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REVIEW

Left atrial appendage occlusion in atrial fibrillation: contemporary techniques, clinical outcomes, and future directions

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Abstract

Left atrial appendage occlusion (LAAO) is an important strategy for stroke prevention in patients with nonvalvular atrial fibrillation (AF) who have contraindications to long-term oral anticoagulation. We differentiate this review from existing literature by integrating recent controversial trial data and device-specific outcomes. Advances in technology and imaging have transformed LAAO into a widely adopted percutaneous therapy. Large trials and registries demonstrate LAAO's non-inferiority to oral anticoagulants. For example, the PRAGUE-17 trial (N=402) found LAAO noninferior to direct oral anticoagulants, while PROTECT AF and PREVAIL 5-year data (N=1114) showed significant reductions in hemorrhagic stroke. The surgical LAAOS III trial (N=4811) demonstrated a 33% long-term reduction in stroke or systemic embolism. Major complications have declined; the SURPASS registry (N=16,446) demonstrated a 0.51% incidence of pericardial effusion for the WATCHMAN FLX. In the Amulet IDE trial, pericardial effusion occurred in 2.4% of Amulet patients *versus* 1.2% of WATCHMAN patients. Recent 2026 NEJM trials (CHAMPION-AF and CLOSURE-AF) reached opposite conclusions in different populations, remaining a central controversy. Emerging technologies like artificial intelligence-guided planning, which accurately predicted device size in 72.7% of cases, and low-thrombogenic devices continue to improve safety. This review summarizes contemporary techniques, imaging, complications, outcomes, and future directions.

Key words: left atrial appendage occlusion, atrial fibrillation, stroke prevention, transcatheter LAAO, device-related thrombus, antithrombotic therapy.

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Introduction

The left atrial appendage (LAA) has emerged as a key therapeutic target in atrial fibrillation, serving as the primary site for thrombus formation and a source of non-pulmonary vein arrhythmogenic triggers.[1] LAA occlusion is now a widely adopted alternative to oral anticoagulation for stroke prevention in nonvalvular atrial fibrillation.[2] As utilization expands, referred patients are increasingly elderly and frail, presenting with multiple comorbidities alongside high baseline CHA2DS2-VASc and HAS-BLED scores.[3] This demographic shift raises clinical questions regarding procedural utility *versus* futility in high-risk populations. Initial randomized controlled trials were not adequately powered to assess how these baseline risk factors impact long-term ischemic outcomes, leaving a significant knowledge gap. While this paper shares themes with existing state-of-the-art reviews, it adds unique value by addressing the field's central open controversies, particularly the conflicting results of the latest 2026 head-to-head trials against modern anticoagulation. To optimize patient selection, this review synthesizes the foundational anatomy and physiology of the appendage alongside contemporary clinical management strategies, procedural techniques, and postprocedural outcomes.

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A comprehensive overview of LAA anatomy, AF-related thrombus formation, contemporary occlusion strategies, postprocedural considerations, and future directions is provided in Figure 1.

Anatomy and embryology

The appendage is a highly variable, finger-like outpouching extending from the muscular wall of the left atrium.[4] It develops during the fourth week of gestation as a remnant of the primordial left atrium. This embryological origin distinguishes it from the main atrial cavity, which develops later as a smooth-walled outgrowth of the pulmonary veins.[5,6] Because of this distinct origin, the interior of the appendage is lined with complex muscular ridges known as pectinate muscles. It lies anteriorly in the atrioventricular sulcus within the pericardial sac.[7] It sits in close proximity to critical structures, including the pulmonary artery superiorly, the left ventricular free wall inferomedially, the epicardial left circumflex coronary artery, the left phrenic nerve, and the left superior pulmonary vein.[7] The structure measures 46 mm in length on average with a volume of approximately 9 ml. It is typically divided into the ostium, neck, body, and tip. The ostium most commonly takes an oval shape, and the body is often multilobed with cavernous dead spaces.[8] Structural morphologies directly correlate with clinical risk and are generally classified into four categories. The chicken wing morphology is the most common and is associated with the lowest stroke risk. It is followed by the windsock shape, the cactus shape, and the cauliflower morphology, which is the least common but carries the highest clinical risk of thromboembolism.[8]

Physiology and functional significance

While once considered a mere anatomical remnant, the appendage plays an active role in cardiac hemodynamics and vol-

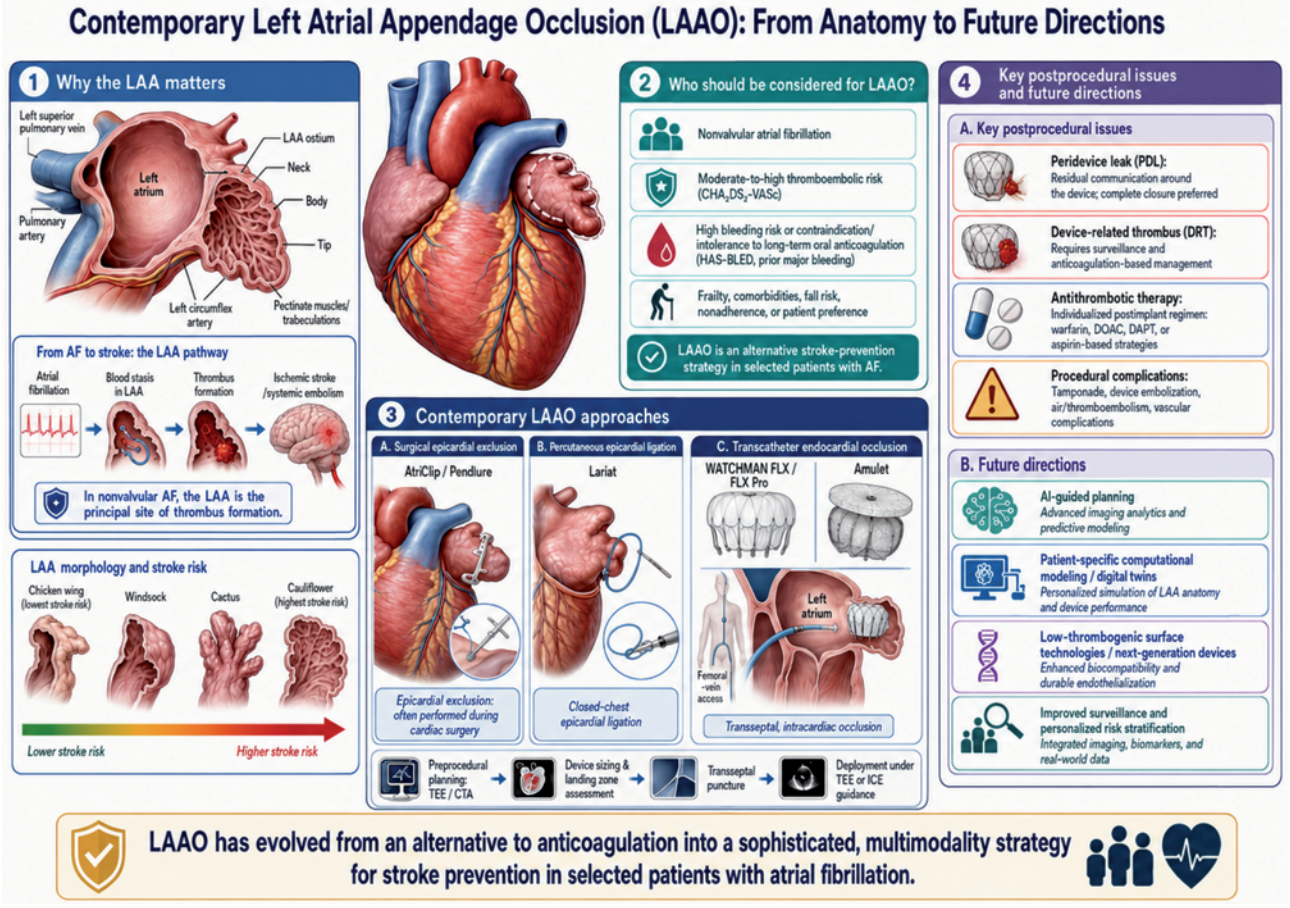


Figure 1. Central illustration.
LAAO, left atrial appendage occlusion; LAA, left atrial appendage; AF, atrial fibrillation; CHA_2DS_2-VASc, congestive heart failure, hypertension, age ≥75 years, diabetes mellitus, stroke/transient ischemic attack/thromboembolism, vascular disease, age 65–74 years, sex category; HAS-BLED, hypertension, abnormal renal/liver function, stroke, bleeding history or predisposition, labile international normalized ratio, elderly age, drugs/alcohol use; PDL, peridevice leak; DRT, device-related thrombus; OAC, oral anticoagulation; DOAC, direct oral anticoagulant; DAPT, dual antiplatelet therapy; TEE, transesophageal echocardiography; CTA, computed tomographic angiography; ICE, intracardiac echocardiography; AI, artificial intelligence.

ume homeostasis. It is two to three times more compliant than the main left atrium. Because of this elasticity, it acts as a critical decompression chamber during states of increased atrial pressure and volume overload.[9,10] The structure is densely innervated with myocardial stretch receptors and contains specialized endothelial cells. It is the primary production site for atrial natriuretic peptides in the human heart, storing roughly 30% of cardiac stores.[11,12] In response to stretching caused by volume overload, hypertension, or heart failure, it releases atrial natriuretic peptide and brain natriuretic peptide into the circulation. These peptides promote diuresis, natriuresis, and vasodilation.[12] They acutely increase glomerular filtration in the kidneys and relax vascular smooth muscle, effectively reducing circulating blood volume and blood pressure.[13]

The unique structure of the appendage makes it a primary culprit in specific cardiovascular pathologies. As the primary site for cardiogenic clots, the LAA accounts for 91% to 100% of thrombi in nonvalvular AF and 57% in valvular AF.[14,15] During atrial fibrillation, the loss of coordinated atrial contraction combined with the trabeculated, cavernous interior leads to severe blood stasis.[13] This promotes thrombus formation within the appendage, which can subsequently embolize and cause ischemic strokes.[10] The exact shape dictates stroke risk, with highly lobulated cauliflower morphologies carrying the highest risk of thromboembolism due to smaller orifices and complex internal trabeculations.[16] Endothelial dysfunction in LAA is driven by increased inflammatory markers like interleukin-6 and C-reactive protein, alongside the up-regulation of asymmetrical dimethylarginine, which directly increases localized thrombogenicity.[13] Beyond stroke pathogenesis, the base and pectinate ridges are highly arrhythmogenic in long-standing persistent atrial fibrillation.[17-19] The generation of these arrhythmias is primarily fueled by the activation of specialized DeBakker cells, mechanical atrial tissue stretch, and fibrosis-related re-entry circuits that disrupt normal electrical pathways.[19] Because of these potent arrhythmogenic properties, the LAA has evolved into a primary therapeutic target not only for mechanical stroke prevention but also for endocardial ablation and epicardial exclusion strategies aimed at reducing overall AF burden.

Evolution of left atrial appendage (LLA) exclusion strategies: surgical LAA exclusion, atri-clip LAA exclusion, lariat LAA exclusion, endocardial LAA exclusion

The surgical approach to exclusion has evolved significantly from early manual excisions and inclusion in the traditional Cox maze procedure to the deployment of advanced epicardial devices.[20,21] First-generation techniques such as manual suture ligation resulted in high rates of incomplete closure. A residual stump of 10 mm or greater is associated with a 12-fold increased risk of stroke compared to no exclusion.[22] Several different surgical techniques for LAA exclusion have been proposed, including excision, endocardial or epicardial suture closure, and stapler occlusion, but heterogeneity in surgical techniques led to incomplete closure of the LAA, thus increasing thromboembolic risk.[23,24] A transesophageal echocardiographic study showed that excision had the highest success (73%), whereas 41% of LAAs contained thrombi when using alternative surgical techniques,[25] because of which routine LAA exclusion during open cardiac surgery fell out of favor. To mitigate this risk, specialized epicardial exclusion devices were developed.

The AtriClip device has demonstrated high procedural success and safety across multiple studies.[26,27] In the first human trial, 34 patients (mean age 71±10 years) undergoing concomitant atrial fibrillation ablation and open cardiac surgery achieved complete left atrial appendage (LAA) exclusion on 3-month computed tomographic angiography, with no device-related complications.[28] Subsequently, the multicenter EXCLUDE (Exclusion of Left Atrial Appendage With AtriClip Exclusion Device) trial enrolled 71 patients with $CHADS_2$ scores >2 undergoing open cardiac surgery and reported successful clip deployment in 95.7% of cases, no device-related serious adverse events, and complete LAA closure in 98.4% of patients at 3-month follow-up.[29] These favorable outcomes have been further supported by several observational studies and a meta-analysis,[30-33] confirming the safety, feasibility, and efficacy of AtriClip-mediated LAA exclusion. Other notable surgical innovations include the Penditure system, a fabric-free clip designed to match atrial anatomy,[34] and the TigerPaw System II, which was permanently withdrawn from the market following FDA recalls related to fatal LAA tears. More recently, Medtronic's Penditure LAA exclusion system has become available, with limited human experience.[35] Bridging the gap between open surgery and purely transcatheter methods, the hybrid epicardial-endocardial approach utilizes the Lariat Suture Delivery Device for closed-chest LAA ligation.[36] This percutaneous system employs magnet-tipped guidewires to deploy a preformed suture that tightly ligates the appendage base, inducing ischemic necrosis and complete occlusion.[37,38] Clinical experience with the Lariat epicardial suture ligation system has demonstrated high procedural success but a notable risk of access-related complications. The initial human study involving 11 patients reported successful LAA ligation in 91% of cases, although one patient required thoracoscopic removal of the snare because of pectus excavatum.[39] A subsequent single-center trial of 89 patients achieved successful ligation in 96% of patients and complete closure in 96.5%, with complete closure increasing to 98% at 1-year follow-up. However, complications included cardiac and arterial perforations, pericarditis, late pericardial effusion, and two unexplained sudden deaths.[40] In a larger multicenter observational study of 712 patients across 18 U.S. centers, successful ligation was achieved in 96% of patients, with a complete closure rate of 98.1%. Despite favorable efficacy outcomes, procedure-related complications included one death, cardiac perforation requiring surgery in 1.44% of patients, and pericarditis or pleural effusion in 4.78% of patients.[42] Additional reports have highlighted risks associated with epicardial access and device-related complications, which have limited widespread adoption of the Lariat system despite its high closure rates.[42-44]

Purely transcatheter endocardial exclusion has significantly expanded therapeutic options for stroke prevention by allowing devices to be placed entirely within the heart via a transseptal puncture.[45] Single-closure systems like the Watchman family function as umbrella-shaped plugs deployed at the ostium but require systemic anticoagulation post-implantation for at least 6 weeks to prevent thrombus formation during endothelialization.[46] Conversely, dual-mechanism devices such as the Amplatzer Amulet utilize an inner lobe to fill the cavernous neck and a proximal disc to definitively seal the ostium, offering versatile solutions for complex anatomies without the need for epicardial access.[47] In reference to this, Table 1 shows closure success rate with different surgical approaches for LAA occlusion.

Patient selection and risk stratification

Clinical guidelines recommend oral anticoagulation for patients with atrial fibrillation possessing two or more non-sex-related

Table 1. Efficacy of surgical left atrial appendage exclusion techniques.

Study & year	Cohort size	Surgical technique	Success criteria	Occlusion rate (%)
Johnson *et al.*, 2000	434	Staple excision (n=43); suture exclusion (n=391)	Not specified	Not assessed uniformly
Katz *et al.*, 2000	50	Endocardial suture	Not specified	Overall: 64%; Intraoperative: 67%; Long-term: 60%
Garcia-Fernandez *et al.*, 2003	58	Endocardial suture	Absence of flow/leak	89.7%
Pennec *et al.*, 2003	60	Endocardial suture (n=30); Excision (n=30)	Not specified	Suture: not fully evaluated; Excision: 100%
Schneider *et al.*, 2005	6	Endocardial suture	Not specified	17%
Healey *et al.*, 2005 (LAAOS)	52	Endocardial suture; Stapler	Flow ≤10 mm or stump <1 cm	Suture: 45%; Stapler: 72%
Kanderian *et al.*, 2008	137	Excision (n=52); Suture occlusion (n=73); Stapler (n=12)	Flow ≤10 mm or stump <1 cm	Excision: 73%; Suture: 23%; Stapler: 0%
Bakhtiary *et al.*, 2008	259	Clamp and epicardial suture	Absence of flow/leak	100% (via intraoperative TEE)
Salzberg *et al.*, 2010	34	AtriClip; Amputation	Absence of flow/leak	Intraoperative: 100% (both); Follow-up CT: AtriClip 100%; Amputation 73%
Ailawadi *et al.*, 2011	70	AtriClip	Absence of flow/leak	Intraoperative: 95.7%; Postoperative: 98.4%
Slater *et al.*, 2012	60	TigerPaw II	Flow ≤10 mm or stump <1 cm	Intraoperative: 93.3%; Follow-up: 100%
Adams *et al.*, 2012	12	Ligation	Absence of flow/leak	Intraoperative: 100%; Follow-up CT: 25%
LAAOS II, 2013	26	Amputation and closure; Stapler	No flow & stump <1 cm	100% (intraoperative)
Emmert *et al.*, 2014	40	AtriClip	Absence of flow/leak	100% (intraoperative TEE & follow-up CT)
Aryana *et al.*, 2015	72	Surgical suture ligation	Absence of flow/leak	Complete closure: 64%; Residual stump: 12%; Incomplete ligation: 24%
Kurfist *et al.*, 2017	101	AtriClip; Amputation	Flow ≤10 mm or stump <1 cm	Intraoperative: 98%; Follow-up TEE: 100% (both)
Ellis *et al.*, 2017	65	AtriClip	Absence of flow/leak	Intraoperative: 100%; Follow-up CT: 93.9%
Caliskan *et al.*, 2018	291	AtriClip	Flow ≤10 mm or stump <1 cm	Intraoperative: 100%; 5-year CT: complete exclusion
Fu *et al.*, 2019	257	Stapler	Flow ≤10 mm or stump <1 cm	76.7% (follow-up TEE)
Suematsu *et al.*, 2020	43	AtriClip	Absence of flow/leak	100% (intraoperative TEE & follow-up CT)
Fleerakkers *et al.*, 2020	13	AtriClip	Absence of flow/leak	100% (intraoperative TEE & follow-up CT)
Peighambari *et al.*, 2021	150	Purse string; Suturing; Resection; Ligation	Absence of flow/leak	Suturing: 75.5%; Resection: 71.4%; Purse string: 56.7%; Ligation: 33.3%
LAAOS III, 2021	2,131	Amputation/closure; Stapler; Double-layer linear closure; AtriClip	No flow & stump <1 cm	100% (intraoperative)
Kiankhooy *et al.*, 2022	100	AtriClip	Flow ≤10 mm or stump <1 cm	Intraoperative: 100%; Follow-up CT: 96%
ATLAS Trial, 2022	376	AtriClip	No flow & stump <1 cm	98.9% (intraoperative TEE)

ATLAS, AtriClip® Left Atrial Appendage Exclusion Concomitant to Structural Heart Procedures; CT, computed tomography; LAA, left atrial appendage; LAAOS, Left Atrial Appendage Occlusion Studies; TEE, transesophageal echocardiography.

CHA2DS2-VASc risk factors, however, the risk of major bleeding remains a significant limitation of long-term anticoagulation therapy, particularly among patients with elevated HAS-BLED scores (≥3).[48] Therefore, patient selection for occlusion requires a comprehensive evaluation encompassing thromboembolic risk using the CHA2DS2-VASc score,[49] contraindications to long-term oral anticoagulation,[50] and a history of major bleeding using HAS-BLED scores and overall patient comorbidities, high fall risk,[48] patient preference, long-term survival, and noncompliance with anticoagulation therapy into the decision matrix.[51] Data from the National Cardiovascular Data Registry demonstrate rapid expansion in procedural use, with real-world patients generally being older and possessing higher risk scores than participants enrolled in landmark clinical trials.[52] Procedural cancellation is associated with substantially higher in-hospital adverse event rates among patients with significant comorbid conditions such as cardiomyopathy and congestive heart failure.[53] Selection of an appropriate strategy must account for operator experience, concomitant cardiac procedures, and anatomical suitability. Patients with prior cardiac surgery, chest radiation, or pericarditis are often suboptimal candidates for epicardial approaches due to pericardial adhesions.[37] Complex morphologies such as a superiorly oriented appendage, width greater than 40 mm, or prominent trabeculations limit the technical success of specific devices.[54] An integrated clinical pathway for patient selection, procedural planning, device deployment, postprocedural surveillance, and management of key findings after LAAO is summarized in Figure 2.

Procedure planning and imaging for left atrial appendage occlusion

Preprocedural imaging

Baseline imaging with transesophageal echocardiography (TEE) or computed tomographic angiography (CTA) is recommended before left atrial appendage occlusion (LAAO), as it improves procedural safety and efficacy. The main objectives of preprocedural imaging are to: 1) exclude left atrial appendage (LAA) thrombus and assess for pericardial effusion; 2) define LAA anatomy, including ostial dimensions, landing zone measurements, and peak emptying velocity; 3) evaluate adjacent cardiac structures; and 4) determine optimal fluoroscopic projections and transseptal puncture (TSP) location.[55]

Recent advances in CTA technology have enabled acquisition of high-quality images with lower radiation exposure. A minimum 128-slice CT scanner is recommended to optimize image quality

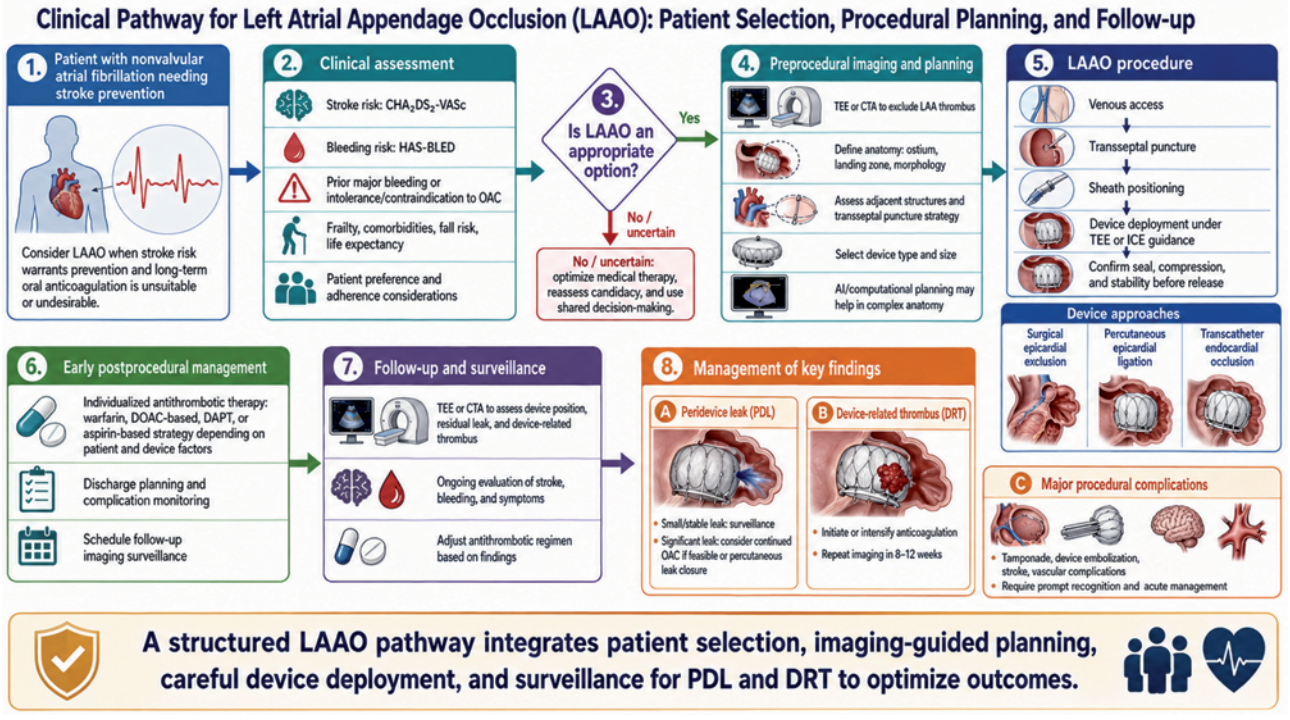


Figure 2. Integrated clinical pathway for left atrial appendage occlusion.
LAAO, left atrial appendage occlusion; CHA_2DS_2-VASc, congestive heart failure, hypertension, age ≥75 years, diabetes mellitus, stroke/transient ischemic attack/thromboembolism, vascular disease, age 65-74 years, sex category; HAS-BLED, hypertension, abnormal renal/liver function, stroke, bleeding history or predisposition, labile international normalized ratio, elderly age, drugs/alcohol use; OAC, oral anticoagulation; TEE, transesophageal echocardiography; CTA, computed tomographic angiography; LAA, left atrial appendage; AI, artificial intelligence; ICE, intracardiac echocardiography; DOAC, direct oral anticoagulant; DAPT, dual antiplatelet therapy; PDL, peridevice leak; DRT, device-related thrombus.

while minimizing radiation dose.[55] Compared with TEE, CTA provides a larger field of view and unlimited multiplanar imaging angles that closely replicate fluoroscopic projections. This facilitates procedural planning by enabling accurate determination of fluoroscopic working angles, optimal TSP location, and coaxial device deployment, potentially reducing the risk of peridevice leak (PDL). CTA is also particularly useful for planning percutaneous suture ligation with the Lariat device, as it helps identify anatomical landmarks for anterior pericardial access.[55]

Advances in image-processing software and computational modeling have further enhanced procedural planning by improving prediction of device size, implantation depth, and deployment angles, with strong correlation to intraprocedural three-dimensional (3D) TEE measurements.[56] Consequently, preprocedural imaging improves device selection, sizing accuracy, and anticipation of anatomical challenges during LAAO procedures.

Artificial intelligence and computational modeling

Artificial intelligence (AI) and patient-specific computational modeling are increasingly being explored to optimize LAAO planning. Ranard et al. evaluated the FEops HEARTguide platform, which combines digital twin technology with AI-enhanced anatomical analysis to simulate LAAO implantation outcomes.[57] The platform enables visualization of different device sizes and implantation depths while assessing device apposition and potential PDL.

The FEops model correctly predicted implanted device size in 72.7% of cases, and simulated device positioning corresponded to postprocedural CT findings in 59% of patients. Strong correlations were observed between FEops-derived and intraprocedural 3D-TEE measurements of LAA dimensions and device compression.[56,58]

Given the heterogeneity of LAA anatomy, computational modeling may improve procedural planning by accounting for variables such as TSP location, sheath orientation, trabeculation, and implantation depth. Ongoing prospective studies, including the PREDICT-LAA trial (NCT04180605), are evaluating whether FEops-guided planning improves procedural outcomes compared with conventional CT-based strategies.[59]

Periprocedural imaging

Intraprocedural imaging during LAAO is typically performed using TEE or intracardiac echocardiography (ICE). A primary objective is the exclusion of left atrial or LAA thrombus before device deployment. TEE remains the gold standard during surgical LAA exclusion because it allows real-time assessment of the residual LAA stump and immediate repositioning if necessary. The development of 3D TEE has significantly improved intraprocedural imaging by allowing anatomical reorientation of images and enhanced visualization of LAA anatomy.[60] Increasing interest in ICE-guided LAAO is driven by the potential for a single-operator approach, avoidance of general anesthesia, and improved procedural efficiency. However, ICE-guided procedures are technically more demanding because optimal imaging often requires catheter positioning within the left atrium.[61]

Although several studies have demonstrated the feasibility and safety of ICE-guided LAAO, available evidence is derived primarily from experienced high-volume centers. Ongoing investigations, including the ICE WATCHMAN trial (NCT04569734), are evaluating the safety and efficacy of ICE-guided WATCHMAN FLX implantation.[62]

Percutaneous left atrial appendage occlusion procedure

Percutaneous occlusion is most performed through right femoral venous access to facilitate optimal transseptal puncture and catheter manipulation. Vascular access is obtained using ultrasound-guided techniques to minimize complications.[63] Although left femoral venous access is feasible, it may complicate TSP and sheath manipulation. At the conclusion of the procedure, hemostasis can be achieved using manual compression, figure-of-eight sutures, or vascular closure devices such as Perclose (Abbott Vascular) or Locket (Catheter Precision). Protamine administration may be considered for reversal of heparin anticoagulation when necessary to facilitate hemostasis.[64]

Systemic anticoagulation with unfractionated heparin is administered either immediately after venous access or around the time of TSP, according to operator preference, with a target activated clotting time (ACT) ≥250–300 seconds. Frequent ACT monitoring throughout the procedure is essential to maintain adequate anticoagulation and reduce thromboembolic risk.[65]

Careful procedural planning dictates the optimal transseptal puncture location to achieve coaxial alignment of the delivery sheath with the appendage. Most appendages are anteriorly oriented, making an inferoposterior puncture preferred, while superiorly directed variants require a more inferior puncture. Advancement of the delivery sheath into the appendage is performed over a pigtail catheter to prevent perforation.[66] Multiple sheath configurations are available to accommodate anatomical variability. The WATCHMAN FLX and WATCHMAN FLX Pro systems may be delivered through single-curve, double-curve, or steerable sheaths, whereas the Amulet device is delivered through 12- or 14-French TorqVue sheaths (Abbott Vascular). Thorough flushing and deairing of these large-caliber delivery systems are essential to minimize the risk of air embolism.[66,67]

Final device sizing should be confirmed using a combination of preprocedural and intraprocedural imaging together with LAA angiography performed under adequate left atrial pressure (≥12 mm Hg).[68] Early-generation steerable sheaths were associated with air embolization related to valve design; however, subsequent modifications have significantly improved procedural safety and delivery performance.[67] Intraprocedural imaging is essential for accurate device deployment, confirmation of adequate device compression, and exclusion of significant peridevice leak (PDL) before device release. For the WATCHMAN FLX device, successful implantation is assessed using the PASS criteria: Position (device shoulders aligned with the LAA ostium and at least two-thirds of the device within the appendage), An-

chor (successful tug test), Size (10-30% device compression with adequate stability), and Seal (absence of significant residual flow, defined as <5-mm PDL on TEE). In contrast, implantation of the Amulet device is evaluated using the CLOSE criteria: Circumflex positioning, appropriate Lobe compression with a tire-shaped appearance, correct Orientation coaxial to the LAA wall, adequate Separation between the lobe and disc, and an Elliptical concave disc configuration.[69]

Left atrial appendage occlusion procedural complications: identification, management, and prevention

Early experience with left atrial appendage occlusion (LAAO) was associated with relatively high rates of procedural complications, including pericardial tamponade, thromboembolism, and air embolism (Table 2). The thin-walled structure of the left atrium and LAA makes these structures particularly susceptible to trauma from large-bore sheaths, guidewires, and occlusion devices. In addition, the low-pressure environment within the left atrium predisposes to air entrainment during catheter manipulation and promotes blood stasis with subsequent thrombus formation.

Over time, improvements in operator experience, procedural techniques, imaging guidance, and device technology have led to substantial reductions in major complications such as cardiac tamponade, device embolization, stroke, and procedural mortality.[70] Careful attention to vascular access technique, optimal transseptal puncture (TSP), meticulous sheath deairing, adequate anticoagulation, and real-time imaging guidance remains essential for minimizing procedural risk and improving procedural success.

Pericardial effusion and cardiac tamponade

Pericardial effusion (PE) and cardiac tamponade remain among the most serious complications of LAAO. In pooled analyses involving the first-generation WATCHMAN 2.5 device, the incidence of PE was approximately 1.3%.[71] In the Amulet IDE (Amplatzer™ Amulet™ Left Atrial Appendage Occluder Randomized Controlled Trial) study, PE occurred more frequently with the Amulet device compared with the WATCHMAN device (2.4% *vs* 1.2%), although all cases resolved without long-term sequelae or surgical intervention.[72] This is in contrast to the Watchman FLX device, for which the incidence was 1.0% in the PINNACLE FLX (Protection Against Embolism for Nonvalvular AF Patients: Investigational Device Evaluation of the Watchman FLX LAA Closure Technology) study and 0.51% in the SURPASS

Table 2. Complications and ischemic outcomes in landmark left atrial appendage occlusion studies clinical trials.

Trial/registry	Study arms (N)	Mean risk score (CHADS2 / CHA2DS2-VASc)	Severe PE	Embolization	Periprocedural stroke	Mortality
PROTECT AF	LAAO: 463 Control: 244	2.2±1.2	4.8%	0.6% (n=3)	1.1%	—
PREVAIL	LAAO: 269 Control: 138	2.6±1.0	0.7%	0.7% (n=2)	0.4%	—
CAP	460 (Registry)	2.4±1.2	2.2%	0%	0%	—
EWOLUTION	1,025 (Registry)	4.5±1.6	0.5%	0.2% (n=2)	0%	0%
Amulet IDE	Amulet: 903 Watchman: 896	2.7±1.1 2.8±1.2	2.4% 1.2%	0.7% 0.2%	0% 0.11%	—
SWISS-APERO	Amulet: 111 Watchman/FLX: 110	4.3±1.4	Amulet: 2.7% Watchman/FLX: 0%	Amulet: 0.9% (n=1) Watchman/FLX: 0.9% (n=1)	Amulet: 1.8% (n=2)[a] Watchman/FLX: 0	Amulet: 1.8% (n=2)[b] Watchman/FLX: 0
NCDR Registry	38,158 (Watchman)	4.6±1.5	1.39%	0.07%	Ischemic: 0.12% TIA: 0.04%	0.19%
PINNACLE FLX	400	4.2±1.5	0%	0%	0.5%	0%
CHAMPION-AF	LAAO: 1,499 NOAC: 1,501	3.5±1.3	—	—	—	—
CLOSURE-AF	LAAO: 456 Control: 456	5.2 ±1.5	—	—	—	—
SURPASS	16,446 (Watchman FLX)	—	0.51%	0.1%	—	—

[a]Associated with one event of air embolism, and one combined post-LAAO/PCI event; [b]associated with one event of air embolism/stroke, and one pericardial effusion event.

Amulet IDE, Amplatzer™ Amulet™ Left Atrial Appendage Occluder Trial; CAP, Continued Access to PROTECT AF; EWOLUTION, Registry on Watchman Outcomes in Real-Life Utilization; LAAO, Left Atrial Appendage Occlusion; NCDR, National Cardiovascular Data Registry; PE, Pericardial Effusion; PINNACLE FLX, Investigational Device Evaluation of the Watchman FLX; PREVAIL, Evaluation of the Watchman LAA Closure Device; PROTECT AF, Watchman Left Atrial Appendage System for Embolic Protection; SWISS-APERO, Comparison of Amulet *versus* Watchman/FLX Device; TIA, Transient Ischemic Attack.

(Watchman FLX Device Surveillance Post Approval Analysis Plan) registry (an analysis of 16,446 Watchman FLX implantations).[73] Clinically significant PE typically occurs within the first 24 hours after the procedure, particularly during the initial 6 hours, and has been associated with increased 1-year mortality.[74] Several patient-, operator-, and device-related factors contribute to the risk of PE. Advanced age, female sex, baseline anticoagulation use, and sinus rhythm have all been associated with increased susceptibility.[75]

Prompt recognition and immediate management are critical in cases of tamponade. Early hemodynamic stabilization and urgent pericardiocentesis remain the cornerstone of therapy. In cases involving overt perforation by a large-bore sheath or device, emergent surgical consultation is required, and the offending sheath or device should not be withdrawn until pericardial access and hemodynamic stabilization have been achieved. Autotransfusion may also be necessary in cases of ongoing hemorrhagic pericardial drainage. Familiarity with device-specific sizing strategies and deployment techniques remains essential for minimizing procedural complications.[76]

Device embolization

Although uncommon, device embolization remains a serious complication because of its association with significant morbidity and mortality. In the NCDR LAAO Registry, device embolization with the WATCHMAN 2.5 device occurred in approximately 0.07% of cases.[2] Reported rates with the WATCHMAN FLX device were 0% in the PINNACLE FLX trial and 0.1% in the SURPASS registry.[77]

In the randomized Amulet IDE trial, device embolization was observed more frequently with the Amulet device than with the Watchman device (0.7% *vs* 0.2%).[72] The largest multicenter analysis of device embolization to date, which included 108 cases occurring between 2004 and 2021, identified the Amplatzer Amulet as the most commonly embolized device, followed by the first-generation Watchman. The study also demonstrated that most embolized devices could be successfully retrieved percutaneously, although failed retrieval attempts were associated with increased morbidity and mortality.[78] Potential mechanisms of embolization include inappropriate device sizing, proximal implantation, and noncoaxial device orientation within the LAA. Most embolization events occur within minutes of device deployment, although delayed embolization occurring weeks after implantation has also been reported. Clinical presentations range from asymptomatic incidental findings to severe hemodynamic instability, acute mitral regurgitation, or ventricular arrhythmias.[79] Various retrieval techniques, including the use of snares, bioptomes, and forceps, have been reported with favorable success rates.[80]

Intraprocedural stroke

Periprocedural stroke during LAAO is rare, with reported rates generally below 0.5%, and most events occur within 24 hours of the procedure. Data from the NCDR LAAO Registry demonstrated ischemic and hemorrhagic stroke rates of 0.12% and 0.01%, respectively.[2] Mechanisms of stroke include air embolism from inadequate sheath preparation, thrombus formation on delivery sheaths in the setting of subtherapeutic anticoagulation, and embolization of pre-existing LAA thrombus.[66] Large-bore delivery sheaths increase the risk of air embolism, and transient ST-segment elevation during the procedure may serve as an important clinical clue. Meticulous sheath preparation, continuous fluid-column connections, appropriate back-bleeding techniques, and maintenance of therapeutic activated clotting time (ACT ≥250-300 seconds) are essential preventive strategies.[81]

Postprocedural imaging

Imaging with transthoracic echocardiography may be beneficial before discharge to monitor for procedure-related complications. In the U.S. Watchman pivotal trials, patients were observed overnight routinely as inpatient status, as mandated by the Centers for Medicare and Medicaid Services.[82] Several studies have now demonstrated the safety of same-day discharge after the LAAO procedure, without any increased risk for adverse events.[83,84] Therefore, repeat echocardiography can be performed several hours later (especially in high-risk patients or difficult implantations) if considering same-day discharge.

Postprocedural endpoints of left atrial appendage occlusion

Peridevice leak

Peridevice leak (PDL) and device-related thrombus represent the most critical postprocedural endpoints following occlusion. PDL refers to persistent communication between the left atrium and the appendage around the occlusion device as detected on imaging modalities such as transesophageal echocardiography (TEE) or computed tomographic angiography (CTA).[85] Transesophageal echocardiography remains the standard surveillance modality, while computed tomographic angiography provides superior characterization of leak morphology and assessment of incomplete endothelialization.[86]

Reported leak rates differ substantially among currently available devices. The prevalence of any PDL at 45 days and 12 months has been reported as 40.9% and 32.1%, respectively, with the first-generation WATCHMAN device 17.2% and 10.5% with the WATCHMAN FLX device 15% and 20% with the Lariat device,[87-89] and approximately 37% with the Amulet device.[72,90]

The clinical significance of PDL remains an evolving area of investigation. Early randomized trials considered leaks <5 mm to be clinically acceptable, which contributed to the initial regulatory approval of the WATCHMAN device. More recently, however, increasing evidence suggests that even smaller leaks may carry clinical importance. Current practice increasingly favors achieving complete closure whenever possible, with residual

leaks <3 mm generally considered acceptable. Importantly, studies have demonstrated that 8-14% of small leaks (<3 mm) may progress over time, emphasizing the importance of continued imaging surveillance.[91,92]

Long-term outcome data suggest that even small PDLs may be associated with adverse thromboembolic outcomes. Pooled analyses from the PROTECT AF, PREVAIL, and CAP studies demonstrated that PDLs <5 mm at 1 year were associated with a significantly increased 5-year risk of ischemic stroke and systemic embolism (adjusted HR: 1.94; *P*=0.014).[93] Interestingly, larger leaks were not consistently associated with worse outcomes, possibly because these patients were more likely to remain on long-term anticoagulation or undergo additional intervention.

The optimal strategy for PDL management remains prevention through meticulous procedural planning, accurate device sizing, adequate device compression, coaxial deployment, and increasing operator experience. However, continuation of OAC may not be feasible in patients undergoing LAAO because of high bleeding risk. In such cases, percutaneous PDL closure may represent an appropriate therapeutic option. Various techniques, including coils, vascular plugs, occluder devices, and radiofrequency ablation, have demonstrated promising safety and efficacy in achieving near-complete leak closure.[94]

Device-related thrombus after left atrial appendage occlusion

Device-related thrombus (DRT) refers to thrombus formation on or adjacent to an implanted left atrial appendage occlusion (LAAO) device, typically involving exposed metallic components or uncovered atrial surfaces of endocardial devices. The morphology of DRT varies according to device type. On the Amulet device, thrombi are often sessile and broad-based, whereas on WATCHMAN devices they tend to be mobile and pedunculated, likely reflecting differences in device geometry and implantation depth.[95] With increasing use of computed tomographic angiography (CTA) for postprocedural surveillance, interpretation challenges have emerged. Hypoattenuated thickening along the atrial surface may mimic thrombus but does not always represent true DRT. In WATCHMAN FLX devices, lack of contrast filling within the screw hub region may also produce a thrombus-like appearance.[96] Therefore, careful interpretation based on morphology, location, and extent is essential to distinguish benign imaging findings from clinically significant thrombus.[97]

The reported incidence of DRT varies according to device type, surveillance strategy, and study population. In pooled analyses of the PROTECT AF, PREVAIL, CAP, and CAP-2 studies involving the WATCHMAN 2.5 device, DRT occurred in approximately 3.7% of patients.[98] In the PINNACLE FLX trial, the incidence of DRT with WATCHMAN FLX was 1.7% at 1 year.[99] In the Amulet IDE trial, DRT occurred in 3.3% of patients treated with the Amulet device and 3.8% of those treated with WATCHMAN devices.[72] However, higher rates have been reported in real-world cohorts such as the EUROC-DRT registry.[100]

Multiple patient-, procedural-, and device-related factors contribute to DRT risk. Proposed predictors include hypercoagulable states, renal insufficiency, non-paroxysmal atrial fibrillation, pericardial effusion, and excessive implantation depth.[101] Excessive device depth may create a residual neoappendage with blood stasis, while noncoaxial implantation and abnormal device angulation may promote turbulent flow and endothelial injury.[102] Because most DRT events occur within the first year after implantation, routine imaging surveillance remains an important component of follow-up.

The clinical significance of DRT remains incompletely defined. In pooled FDA trial analyses, DRT was associated with significantly increased risks of ischemic stroke and systemic embolism, with relative risks ranging from 3.2 to 3.5.[103] Multiple observational studies have similarly demonstrated increased thromboembolic risk in patients with DRT.[104,105] However, findings from real-world registries such as EWOLUTION did not demonstrate a statistically significant increase in ischemic stroke or transient ischemic attack, although event numbers were limited.[106] These discrepancies likely reflect differences in patient populations, imaging protocols, and management strategies.

Prompt initiation or intensification of anticoagulation remains the cornerstone of DRT management. In anticoagulation-naïve patients, vitamin K antagonists or direct oral anticoagulants (DOACs), with or without aspirin, are typically administered for 8-12 weeks. In patients already receiving anticoagulation, therapy may be optimized by improving adherence, increasing INR targets, or switching to an alternative DOAC. Persistent DRT despite therapy occurs in approximately 20-25% of cases, and recurrence after thrombus resolution is also common, underscoring the importance of repeat imaging surveillance.[105] Surgical intervention is rarely required but may be considered in cases of large, recurrent, or refractory thrombi.

Emerging evidence suggests lower thrombogenicity with newer-generation devices and surface-modified technologies. Preclinical studies have demonstrated improved endothelialization and reduced thrombogenicity with fluoropolymer-coated devices such as WATCHMAN FLX Pro.[107] Investigational systems designed to minimize blood-device interaction and achieve complete appendage exclusion have also shown promising early results.[108]

Antithrombotic therapy and clinical outcomes after left atrial appendage occlusion

The optimal antithrombotic regimen after left atrial appendage occlusion (LAAO) remains uncertain, and clinical practice varies considerably across centers and device platforms. Early postprocedural strategies were largely based on the PROTECT AF and PREVAIL trials, in which patients received warfarin plus aspirin for 45 days, followed by dual antiplatelet therapy (DAPT) for 6 months and lifelong aspirin thereafter. This approach

formed the basis of the original FDA-approved protocol in the pre–direct oral anticoagulant (DOAC) era.[109]

However, real-world experience has shown limited adherence to this regimen, largely because many patients undergoing LAAO have a high baseline bleeding risk. In addition, pooled analyses from PROTECT AF and PREVAIL suggested that the addition of aspirin to warfarin did not meaningfully reduce thromboembolic events but increased bleeding risk, particularly during the early post implantation period. Bleeding rates declined substantially after transition to aspirin monotherapy.[110]

With the introduction of newer-generation devices such as WATCHMAN FLX, postprocedural management has increasingly shifted toward DOAC-based strategies. The PINNACLE FLX trial supported the use of DOAC plus aspirin for 45 days, leading to updated FDA labeling permitting this regimen as an alternative to warfarin-based therapy.[111] Reduced-intensity approaches, including half-dose DOAC regimens, have also gained interest in high bleeding-risk populations.

Nevertheless, concerns remain regarding the comparative safety of DAPT.[112] Observational analyses have suggested higher rates of major bleeding and DRT with DAPT compared with anticoagulation-based regimens.[113,114] Consequently, antithrombotic therapy after LAAO should be individualized according to thromboembolic risk, bleeding risk, device type, implantation quality, and patient comorbidities.

Over the past two decades, LAAO has emerged as an effective alternative to long-term oral anticoagulation for stroke prevention in patients with nonvalvular atrial fibrillation (AF), particularly among those with elevated bleeding risk or contraindications to anticoagulation.

Impact of left atrial appendage occlusion on stroke, bleeding, rhythm control, and cost-effectiveness

Left atrial appendage occlusion *versus* oral anticoagulation

Comparative studies have demonstrated that LAAO provides stroke prevention comparable to oral anticoagulation while reducing hemorrhagic complications. Long-term follow-up of the pivotal PROTECT AF and PREVAIL trials, which enrolled a combined 1114 patients, showed that LAAO was associated with significant reductions in disabling stroke, hemorrhagic stroke, unexplained or cardiac mortality, and all-cause mortality at 5 years compared with warfarin.[85] These findings were further supported by the FDA-mandated CAP and CAP-2 registries, which enrolled 1144 patients and demonstrated substantially lower observed ischemic stroke rates than predicted by CHA_2DS_2-VASc scores, along with very low rates of hemorrhagic stroke.[115]

The PRAGUE-17 trial, the only randomized controlled trial directly comparing LAAO (Watchman or Amulet) with direct oral anticoagulants (DOACs), enrolled 402 high-risk patients and demonstrated that LAAO was noninferior to DOAC therapy for the composite endpoint of stroke, systemic embolism, cardiovascular death, clinically relevant bleeding, or procedure/device-related complications.[116] No significant differences were observed in stroke, transient ischemic attack, or cardiovascular death; however, LAAO was associated with significantly lower rates of nonprocedural clinically relevant bleeding, particularly late bleeding events. These findings were corroborated by pooled patient-level meta-analyses of PROTECT AF, PREVAIL, and PRAGUE-17, which further suggested reductions in cardiovascular and all-cause mortality with LAAO, largely driven by lower rates of hemorrhagic stroke and nonprocedural bleeding.[116-118] Furthermore, two major 2026 NEJM trials, CHAMPION-AF and CLOSURE-AF,[119-120] now represent the largest and most current head-to-head comparisons against modern anticoagulation. These two trials reached opposite conclusions in differently selected populations and, as of this review, remain the field's central open controversy. However, their contrasting findings should be interpreted in the context of differences in patient selection, comparator strategies, and endpoint definitions rather than as a simple contradiction.

CHAMPION-AF randomized 3000 patients with atrial fibrillation who were candidates for oral anticoagulation to LAA closure or NOAC therapy. The population had a mean CHA_2DS_2-VASc score of 3.5. LAAO met the prespecified criterion for noninferiority for the composite of cardiovascular death, stroke, or systemic embolism and was associated with significantly less non-procedure-related bleeding. These findings support LAAO as a potential alternative to NOAC therapy in anticoagulation-eligible patients, particularly when long-term bleeding risk is an important consideration.[119]

In contrast, CLOSURE-AF enrolled 912 patients at substantially higher thromboembolic and bleeding risk, with mean CHA_2DS_2-VASc and HAS-BLED scores of 5.2 and 3.0, respectively. LAAO was compared with physician-directed best medical therapy, and the primary endpoint incorporated ischemic or hemorrhagic stroke, systemic embolism, major bleeding, and cardiovascular or unexplained death. LAAO did not meet the prespecified criterion for noninferiority, with the primary endpoint occurring more frequently in the LAAO group.[120]

Several factors may explain the divergent results. CHAMPION-AF directly compared LAAO with NOACs in a broadly anticoagulation-eligible population, whereas CLOSURE-AF studied a higher-risk population receiving individualized medical therapy. Furthermore, their composite endpoints differed substantially, making direct comparison of event rates difficult. Importantly, the individual outcome signals suggest a trade-off between thromboembolic and bleeding outcomes, with LAAO reducing nonprocedural bleeding while raising continued questions regarding ischemic stroke risk.

Taken together, these trials suggest that the contemporary question is not simply whether LAAO is superior or inferior to anticoagulation, but which patient phenotypes derive the greatest net clinical benefit. Their contrasting findings highlight the importance of baseline thromboembolic and bleeding risk, comparator selection, procedural risk, and the relative weighting of

ischemic *versus* bleeding outcomes. Thus, CHAMPION-AF and CLOSURE-AF should be viewed as complementary evidence that may help refine patient selection for LAAO rather than as directly contradictory trials.

Single-mechanism closure *vs* dual-mechanism closure

Evidence comparing single-lobe and dual-mechanism LAAO devices has accumulated through several registries and randomized trials. The Prospective Global Amulet Observational Registry was established following CE mark approval of the second-generation Amplatzer Amulet device and provided important real-world data on the performance of dual-mechanism LAAO technology.[121] In the randomized Amulet IDE trial, the Amulet device was noninferior to the Watchman device for both the primary safety endpoint (14.5% *vs* 14.7%) and the primary efficacy endpoint of ischemic stroke or systemic embolism (2.8% *vs* 2.8%).[122] Similarly, the SWISS-APERO trial demonstrated lower rates of peri-device leak with the Amulet device but higher rates of procedure-related complications, primarily pericardial effusion and bleeding, compared with the Watchman/Watchman FLX devices.[123] No significant differences were observed between devices with respect to LAA patency, device-related thrombus, or the composite outcome of cardiovascular death, stroke, and systemic embolism at 45 days or 1 year.[123,124]

Surgical left atrial appendage exclusion and stroke

Early surgical studies established the feasibility and effectiveness of LAA exclusion. LAAOS I demonstrated that complete LAA excision was superior to simple oversewing,[125] while LAAOS II confirmed the safety of surgical LAA amputation with a 100% procedural success rate.[126] The landmark LAAOS III trial randomized 4811 patients with AF undergoing cardiac surgery and demonstrated a 42% reduction in ischemic stroke or systemic embolic events beyond 30 days and a 33% reduction during long-term follow-up (3.8 years) with concomitant LAA exclusion.[127] In a multicenter registry of 291 patients undergoing AtriClip placement during cardiac surgery, the incidence of stroke or systemic embolism was 0.5 per 100 patient-years, corresponding to an 87.5% relative risk reduction compared with expected rates based on CHA_2DS_2-VASc scores.[128] Additionally, the ATLAS trial demonstrated a 51% reduction in thromboembolic events among patients without preoperative AF who developed postoperative AF and underwent concomitant AtriClip exclusion during cardiac surgery.[129]

Percutaneous epicardial left atrial appendage ligation and stroke prevention

Long-term observational data suggest that percutaneous epicardial LAA ligation may reduce thromboembolic risk. In a study of patients undergoing Lariat ligation, the annual rate of stroke or systemic embolism was 1% over a median follow-up of 2.9 years, representing an 84% relative risk reduction compared with expected rates in patients with similar CHA_2DS_2-VASc scores not receiving anticoagulation.[130] Comparable thromboembolic event rates (<2%) have been reported in subsequent Lariat registries.[72,131,132] However, no randomized controlled trials have yet evaluated the efficacy of percutaneous epicardial suture ligation for stroke prevention in patients with nonvalvular atrial fibrillation.

Left atrial appendage occlusion and impact on atrial fibrillation burden and rhythm control

Experimental and clinical studies suggest that LAA exclusion may contribute to rhythm control through electrical isolation and favorable atrial remodeling. Initial animal studies demonstrated that Lariat-mediated LAA ligation resulted in electrical isolation of the appendage.[37,133] Subsequent human studies confirmed immediate elimination of LAA electrical activity and significant reductions in unipolar and bipolar voltage following Lariat ligation, supporting a mechanistic role in reducing AF burden.[134] Furthermore, LAA ligation has been associated with favorable electrical remodeling, including reduced P-wave duration and increased P-wave amplitude, suggesting left atrial debulking and reverse atrial remodeling as additional mechanisms underlying rhythm improvement.[135] Clinical evidence also supports the role of LAA isolation in rhythm control; circumferential LAA electrical isolation was associated with significantly lower 1-year AF recurrence compared with focal LAA ablation or no LAA ablation (15% *vs* 68% *vs* 78%, respectively; P<0.001).[136] Improved clinical outcomes following Lariat-mediated LAA exclusion have also been reported.[137]

In contrast, the randomized aMAZE trial evaluating adjunctive Lariat ligation plus pulmonary vein isolation (PVI) did not demonstrate a significant reduction in recurrent AF compared with PVI alone (64.3% *vs* 59.9%), although a potential benefit was observed in patients with early persistent AF and larger left atrial volumes (>130 mL).[138] Surgical LAA exclusion may provide additional advantages by achieving both electrical and mechanical isolation of the appendage, potentially reducing arrhythmia recurrence while simultaneously lowering thromboembolic risk. However, incomplete exclusion remains a concern and may limit efficacy.[139]

Cost-effectiveness of left atrial appendage occlusion

LAAO has also demonstrated favorable long-term cost-effectiveness despite relatively high upfront procedural costs. Economic analyses have shown reductions in stroke, bleeding, hospitalization, and long-term healthcare utilization compared with both warfarin and DOAC therapy.[140] Improvements in quality-adjusted life-years and lower cumulative healthcare costs have been consistently demonstrated across multiple studies and healthcare systems.[141]

Reflecting the growing body of evidence supporting safety and efficacy, current guidelines from major cardiovascular societies now recommend LAAO as a reasonable alternative for patients with nonvalvular AF who are at moderate-to-high stroke risk and have contraindications to long-term anticoagulation.

Clinical outcomes

Collectively, contemporary studies demonstrate that newer-generation devices are associated with lower rates of complications compared with earlier systems. Long-term randomized and registry data have consistently demonstrated significant reductions in disabling stroke, hemorrhagic stroke, cardiovascular mortality, and all-cause mortality compared with warfarin therapy. Occlusion is noninferior to direct oral anticoagulant therapy for the prevention of stroke and systemic embolism, while providing superior reductions in late nonprocedural bleeding events. Concomitant surgical occlusion during cardiac surgery significantly reduces ischemic stroke risk irrespective of ongoing anticoagulation use, without increasing operative morbidity. Percutaneous epicardial ligation has demonstrated favorable long-term thromboembolic outcomes with significant relative risk reductions compared with expected untreated populations. Electrical isolation of the appendage may reduce atrial voltage and promote reverse remodeling, influencing long-term rhythm control. Occlusion demonstrates sustained cost-effectiveness profiles. High initial procedural costs are offset by long-term reductions in stroke, bleeding-related hospitalizations, and lifelong pharmacotherapy expenses, making the procedure less costly than direct oral anticoagulants over extended follow-up.

Current limitations and future directions

Currently utilized risk scores lack the precision to capture appendage-specific anatomical risks, highlighting the need for integrated computational risk stratification models that incorporate patient-specific variables. Ongoing randomized clinical trials are expected to provide definitive comparative effectiveness data against contemporary direct oral anticoagulants across broader populations, prioritizing specific clinical outcomes over composite endpoints. The applicability of occlusion in extremely frail cohorts, octogenarians, and those with absolute contraindications to anticoagulation requires dedicated prospective study. Universal consensus is needed regarding optimal imaging surveillance protocols, clinically significant peridevice leak thresholds, and standardized management strategies for persistent device-related thrombus. Emerging device innovations are designed to improve endothelialization, eliminate the blood-device interface, and simplify implantation. The intersection of occlusion and rhythm control, specifically the impact of appendage electrical isolation on long-term atrial fibrillation recurrence and the feasibility of subsequent catheter ablation, represents a highly active frontier in cardiovascular research.

Conclusions

Left atrial appendage occlusion has evolved from an investigational alternative to anticoagulation into an increasingly sophisticated and evidence-based strategy for stroke prevention in selected patients with atrial fibrillation. Ongoing advances in device technology, imaging integration, computational modeling, and individualized antithrombotic therapy are expected to further improve procedural safety and long-term outcomes. Future randomized studies and real-world registries will remain essential for refining patient selection, optimizing postprocedural management, and defining the expanding role of left atrial appendage occlusion in contemporary cardiovascular care.

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