

Understanding the rationale behind HA of AF requires recognizing how each anatomic structure contributes to the evolution of AF and can be differently affected by epicardial and/or endocardial treatment. While the role of PVs and their antral confluence as the primary factor in onset and maintenance of PAF is clearly established, as evidenced by the efficacy of PVs catheter ablation, intervention limited to such targets has demonstrated suboptimal outcomes for PsAF. There is increasing evidence that the pathogenesis of PsAF and LSAF may be linked
to the LAPW as this is the site where chronic changes preferentially occur. Progressive fibrosis and varying fiber orientation in this area leads to heterogenous conduction velocity, functional block and anisotropy that when coupled with shorter refractory periods favors local re-entry.\textsuperscript{21} In addition, the LAPW is in close proximity to the anterior wall of the esophagus and is traversed by a pericardial reflection connecting the left and right superior PVs separating the transverse from the oblique sinuses. These anatomical features can limit both the endocardial approach, due to elevated risk of esophageal thermal spreading, as well as the epicardial approach because of restricted access to the superior and lateral aspects of the LAPW. The combination of epicardial and endocardial ablation has therefore been found to be complimentary, helping overcome certain anatomical constraints (Figure 4B). Unfortunately, despite the success of the sub-xiphoid epicardial approach, limitations remain including suboptimal exposure of the intended anatomic structures, ability to safely complete the procedure and options to extend the ablation lesion set.\textsuperscript{22}

When we embarked on our minimally invasive HA program, the robotic platform was utilized primarily to facilitate LAAO via AtriClip placement. The robotic technology, based on our institutional expertise and asset availability, allowed us to subsequently include the entire epicardial ablation lesion set exclusively through the left chest. In time, we have found that such approach offers several potential advantages compared to others, including sub-xiphoid pericardioscopy or standard VATS. First, its feasibility is entirely independent from body habitus and size. When using the sub-xiphoid approach, we found that with larger patients the insertion of a pericardioscopic cannula and the advancement of the ablating probe were challenging due to forced angulation required to adequately perform the procedure (supplemental figure 5B).
When considering the average BMI in our cohort, the evolution towards a unilateral, left robotic approach eliminated this difficulty. Additionally, especially in larger patients, a sub-xiphoid incision is not free of complications and indeed in our first 9 procedures using sub-xiphoid, pericardioscopic access to the LAPW, two patients experienced wound complications, including incisional hernia. We feel the most effective way to eliminate this complication is to avoid a sub-xiphoid incision altogether.

Second, the exposure offered by a lateral robotic approach is superior and decreases the frequency of esophageal heating. The insertion of a sub-xiphoid pericardioscopic cannula with its intrinsic “tunnel” view (supplemental figure 5C) appeared to cause a rather limited excursion of the ablating probe hindering its precise placement, with frequent overheating of the esophagus, as well as need for frequent repositioning of both thoracoscopic camera and probe. As previously reported, the mid-lower aspect of the LAPW has an average distance from the anterior wall of the esophagus of just 2.6 mm and extends downward for several cm representing a limiting factor. The robotic-assisted approach takes advantage of its lowermost port to gradually retract the infero-posterior aspect of the heart upward hence increasing the distance between LAPW and the retro-pericardial structures with a much-improved exposure that is hemodynamically well tolerated. The increased distance between LAPW and esophagus is protective against its overheating. Very rarely does the esophageal temperature require cessation or pauses of the ablation, therefore leading to a more efficient process. Prominent curvature of the thoracic spine, large-sized left atria and pre-operative severity of ventricular dysfunction proved not to impact either the flow of the procedure or completion of the lesion set.

Thirdly, we opted for a single, left-sided, access as previous reports have also suggested that unilateral approach not only has no appreciable detrimental effects on the overall success of
the hybrid procedure, but may also be associated with increased pulmonary tolerance and a
significantly shorter LOS.\textsuperscript{24} Similarly, epicardial lesions such as superior to inferior vena cava
linear ablation typically achieved through a right lateral approach do not significantly impact
recurrence of atrial arrhythmias in the short-term, and are best addressed through a cavo-
tricuspid flatter line ablation performed at the time of endocardial completion.\textsuperscript{22} Moreover,
camera 3D-magnification and intrathoracic 360-degree robotic instruments articulation allow for
decreased rib traumatic injury, more precise identification and dissection of targeted anatomic
structures, as well as safer navigation through pericardial adhesions of either inflammatory or
post-sternotomy origin, as we found in 7 of our patients. These cases would presumably have
been aborted if attempted via a sub-xiphoid approach and, although they may have been
completed using standard thoracoscopic instrumentation, this would have been a significant
challenge.

The decreased invasiveness offered by robotic surgery has profound impact on post-
operative care. No blood products were administered and, except for one patient affected by
chronic congestive heart failure and requiring weaning from pharmacologic support in the ICU,
all others recovered effectively on the regular floor with an average LOS of 1.7 days. At post-
operative follow-up, patients reported minimal left-sided discomfort and exhibited faster
resumption of daily life activities.

One final technical consideration is that the proposed technique was developed using
robotic instruments and epicardial ablation tools designed for very different purposes. Should
this approach confirm its promising initial results and tools be developed specifically for AF
treatment, it is foreseeable that the procedure may be further streamlined, thus becoming widely
reproducible. This may, in turn, allow such technique to be applied to an even greater number of
AF patients, a population which is currently undertreated. Nonetheless, incorporating such approach into a clinical practice may require basic robotic thoracic skills with proper initial patient selection based on favorable anatomy and minimal comorbidities, as well as 5 proctored cases.

While all the above noted advantages are beneficial, the use of the robotic platform for HA would be unsatisfactory if not associated with promising results as far as treatment of AF. In our series, 47 (73.4%) patients maintained a sinus rhythm at 3 months from completion of both stages. Following this timepoint, 23 patients previously on class I/III AAD, had these discontinued. Half of our cohort reached the 12 months rhythm follow-up since implementation of our hybrid approach and the observed trend towards freedom from supraventricular tachyarrhythmias remained consistent among all those patients where class I/III anti-arrhythmic drugs had been discontinued before this point in time (13 out of 23, 73.9%). Cardiac CTA and/or TEE demonstrated effective LAAO in all (98.4%) but one patient, confirming the reported feasibility of this critical step of AF management when performed with robotic technology. This lead to discontinuation of OAC in 53 (89.8%) of patients.

The presented approach appears to also seamlessly favor bidirectional block testing by means of either commercially available pacing/sensing pens or more sophisticated, high density, epicardial mapping systems when available. Validation of epicardial ablation during hybrid treatment of AF has been questioned in the past due to the possibility of false-positive results related to tissue edema. Such assumption, however, has been challenged and even in unilateral left-sided thoracoscopy where the RSPV can be difficult to reach, epicardial bidirectional conduction block appears to correlate well with findings obtained through endocardial testing.
In terms of clinical efficacy, our results are in line with contemporary, larger, series and systematic meta-analyses utilizing a similar unilateral approach where freedom from AF without AAD ranges between 65 and 80%. We observed lower rates of perioperative complications, ICU requirement, LOS and readmission rate that could make the robotic approach more appealing to patients and further enhance multidisciplinary approach to AF treatment.

**Limitations**

This study presents several limitations. It is a single-center, retrospective study conducted at a tertiary center that represents a state-wide referral for management of patients with all types of atrial tachy-arrhythmias. The institution routinely manages a high volume of robotically-assisted cardiothoracic surgery cases and the authors are surgeons with advanced robotic skills, which may not reflect the general practice. In addition, the patient sample size offers difficulties in terms of adjusting for baseline differences and generalization of the results in the long-term. This is in part also due to factors such as surgeons’ experience, performance of the early cases with a partially different surgical approach (i.e. subxiphoid incision), and lack of reliable rhythm follow-up in 18% of patients (i.e. continuous EKG rather than wearable monitors due to restrictions related to COVID-19 pandemic). Studies comparing robotic to other thoracoscopic approaches for the epicardial stage of hybrid AF ablation, including longer follow-up, will be necessary. Finally, the feasibility of this approach in patients with prior sternotomy will require evaluation in a larger cohort.

**CONCLUSIONS**
Hybrid management of PsAF or LSAF where a robotic-enhanced approach is utilized for the epicardial ablation stage is feasible, safe and effective in the short-term. The unique technical advantages offered by robotic surgery also favor shorter LOS and prompt recovery.

REFERENCES


**TABLES**

**Table 1.** Baseline characteristics of RE-HA patients (N= 64)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>64.5 ± 9</td>
</tr>
<tr>
<td>Male Sex</td>
<td>47 (73.4 %)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>34.1 ± 6.3</td>
</tr>
<tr>
<td>NYHA Class</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>5 (7.8 %)</td>
</tr>
<tr>
<td>II</td>
<td>42 (65.6 %)</td>
</tr>
<tr>
<td>III</td>
<td>17 (26.5 %)</td>
</tr>
<tr>
<td>Arrhythmia History</td>
<td></td>
</tr>
<tr>
<td>AF Duration (months)</td>
<td>85 ± 68.5</td>
</tr>
<tr>
<td>AF Type</td>
<td></td>
</tr>
<tr>
<td>Paroxysmal</td>
<td>4 (6.2%)</td>
</tr>
<tr>
<td>Persistent</td>
<td>45 (70.3%)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
<td>-----</td>
</tr>
<tr>
<td>Long-standing</td>
<td>15 (23.4%)</td>
</tr>
<tr>
<td>Previous Cardioversion</td>
<td>48 (75%)</td>
</tr>
<tr>
<td>CHA(_2)DS(_2)-VASC</td>
<td>2.7 ± 1.6</td>
</tr>
<tr>
<td>HAS-BLED</td>
<td>3 ± 1.4</td>
</tr>
<tr>
<td>Medical History</td>
<td></td>
</tr>
<tr>
<td>Hypertension</td>
<td>50 (78.1%)</td>
</tr>
<tr>
<td>Diabetes</td>
<td>20 (31.2%)</td>
</tr>
<tr>
<td>Dyslipidemia</td>
<td>32 (50%)</td>
</tr>
<tr>
<td>Obesity</td>
<td>43 (67.2%)</td>
</tr>
<tr>
<td>Thyroid Disorders</td>
<td>12 (18.7%)</td>
</tr>
<tr>
<td>Obstructive Sleep Apnea</td>
<td>29 (45.3%)</td>
</tr>
<tr>
<td>Anxiety Disorder</td>
<td>10 (15.6%)</td>
</tr>
<tr>
<td>Stroke/TIA</td>
<td>7 (10.9%)</td>
</tr>
<tr>
<td>Chronic Kidney Disease</td>
<td>7 (10.9%)</td>
</tr>
<tr>
<td>HFrEF</td>
<td>9 (14%)</td>
</tr>
<tr>
<td>Coronary Artery Disease</td>
<td>12 (18.7%)</td>
</tr>
<tr>
<td>COPD</td>
<td>5 (7.8%)</td>
</tr>
<tr>
<td>Pre-Operative Management of AF</td>
<td></td>
</tr>
<tr>
<td>Class I/III Anti-Arrhythmic Drug</td>
<td>42 (65.6%)</td>
</tr>
<tr>
<td>Oral Anticoagulant</td>
<td>60 (93.7%)</td>
</tr>
<tr>
<td>Pre-operative Echocardiogram</td>
<td></td>
</tr>
<tr>
<td>LV Ejection Fraction (%)</td>
<td>54.6 ± 10.3</td>
</tr>
<tr>
<td>LA Volume (ml)</td>
<td>104.5 ± 41.3</td>
</tr>
<tr>
<td>Procedure</td>
<td>Value</td>
</tr>
<tr>
<td>-----------</td>
<td>-------</td>
</tr>
<tr>
<td>LA Volume Index (ml/m²)</td>
<td>47.5 ± 18</td>
</tr>
<tr>
<td>Previous PM/ICD/CRT Implantation</td>
<td>12 (18.7 %)</td>
</tr>
<tr>
<td>Prior Sternotomy</td>
<td>3 (4.7%)</td>
</tr>
</tbody>
</table>

**Table 2.** Procedural features (N= 64)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between stages (months)</td>
<td>5.9 ± 4.1</td>
</tr>
<tr>
<td>Epicardial Procedure Completion</td>
<td></td>
</tr>
<tr>
<td>Lesion Set</td>
<td>64 (100%)</td>
</tr>
<tr>
<td>LAAO</td>
<td>63 (98.4%)</td>
</tr>
<tr>
<td>Aborted</td>
<td>0</td>
</tr>
<tr>
<td>Conversion to Thoracotomy/Sternotomy</td>
<td>0</td>
</tr>
<tr>
<td>Cardiopulmonary Bypass Requirement</td>
<td>0</td>
</tr>
<tr>
<td>Blood Products Transfusion</td>
<td>0</td>
</tr>
<tr>
<td>Admission to ICU</td>
<td>1 (1.5%)</td>
</tr>
<tr>
<td>Length of Stay (days)</td>
<td>1.7 ± 1.3</td>
</tr>
</tbody>
</table>
### Table 3. Postoperative Complications (N= 64)

<table>
<thead>
<tr>
<th>Complication</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Death (at 30 days)</td>
<td>0</td>
</tr>
<tr>
<td>Atrio-esophageal fistulas</td>
<td>0</td>
</tr>
<tr>
<td>Costochondral Fracture</td>
<td>1 (1.5%)</td>
</tr>
<tr>
<td>Hemidiaphragm Paralysis</td>
<td>2 (3.1%)</td>
</tr>
<tr>
<td>Pleural effusion/Thoracentesis</td>
<td>2 (3.1%)</td>
</tr>
<tr>
<td>Pacemaker Insertion (at 30 days)</td>
<td>0</td>
</tr>
<tr>
<td>Subcutaneous Emphysema</td>
<td>1 (1.5%)</td>
</tr>
<tr>
<td>Stroke/TIA</td>
<td>0</td>
</tr>
<tr>
<td>Peripheral Thromboembolism</td>
<td>0</td>
</tr>
<tr>
<td>Wound complication</td>
<td>2 (3.1%)</td>
</tr>
</tbody>
</table>
**Table 4. Follow-up**

<table>
<thead>
<tr>
<th>Type of Follow-Up</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Follow-up (months, range)</td>
<td>11.4 (1 - 27)</td>
</tr>
<tr>
<td>Serial EKG/Clinical</td>
<td>12 (18.7%)</td>
</tr>
<tr>
<td>PM/ICD/CRT Interrogation</td>
<td>14 (21.9%)</td>
</tr>
<tr>
<td>Loop Recorder</td>
<td>7 (11%)</td>
</tr>
<tr>
<td>7-Day Holter</td>
<td>31 (48.4%)</td>
</tr>
<tr>
<td>Readmission (AF related)</td>
<td>4 (6.2%)</td>
</tr>
<tr>
<td>LAA Exclusion (at 3 months)</td>
<td>62/63 (98.4%)</td>
</tr>
<tr>
<td>Pacemaker Insertion</td>
<td>4 (7.7%)</td>
</tr>
<tr>
<td>Mortality</td>
<td>0</td>
</tr>
<tr>
<td>AF-related</td>
<td>0</td>
</tr>
</tbody>
</table>
Non-AF related

<table>
<thead>
<tr>
<th>Follow-up</th>
<th>64/64 (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 months</td>
<td>32/64 (50%)</td>
</tr>
<tr>
<td>12 months</td>
<td>47/64 (73.4%)</td>
</tr>
<tr>
<td>Freedom from AF at 3 months</td>
<td>23/32 (71.9%)</td>
</tr>
<tr>
<td>Freedom from AF at 12 months</td>
<td>53/59 (89.8%)</td>
</tr>
<tr>
<td>OAC discontinuation at 12 months</td>
<td></td>
</tr>
</tbody>
</table>

**LEGENDS**

**Central Picture.** Access to left atrial posterior wall and pulmonary veins: (A) Sub-xiphoid vs (B) unilateral, left-sided, robotic view.

**Figure 1.** Patient cohort and features of the study.

**Figure 2.** Diagram of the robotic-enhanced epicardial ablation lesion set.

**Figure 3.** Robotic port placement on the left hemithorax.

**Figure 4.** Electrocardiographic mapping showing extent of epicardial ablation (A, in red) progressively tapering into the pericardial reflections (purple), and endocardial, catheter-based, completed ablation of the LAPW and PVs (C). Diagram of posterior pericardial reflections (B, courtesy of John-Ross D. Clarke, MD).
Supplemental figures

Supplemental Figure 1. Institutional protocol for treatment and follow-up of patients with PsAF and LSAF undergoing RE-HA.

Supplemental Figure 2. Robotic view of the left lateral aspect of the pericardium and phrenic nerve (PN).

Supplemental Figure 3. Robotic magnification of the sinus transversus, following division of the ligament of Marshall, with optimized view of the roof of the left atrium (R), right atrial appendage (RAA), superior vena cava (SVC), and left atrial appendage (LAA).

Supplemental Figure 4. Robotic magnification of the left atrial posterior wall (LAPW) with optimized view of the right inferior pulmonary vein (RIPV), right superior pulmonary vein (RSVP), pericardial reflection (PR), left inferior pulmonary vein (LIPV) and “floor” line.

Supplemental Figure 5. Diagram of the sub-xiphoid incision and pericardial access to the LAPW (A), trajectory of the pericardioscopic cannula in the mediastinum (B), view of the LAPW through the pericardioscopic cannula (PC).
Robotic-Enhanced Hybrid Ablation for Persistent and Long-Standing Atrial Fibrillation

METHODS
- 64 patients with persistent and long-standing AF
- Hybrid ablation (robotic epicardial → catheter endocardial)
- January 2021 – June 2023, single-center, retrospective, study
- Rhythm follow-up at 3 and 12 months
- Feasibility, safety and efficacy

RESULTS
- Mean AF duration: 85 months
- Mean LAVI: 47.5 ml/m²
- CHA-DS2-Vasc: 2.7 ± 1.6
- BMI: 34.1 ± 6.3 kg/m²
- No thoracotomy/CPBP
- No deaths/CVA/esophageal injury
- 100% lesion set completion
- No blood products
- Average LOS 1.7 days
- No readmissions
- Freedom from AF at 3 months: 73.4%
- Freedom from AF at 12 months: 71.9%
- LAAO: 98.4% (OAC discontinuation: 89.8%)

IMPLICATIONS
A robotic approach to hybrid ablation of persistent and long-standing AF is feasible, safe and effective. It improves exposure of the intended anatomic targets, and favors short hospital stay and return to activity.
Robotic-Enhanced Hybrid Ablation of Persistent and Long-Standing AF
(Froedtert Hospital/Medical College of Wisconsin Protocol)

Inclusion Criteria

- All adult patients with diagnosis of persistent or long-standing AF, refractory to medical and/or catheter-ablation therapy

Exclusion Criteria

- Concomitant severe coronary or valvular/structural abnormalities for which surgery is indicated
- Prior AV nodal ablation with permanent pacemaker placement
- Pre-existing severe cardiomyopathy (EF <30%)
- Severe pulmonary impairment (O₂-dependent COPD, pulmonary idiopathic fibrosis, etc.)
- Significant frailty (week grip strength, slow gait speed, low physical activity level, unintentional weight loss) at pre-operative assessment

```
Robotic epicardial ablation       2 weeks       Outpatient Clinic Follow-up
                                 12-24 weeks

Catheter endocardial ablation   12 weeks       Imaging/Rhythm Follow-up

                          3 months      Cardiac CTA
                          7-day Holter, device interrogation, EKG
                          12 months      7-day Holter, device interrogation, EKG
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Callkins et al. J Am Heart Rhythm 2017; 4: e495-e494