INTERVENTIONAL CARDIOLOGY

Left atrial appendage: anatomy and imaging landmarks pertinent to percutaneous transcatheter occlusion

José Angel Cabrera,[1] Farhood Saremi,[2] Damián Sánchez-Quintana[3]

▸ Additional references are published online only. To view please visit the journal online (http://dx.doi.org/10.1136/heartjnl-2013-304464).

[1]Hospital Universitario Quirón-Madrid, European University of Madrid, Madrid, Spain
[2]Department of Radiology, University of Southern California, Los Angeles, California, USA
[3]Department of Anatomy and Cell Biology, Faculty of Medicine, University of Extremadura, Badajoz, Spain

Correspondence to
Dr JA Cabrera, Hospital Universitario Quirón-Madrid, European University of Madrid, Calle de Diego de Velázquez. Pozuelo de Alarcón, Madrid 28223, Spain; jac11339@yahoo.uk

Published Online First 6 March 2014

To cite: Cabrera JA, Saremi F, Sánchez-Quintana D. *Heart* 2014;**100**:1636–1650.

Percutaneous left atrial appendage (LAA) closure represents a complementary option and effective treatment for patients at risk of thromboembolism, especially in patients for whom it may be difficult to achieve satisfactory anticoagulation control or where anticoagulation treatment is not possible or desirable.

Effective and safe transcatheter LAA occlusion requires a detailed knowledge of crucial anatomic landmarks and endocardial morphologic variants of the LAA and its neighbouring structures.[1 2 w1–w3] Our aim in this article is to provide the basic anatomic information that is important for the interventional cardiologist to know when planning an LAA occlusion procedure.

ATRIAL COMPONENTS

The right atrium (RA) forms the rightward and anterior part of the cardiac mass. This overlaps the right band margin of the left atrium (LA). The leftward margin of the RA is marked posteriorly by the interatrial groove, which lies between the superior caval vein and the right pulmonary veins. Owing to the obliquity of the interatrial septum (IAS) plane (approximately 65° from the sagittal plane), and to the different levels of the mitral and tricuspid valve orifices, the left atrium is turned and situated posterior and superior to the right atrium. Only the tip of the LAA contributes to the left cardiac silhouette in a frontal fluoroscopic view of the body (figure 1).

From a gross anatomical viewpoint, both atria have a venous component, a vestibule, and an appendage, and share the IAS.[1 w1] In reality, both atria also possess a body. This is best seen in the LA, and represents the smooth walled component interposed between the vestibule and the venous component. The body of RA is much smaller, and represents the space between the left venous valve, when this structure can be recognised, and the IAS. The venous component of the RA is located posterolaterally and receives the systemic venous return from the superior vena cava, the inferior vena cava, and the coronary venous return from the coronary sinus (figure 1). The venous component located posterosuperiorly is the major part of the LA and receives the pulmonary veins (PVs) at the four corners, enclosing a prominent atrial dome (figure 1). A common ending for the left superior and inferior PVs can be seen in about a quarter of hearts. The vestibule on both atria represents the smooth muscular wall around the atrioventricular (AV) valve orifices that supports the leaflets of the tricuspid or mitral valves (figure 2). The posterior portion of the LA vestibular component directly apposes the wall of the coronary sinus. Just proximal to the vestibular component, the left atrial wall usually is smooth and, unlike the RA, is without an array of pectinate muscles.

The walls of the LA are non-uniform in thickness and in general appear thicker than the RA (figures 3, 4). The walls can be described as being anterior, superior, left lateral, septal, and posterior. The anterior wall is located behind the ascending aorta and the transverse pericardial sinus (figure 3). Part of the anterior wall immediately inferior to the Bachmann bundle and posterior to the aorta can be very thin (1–2 mm).[3] The roof of the superior wall is relatively thick and is in close proximity to the right pulmonary artery. The posterior wall can be the thickest (6.5±2.5 mm) part of the LA but it becomes thinner at the veno-atrial junctions (2.2 ±0.3 mm)[w4] (figure 3) (box 1).

LATERAL RIDGE OF THE LA

The left lateral ridge (LLR) between the orifices of the left PVs and the ostium of the LAA is the most relevant structural prominence on the endocardial side of the LA and therefore an important anatomic determinant during the LAA occlusion procedure. This structure is actually an infolding of the lateral atrial wall protruding into the endocardial LA surface as a prominent crest or ridge.[4] A 3D study using MRI showed that the ridge was narrower than 5 mm in the majority of patients.[5] Our anatomical study demonstrated that the LLR has a narrower width and thicker myocardium superiorly rather than inferiorly.[4] The spatial relationship between the orifices of the LAA and the left superior pulmonary vein (LSPV) is also of relevance. Anatomical studies using multidetector CT[5 6] have shown that in most patients (58–64%) the LAA and LSPV orifices are at the same level. The LAA orifice is shown to be located superior to the LSPV ostium in 22–30% of cases and inferior to it in 12–13%[5] (figure 5) (box 1).

IAS AND TRANSSEPTAL PUNCTURE

It is essential to understand the detailed anatomy of the IAS in order to perform a safe transseptal approach to the LAA. The PLATOO device was the first percutaneous LAA occluder to be introduced in 2002. Despite good preliminary results, the development programme was suspended and the device has been removed from the market.

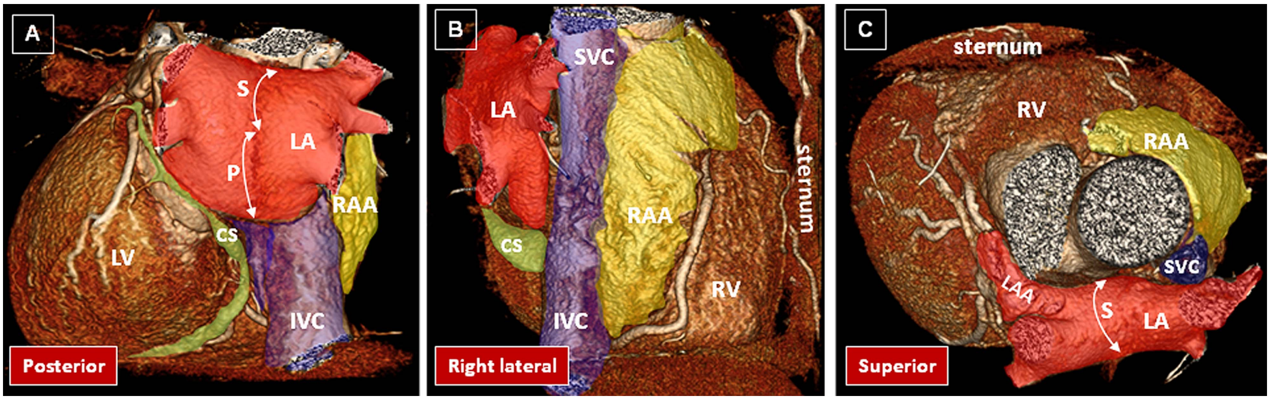

Figure 1 Spatial relationship of the atrial structures as they lie in the body. Posterior, right lateral, and superior view of volume rendered CT angiographies are shown. The left atrium (LA in red) is located superior and posterior to the right atrium. Its superior (S) and posterior (P) walls are shown by double-headed arrows. The right atrial appendage (RAA) is shown in yellow and the venous component of the right atrium in blue. The coronary sinus (CS) tributaries are shown in green. IVC, inferior vena cava; LAA, left atrial appendage; LV, left ventricle; RV, right ventricle; SVC, superior vena cava.

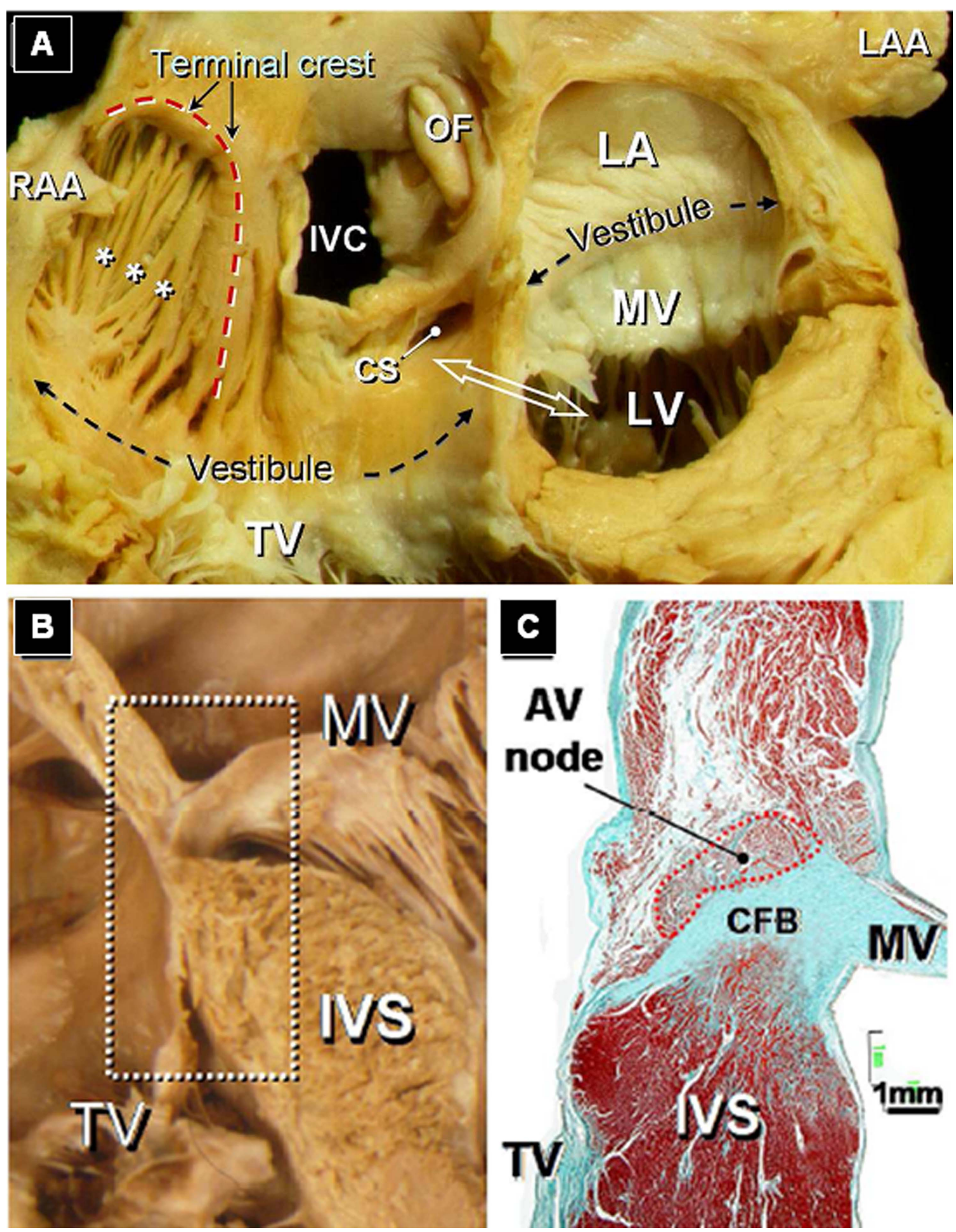

Figure 2 (A) Opened right atrium (RA) and left atrium (LA) in human specimens. Note the tricuspid valve (TV) displaced apically in relation to the mitral valve (MV) and the apposition between the inferior/medial RA and the posterior region of the left ventricle (LV) (double white arrow). The smooth circumferential area of atrial wall surrounding the orifice of the TV and MV is described as the vestibule. The trabeculated wall of the RA anterior to the terminal crest is the right atrial appendage (RAA) and contains multiple pectinate muscles (asterisks), which arise from the crest and extend all around the vestibule. (B) Four chamber section to show the different attachment of the mitral (MV) and tricuspid valve (TV). (C) Histological section corresponding to the location of the atrioventricular (AV) node stained with Masson trichrome. Note the semi-oval shape of the compact AV node that lies over the central fibrous body (CFB). CS, coronary sinus; IVC, inferior vena cava; IVS, interventricular septum; LAA, left atrial appendage, OF, oval fossa.

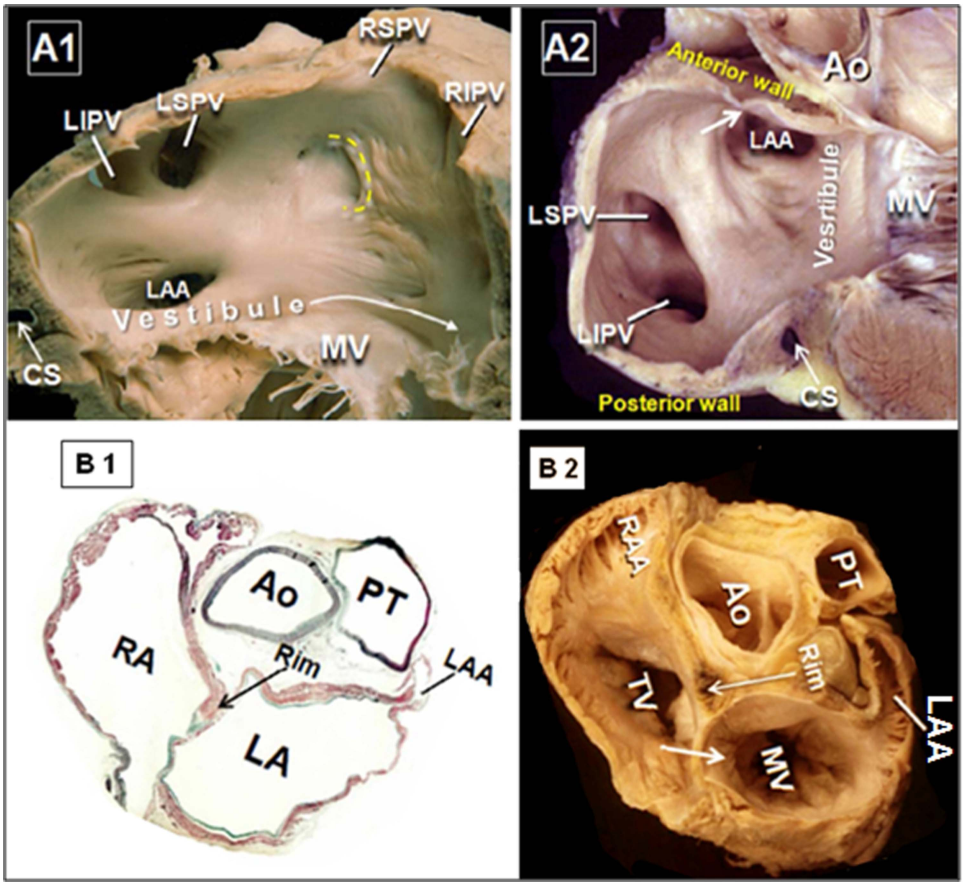

Figure 3 (A1) Dissection of the posterior wall of the left atrium (LA) close to the posterior interatrial groove. The septal aspect of the LA shows the crescentic line of the free edge of the flap valve (yellow dotted line) against the rim of the oval fossa. The orifices of the right superior and inferior pulmonary veins (RSPV and RIPV) are adjacent to the plane of the septal aspect of the LA. (A2) Sagittal section of the heart showing the anterior wall of the LA behind the ascending aorta can become very thin at the area near the vestibule of the mitral valve (arrow). (B1) Histological section with Masson trichrome taken through the short axis of the heart to show the thin flap valve and the muscular rim of the fossa. (B2) Short axis through the interatrial septum (arrow). Ao, aorta; CS, coronary sinus; LAA, left atrial appendage; LIPV, left inferior pulmonary vein; LSPV, left superior pulmonary vein; MV, mitral annulus; PT, pulmonary trunk; RA, right atrium; RAA, right atrial appendage; TV, tricuspid annulus.

Currently, the two devices most frequently used worldwide are the Watchman system (Boston Scientific Natick, Boston, Massachusetts, USA) and the Amplatzer Cardiac Plug (ACP) (St Jude Medical Inc, Minnesota, USA). Both prostheses are implanted at the LAA ostium via the transseptal pathway using the femoral vein access. A newly introduced device is LARIAT (Sentre HEART Inc, Redwood City, California, USA), which employs delivery of an epicardial suture to snare and ligate the LAA after percutaneous pericardial and transseptal access.[w5]

The true IAS is the oval fossa, which is seen as a relatively central depression in the right atrial aspect of the septum. The floor of the oval fossa is formed by the embryonic septum primum which, in most individuals, completely adheres to the periphery (rim or limbus) of the oval fossa[1] (figures 2 and 3). On the left atrial side of the IAS, the floor of the oval fossa is usually indistinguishable from the rest of the atrial wall, except for a small crescent-like edge that marks the free margin of the septum primum.[1] The rim of the oval fossa at the anterosuperior and posteroinferior margins is formed by the infolded muscular right atrial wall and is not considered a true septum. This atrial muscular fold is filled with epicardial fibro-fatty tissue and termed the 'interatrial groove' (also known to cardiac surgeons as the Waterston groove).[w1] The anteroinferior rim, which anchors the flap valve, is also a septal structure which continues into the atrial vestibules on both sides of the septal component and into the Eustachian ridge (sinus septum) on the right atrial side. The anteroinferior rim is continuous with the Eustachian ridge (sinus septum) and the atrial vestibule (figure 2). The anteroinferior rim is separated from ventricles by the fat-filled inferior pyramidal space, through which the AV nodal artery passes.[1]

The IAS has an oblique course from a left anterior to a right posterior position. The angle in relation to the sagittal plane varies with the size of the atrial chambers and the orientation of the heart. Fluoroscopic angulations used for transseptal

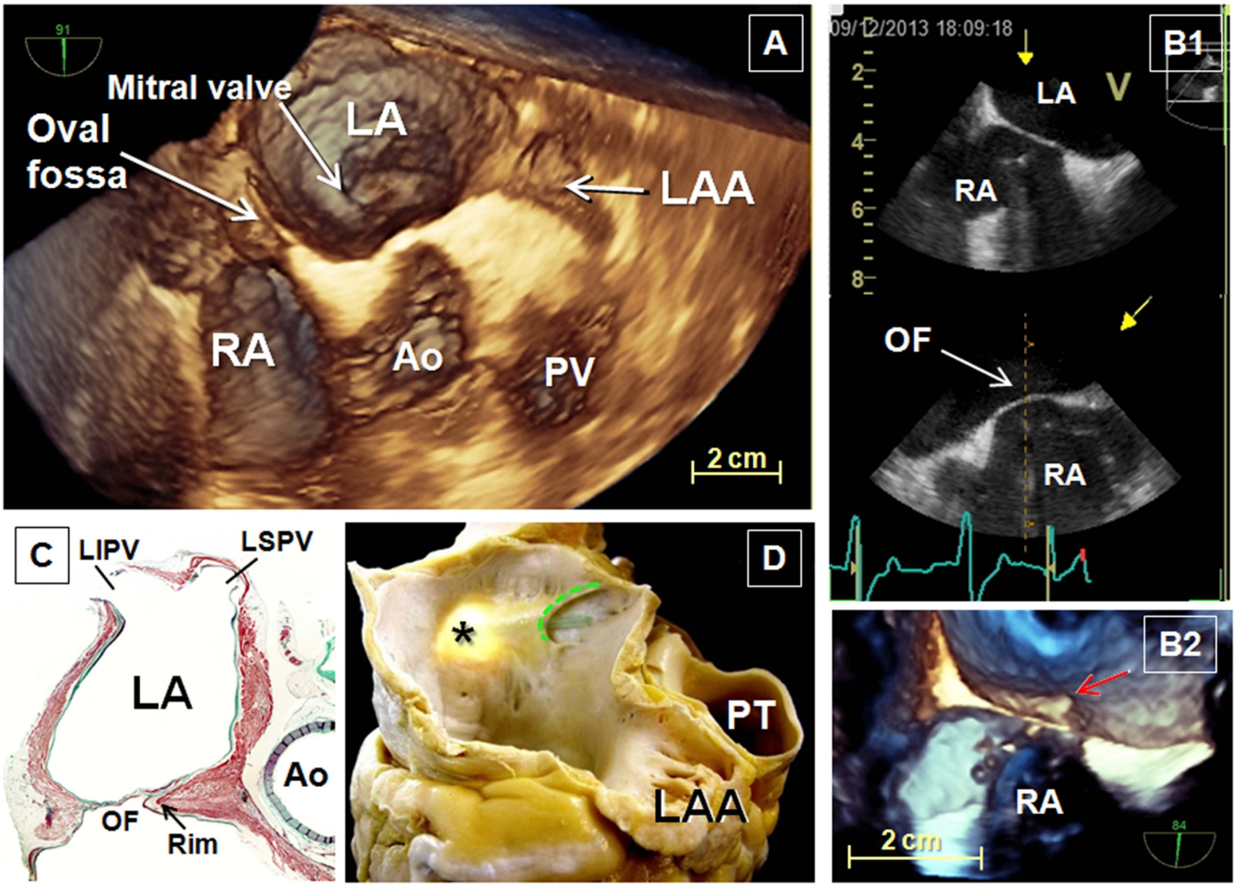

Figure 4 (A) 3D transoesophageal echocardiography (TOE) reconstruction showing the spatial relationship of the oval fossa with the atrial structures and the left atrial appendage (LAA). (B1, B2) 2D and 3D TOE views of transeptal puncture to access the left atrium (LA) through the oval fossa. (B1) Biplane view of the interatrial septum acquired with a 3D matrix array probe that permits simultaneous visualisation of the oval fossa from different angles. The upper image shows the interatrial septum from the mid oesophageal short axis view of the aortic valve, and the bottom panel shows the bicaval view and the tenting of the needle in a superior position (in relation with the superior vena cava). (B2) 3D zoom image reconstruction to visualise the tenting of the fossa (red arrow). Whether the attempted transseptal puncture is posterior or anterior is not well appreciated. (C) Cross-histological section, Masson's trichrome stain. Note the variable myocardial content of the walls of the LA and the oval fossa. (OF). (D) The roof of the LA has been removed and the left atrial side of the septum can be seen by transillumination of the oval fossa (asterisk). It should be noted that panel D is rotated to match other images. In the case of patent foramen ovale, the LA can be accessed from the right atrium (RA) through a crevice (blue dotted line) that is the last part of the valve to be sealed to the rim. Ao, aorta; LIPV, left inferior pulmonary vein; LSPV, left superior pulmonary vein; PT, pulmonary trunk.

punctures must be individualised because of the variability in the position of the heart in the thorax. In the left anterior oblique projection, the interatrial groove is almost perpendicular to the plane of the image intensifier. It is important to remember that all transseptal punctures to access the LA should be performed through the oval fossa. It is the thin floor of the oval fossa (approximately 1–3 mm in thickness) in normal hearts that allows direct access between the atrial chambers (figures 2–4).[w1] It comprises a bilaminar arrangement of myocytes with variable amounts of fibrous tissue.[w1]

The location and size of the oval fossa varies from case to case, as does the profile or prominence of the muscular rim. To minimise the risk of cardiac perforation during LAA occlusion, a low posterior transseptal puncture should be performed to facilitate a frontal approach to the LAA orifice (box 1). Since the anterosuperior rim of the IAS is closely related to the aortic root (figure 1), an accidental puncture in this region and entrance into the transverse pericardial sinus may result in haemopericardium, especially in highly anticoagulated patients.

Precise evaluation of the size of the oval fossa and morphology of a patent foramen ovale (PFO) are crucial at the time of the procedure. In PFO the anterosuperior aspect of the rim is not sealed. Transcatheter LAA closure needs an access that is more inferior, therefore in these cases a lower transseptal puncture should be performed. Other relevant anatomic variants include aneurysm of the IAS, atrial septal defect, and lipomatous hypertrophy of the septum. The latter is characterised by increased deposition of fat in the interatrial groove (not within the true septum) and may

Box 1 Anatomic and imaging determinant for LAA occlusion

Left atrium

Dimensions of the LA: for all devices
Myocardial thickness: anterior wall and venoatrial junctions may be very thin
Distance from the OF to the LAA ostium: for all devices
Accessory LAA: mainly anterior wall and mitral isthmus
Webs and septa
Interatrial septum: should be a low posterior transseptal puncture. OF dimensions, rim thickness, proximity to the aortic root, PFO, patches, occluder devices, and septal aneurysm

Left atrial appendage

Morphological variants: LAA apex directed behind the pulmonary trunk (exclusion criteria for LARIAT)
Ostial diameters/circumference: 17–31 mm (Watchman) and 12.6–28.5 mm (ACP)
LAA length: LAA width >40 mm (LARIAT), should exceed the maximal ostial diameter (Watchman)
LAA angulation: for all devices, less able to be angled a special concern for the Watchman
Maximal length of dominant lobe: for all devices
Multilobular LAA: multilobed LAA oriented in different planes >40 mm (exclusion criteria for LARIAT)
Distance from the ostium to the first bend of the LAA: landing zone that exceeds the maximal ostial diameter for the Watchman, landing zone ≥10 mm for the ACP
Trabeculations (pectinate muscle): should not be mistaken for thrombus
Myocardial thickness: thinner posterior wall and risk of cardiac perforation for all devices
Extra-appendicular trabeculations: risk of cardiac perforation and periprosthetic leaks
Ostial diameters of LSPV
Relation LSPV and LAA orifices: usually at the same level
Lateral ridge orientation and width: poor definition of the orifice limits in ellipsoid LAA
Thrombus: contraindication for ablation

Neighbouring structures

Left circumflex artery: risk for artery compression between the anchoring lobe and the disc for the ACP
Left SAN artery
Great cardiac vein and obtuse marginal vein
Persistent left superior vena cava
Post-CABG venous grafts
Pericardial adhesions: of special concern for the LARIAT
Left phrenic nerve: of special concern for the LARIAT

ACP, Amplatzer Cardiac Plug; CABG, coronary artery bypass graft; LA, left atrium; LAA, left atrial appendage; LSPV, left superior pulmonary vein; OF, oval fossa; PFO, patent foramen ovale; SAN, sinoatrial node.

result in a thickened rim, especially in its anterosuperior and inferior rims, and consequently constriction of the oval fossa. Transatrial access to the LA can be challenging in interatrial communications with patches or occluder devices, and in the presence of an IAS aneurysm or thickened fibrotic septum due to previous transseptal interventions. Transoesophageal echocardiography (TOE) or intracardiac echocardiography remain the imaging methods of choice to facilitate the transseptal approach[2 w2 w3] (figure 4). Anatomical detail can also be clearly evaluated by preprocedure CT angiography of the heart.

MORPHOLOGICAL VARIANTS OF THE LAA

The LAA is seen on the left border between the left ventricle and the pulmonary outflow tract. The tip of the LAA can be in a variety of positions, lying over the pulmonary trunk and the left anterior descending coronary artery, pointing posteriorly, or even directed medially towards the back of the aorta[w6] (figure 6). The LAA tends to have a tubular shape with one or several bends resembling little fingers. A relevant anatomic study in 500 postmortem specimens established that the LAA is multilobed in 80% (two or more lobes) of cases.[7] In this study[7] a lobe was anatomically defined as: (1) a visible ‘outpouching’ from the main tubular LAA, often demarcated externally by a ‘crease’; (2) able to accept a 2 mm probe internally; (3) possibly associated with a change in the main tubular LAA direction; and (4) lying in a different plane from the main tubular LAA. In a recent autopsy study, two and three lobes were observed in 64.3% and 35.7% of specimens, respectively.[8] Accurate sizing of the LAA and knowledge of its gross morphological features are crucial to reduce the frequency of complications associated with percutaneous LAA occlusion (box 1). Using the LARIAT device and based on LAA anatomy, exclusion criteria included: (a) LAA width <40 mm; (b) a superiorly oriented LAA with the LAA apex directed behind the pulmonary trunk; (c) a bilobed LAA or multilobed LAA in which lobes were oriented in different

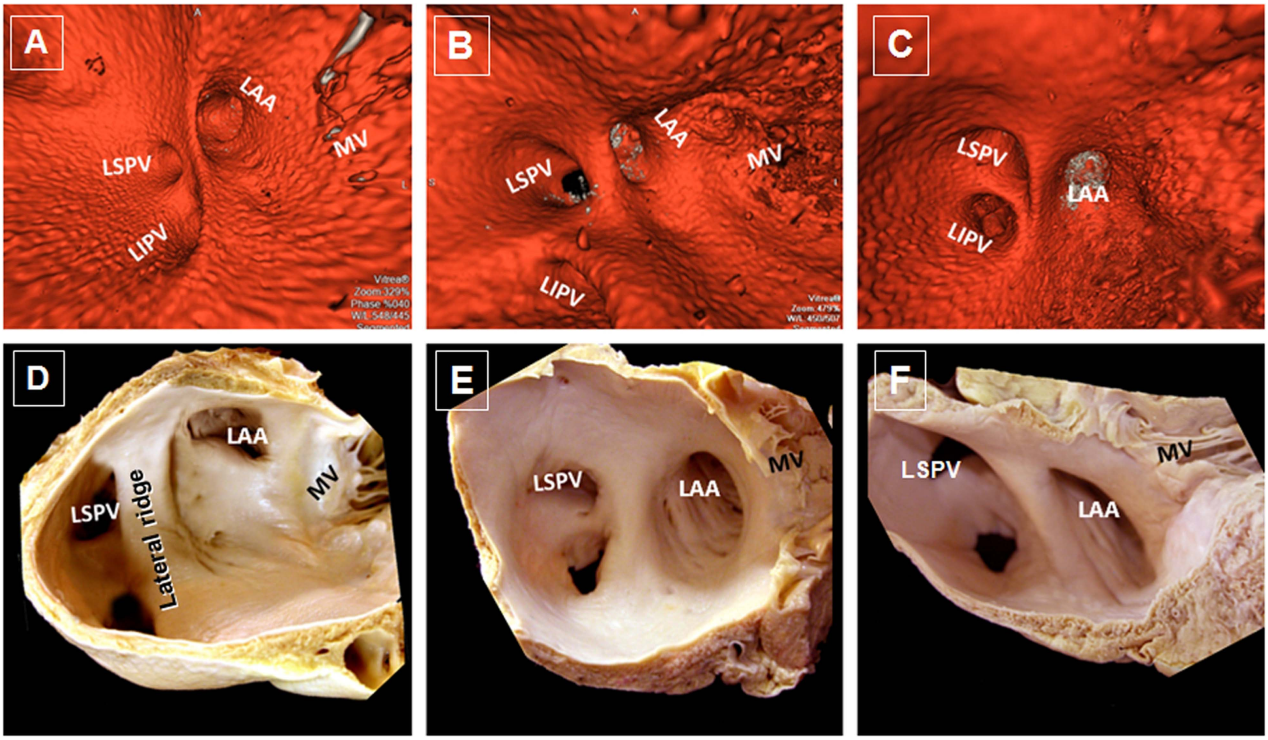

Figure 5 Endoluminal CT (upper row A, B, C) and postmortem (lower row D, E, F) views of the lateral wall of the right atrium showing the ostial relationship of the left superior pulmonary vein (LSPV) and the left atrial appendage (LAA). In the most common variant, the LAA ostium is seen at the same level (B) or anterosuperior (A) to the LSPV ostium. Note that the thickness of the ridge between the pulmonary vein and LAA ostia varies in different examples. LIPV, left inferior pulmonary vein; MV, mitral valve annulus.

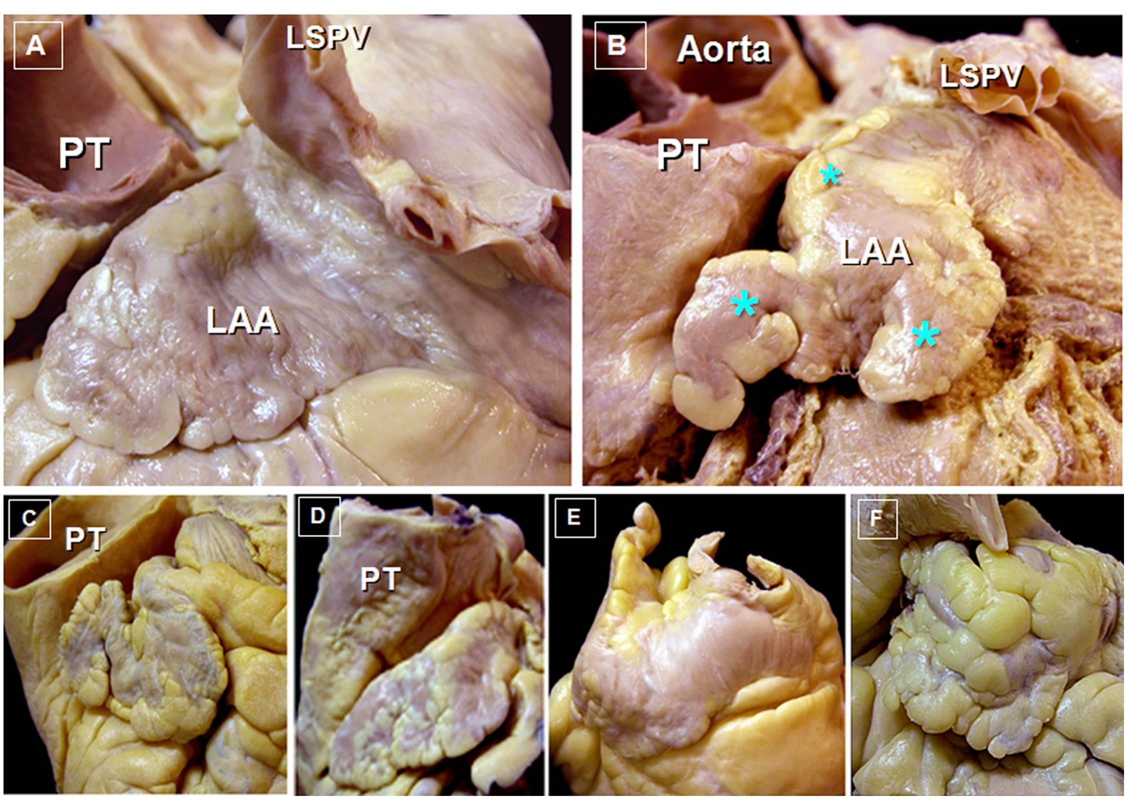

Figure 6 Postmortem specimens. Morphological variants of the left atrial appendage (LAA). Panels A and B show the different morphologies of the LAA including a single lobe (A) and multilobed (B, asterisks). (C–F) Common variants of the gross morphology of the LAA: chicken wing (C), windsock (D), cactus (E), and cauliflower (F). LSPV, left superior pulmonary vein; PT, pulmonary trunk.

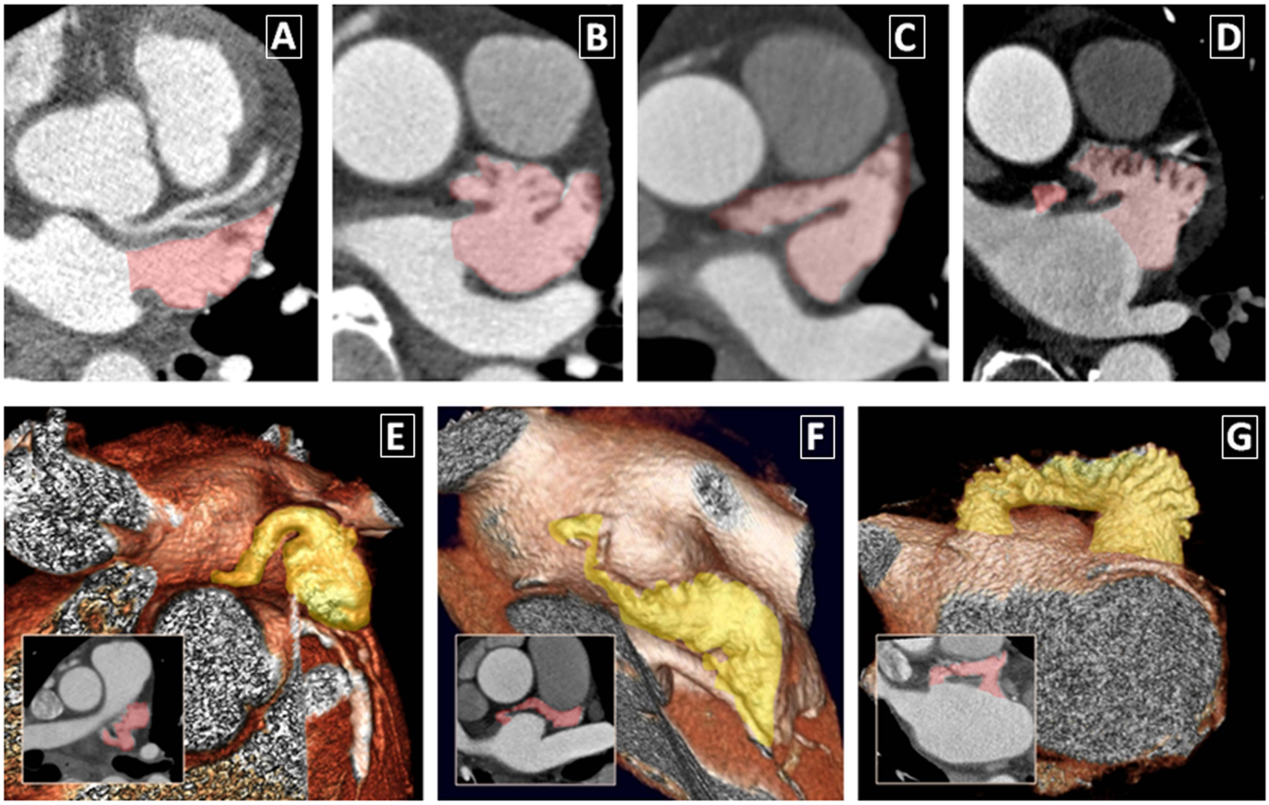

Figure 7 Morphological variations of the left atrial appendage (LAA). (A–D) Axial CT images at the left of the neck of the LAA showing common variants of the LAA. (E, F) Sculpted volume rendered CT views of the left atrium along with inlay axial 2D images at the level of the LAA showing three rare variants of the LAA. The LAA is colour coded. The most common variant is the LAA with two lobes (B, D). It is not uncommon to see that the tip of the LAA is medially rotated (C, E). Small accessory appendages arising from the anterior wall are not uncommon (D) and in rare instances may connect to the tip of a medially rotated LAA (F, G). Panels C, E, and F are not candidates for an epicardial approach to percutaneous LAA exclusion.

planes exceeding 40 mm; and (d) a posteriorly rotated heart.[w5]

Comprehensive imaging of the entire LAA is important in order to evaluate the LAA morphological variants and diagnose an intraluminal thrombus. The LAA is the major source of cardiac thrombi in atrial fibrillation (AF) and plays a major role in cardioembolic events.[w4 w6] CT and MRI can be used to assess the LAA morphology and thrombus (figures 7, 8). However, TOE remains the imaging method of choice to exclude LAA thrombus. The main echocardiographic exclusion criterion for percutaneous LAA occlusion is the presence of thrombus in the LAA, although the presence of spontaneous echo contrast and significant valve disease should be noted.[w2 w7] In a recent study, Di Biase *et al*[9] analysed gross morphology of the LAA in patients with AF using CT and MRI. The LAA morphologies were classified as cactus (30%), chicken wing (48%), windsock (19%), and cauliflower (3%). The study showed that patients with chicken wing LAA morphology were less likely to have an embolic event.

Left atrial contour abnormalities such as cauliflower-like accessory LAAs have been increasingly recognised with the improved spatial resolution of modern non-invasive imaging modalities[10] (figure 7). These outpouchings of the LA have been reported in 10–15% of the adult population and are usually seen in two anatomic locations: the anterior wall of the LA (projecting into the transverse sinus); and the left atrial isthmus. These accessory atrial appendages may be the source of unexplained embolic stroke or interfere with interventional procedures.[10]

OSTIUM OF THE LAA

In autopsy specimens and imaging studies, the LAA ostium is usually elliptical or round and in elliptical-shaped variant, its long axis is obliquely orientated relative to the mitral annulus.[8 11] The mean longest diameter of the LAA orifice is 16–17 mm and the mean shortest diameter is around 10–11 mm.[8 11] Wang *et al*[6] performed a cardiac CT study in patients with or without AF and classified the orifice into five types: oval (68.9%), foot-like (10%), triangular (7.7%), water drop-like (7.7%), and round (5.7%). A real-time 3D TOE study demonstrated a progressive increase in LAA orifice, becoming more round-shaped with increasing frequency of AF.[12] Attention should be given to these variations in shape of the LAA orifice before

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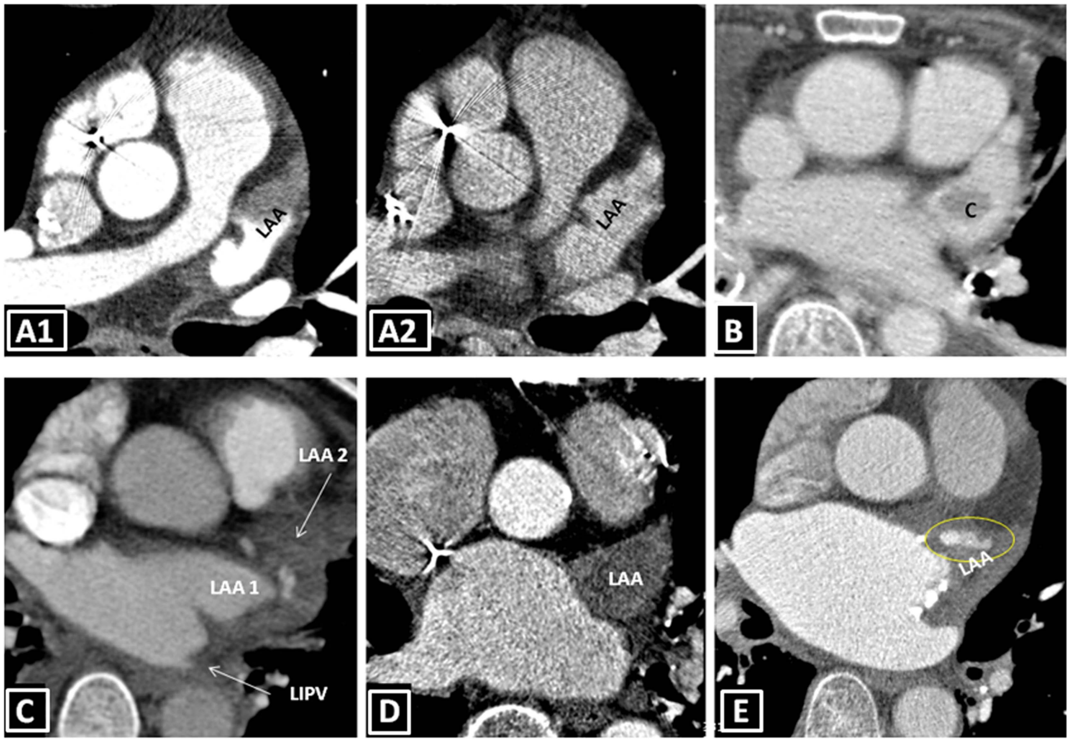

Figure 8 CT findings in patients with atrial fibrillation in relation to the left atrial appendage (LAA). (A1, A2) Axial CT image at first pass of contrast showing filling defect in the LAA which disappears on the delayed phase (A2) consistent with pseudothrombus. This phenomenon is very common in patients with atrial fibrillation at the time of scan. (B) Delayed post-contrast axial CT showing a real thrombus (c) in the LAA lumen. (C) Axial CT same day after Maze ablation showing partial exclusion of the LAA (LAA2). Residual patent LAA (LAA1) and occluded left inferior pulmonary vein (LIPV) are evident. (D) LAA appearance after successful percutaneous exclusion. (E) Incomplete LAA occlusion after ablation showing contrast extravasation into the ablated part (circle).

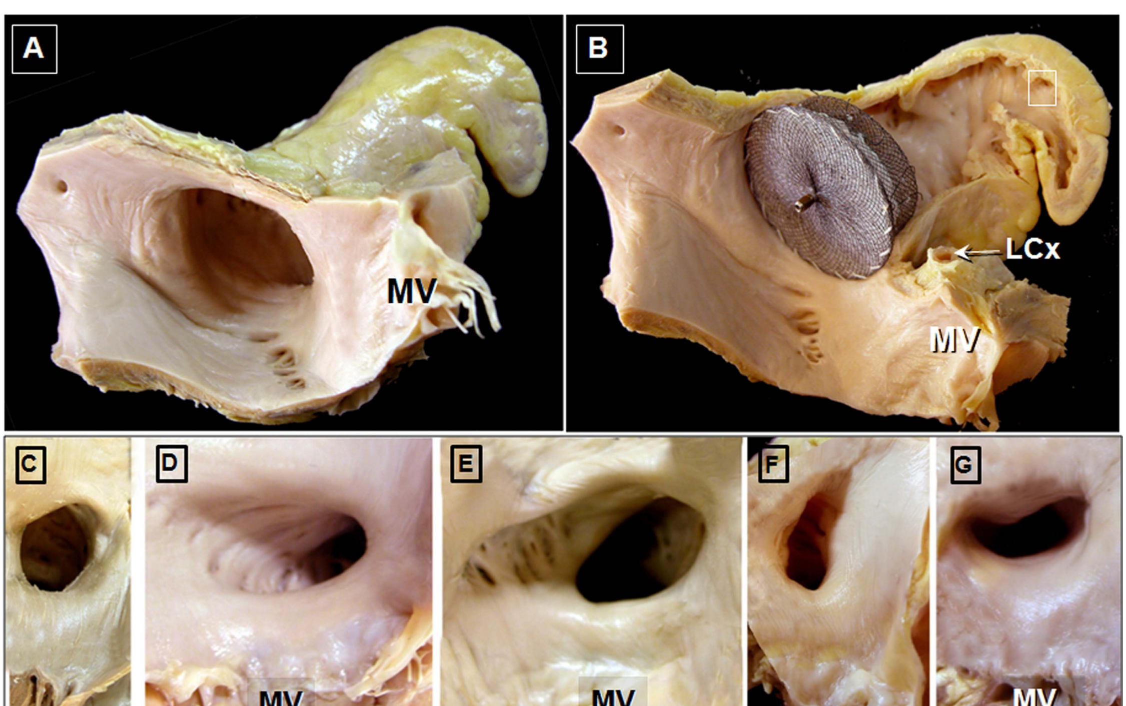

Figure 9 Morphological shape in postmortem specimens of the left atrial appendage (LAA) ostium and its variations. (A) LAA in chicken wing morphology with a round ostium. (B) The LAA was opened and an Amplatzer Cardiac Plug was implanted with the lobe at ∼10 mm from the ostium and the disc covering the entrance to the LAA. (C, D) Two common variants of the ostium of the LAA, round and elliptic, respectively. (E–G) LAA ostia vary in different examples: triangular (E), water drop-like (F), and foot-like (G). LCx, left circumflex artery; MV, mitral valve annulus.

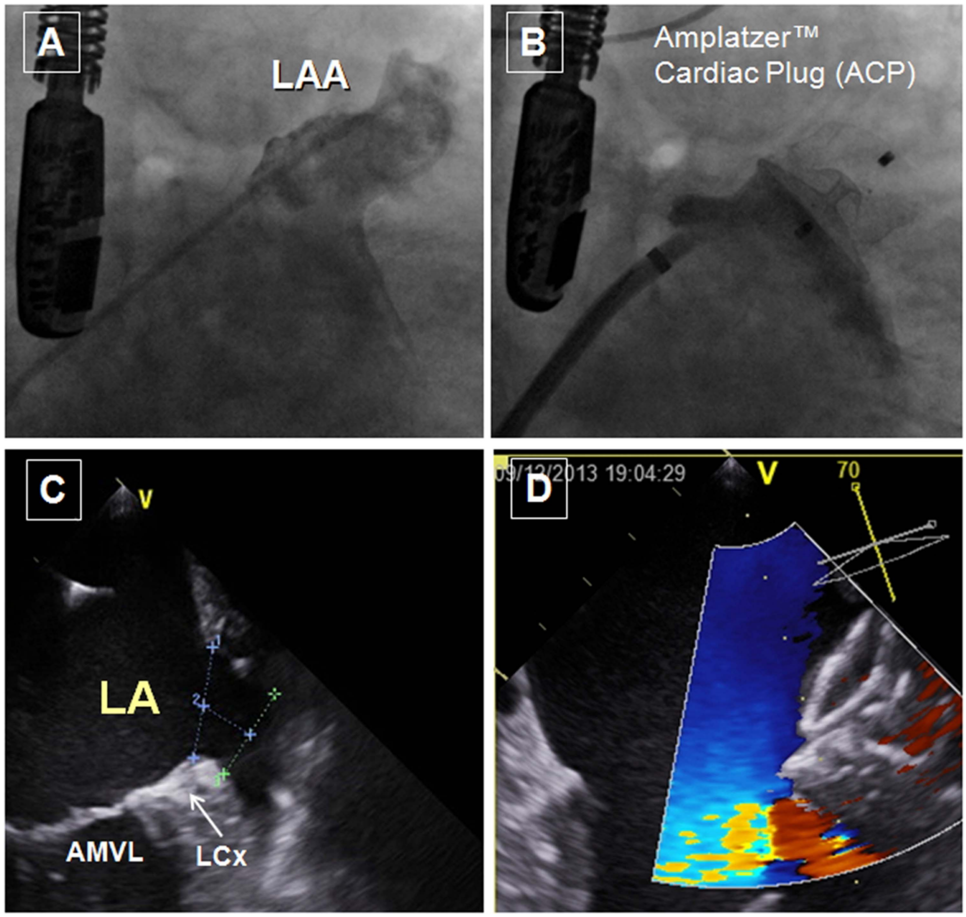

Figure 10 (A) Angiographic imaging of the left atrial appendage (LAA). (B) Position of the Amplatzer Cardiac Plug (ACP) device after implantation in the LAA and angiographic control to assess the success of occlusion immediately post-procedure. (C) 2D multiplanar transoesophageal echocardiography assessment of the ostial dimension of the LAA to determine the size of the device required. The green line represents the dimension taken for the landing zone of the ACP device. (D) Colour Doppler echocardiography post-implantation demonstrating lack of flow. AMVL, anterior mitral valve leaflet; LA, left atrium; LCx, left circumflex artery.

percutaneous occlusion device placement is undertaken (figure 9) (box 1).

Pre-procedural assessment of the ostial dimensions of the LAA is crucial for correct sizing and safe placement of the device required. The principal difference between the two occlusive devices is their shape. The Watchman system is implanted at 10 mm from the ostium of the LAA, and therefore does not cover it. The ACP contains a distal anchoring lobe that is implanted 10–15 mm from the ostium and a proximal disc that covers the entrance to the LAA. The maximal cross-sectional diameter of the LAA orifice recommended for device implantation ranges from 17–31.9 mm for the Watchman and 12.6–28.5 mm for the ACP device. With the ACP device, care should be taken to size the landing zone of the anchoring lobe, since the device cannot be used if this area is <10 mm in width[13] (figure 10). In addition, the distal lobe should be 1.5–3.4 mm larger than the diameter. For the Watchmann device, an important anatomic determinant is that the LAA length should exceed the maximal ostial diameter to ensure a landing zone. Stöllberger *et al*[14] compared TOE measurements of the LAA with postmortem casts and demonstrated that the LAA size and orifice can be assessed reliably by echocardiography, especially in the horizontal plane.

Accurate measurement of the LAA ostial diameters and circumference is critically important for successful device ostial closure; 2D TOE significantly underestimates LAA dimension and orifice size as compared with 3D TOE[15] (figure 11). Some groups use only intracardiac echocardiography, or even angiographic control, to guide the procedure. CT can also provide precious information. It should be noted that the dimensional axes obtained by different imaging techniques may not be the same. Discrepancies found in ostial measurements between different imaging techniques are more frequent in the LAA with ellipsoid morphology due to the proximity of the posterosuperior rim of the ostium with the LLR, causing a poor definition of the orifice limits. CT may facilitate the implantation strategy and selection of the appropriate device occluder size in these cases. Additional information that can be best obtained with CT or 3D TOE includes spatial relationship and orientation of the LAA with surrounding structures.[w7–10]

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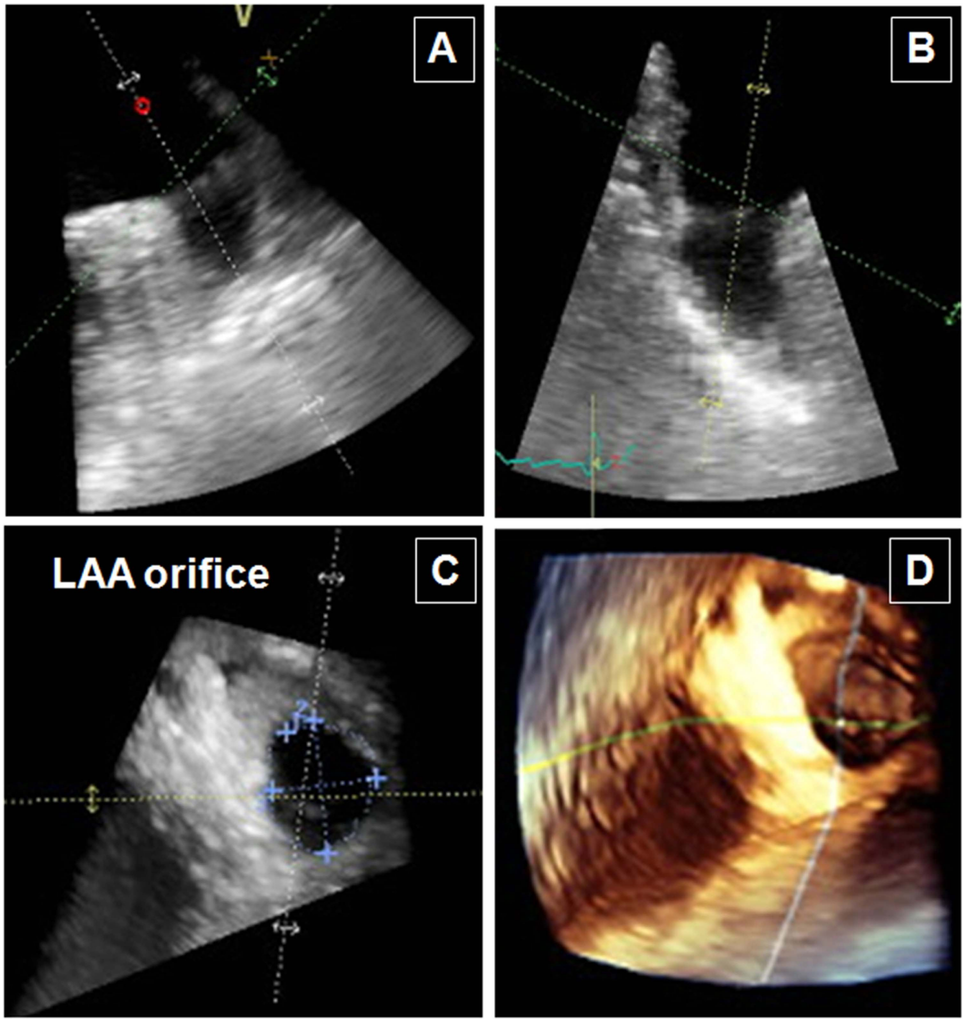

Figure 11 (A, B) Left atrial appendage (LAA) obtained using 3D transoesophageal echocardiography. The LAA long axes were aligned allowing visualisation of the LAA orifice in the short axis and the landing area where the measurements of the LAA should be performed to select the Amplatzer Cardiac Plug device size. (C) The area of the LAA orifice, as well as the maximum and minimum diameters of the LAA, can be obtained. (D) 3D reconstruction of the LAA orifice.

PECTINATE MUSCLES OF THE LAA

A complicated network of fine pectinate muscles lines the endocardial surface of the LAA (figure 12). The pectinate muscles have been thicker than 1 mm in most of our autopsy hearts (95–97%). Pectinate muscles <1 mm in size have been noted only in the specimens from the first or last decade of life.[7] Between the muscle bundles, the LAA wall can be paper-thin (figure 12). When investigating the LAA by TOE or contrast enhanced CT, the pectinate muscles should not be mistaken for thrombus. In a recent study, Anselmino *et al*[16] correlated the LAA morphology and the amount of trabeculations as detected by CT with the burden of silent cerebral ischaemia as a new thromboembolic risk marker in AF patients. They observed mild trabeculations in LAAs with a chicken wing morphology, moderate trabeculations in cases with a cactus morphology, and extensive trabeculations in LAAs with a cauliflower morphology. Although cauliflower morphology with extensive trabeculations was the uncommon type in their series (5.2%), they were more likely to have a silent cerebral ischaemia.

In some specimens (28%), muscular trabeculations can be found extending inferiorly from the appendage to the vestibule of the mitral valve.[4] These extra-appendicular myocardial bands correspond to the small set of posterior pectinate muscles originating from the myocardial bundles to embrace the LAA (figure 12). In those hearts with extra-appendicular posterior pectinate muscles, the areas between the muscular trabeculae and the atrial wall become exceptionally thin (0.5 ±0.2 mm),[4] increasing the risk of cardiac perforation during transcatheter closure devices. Large muscular extra-appendicular trabeculations in the area close to the ostium of the LAA may also facilitate periprosthetic leaks after the device implantation. Postmortem and explanted heart studies from patients with AF showed larger volumes (three times) and orifices of the LAA than those

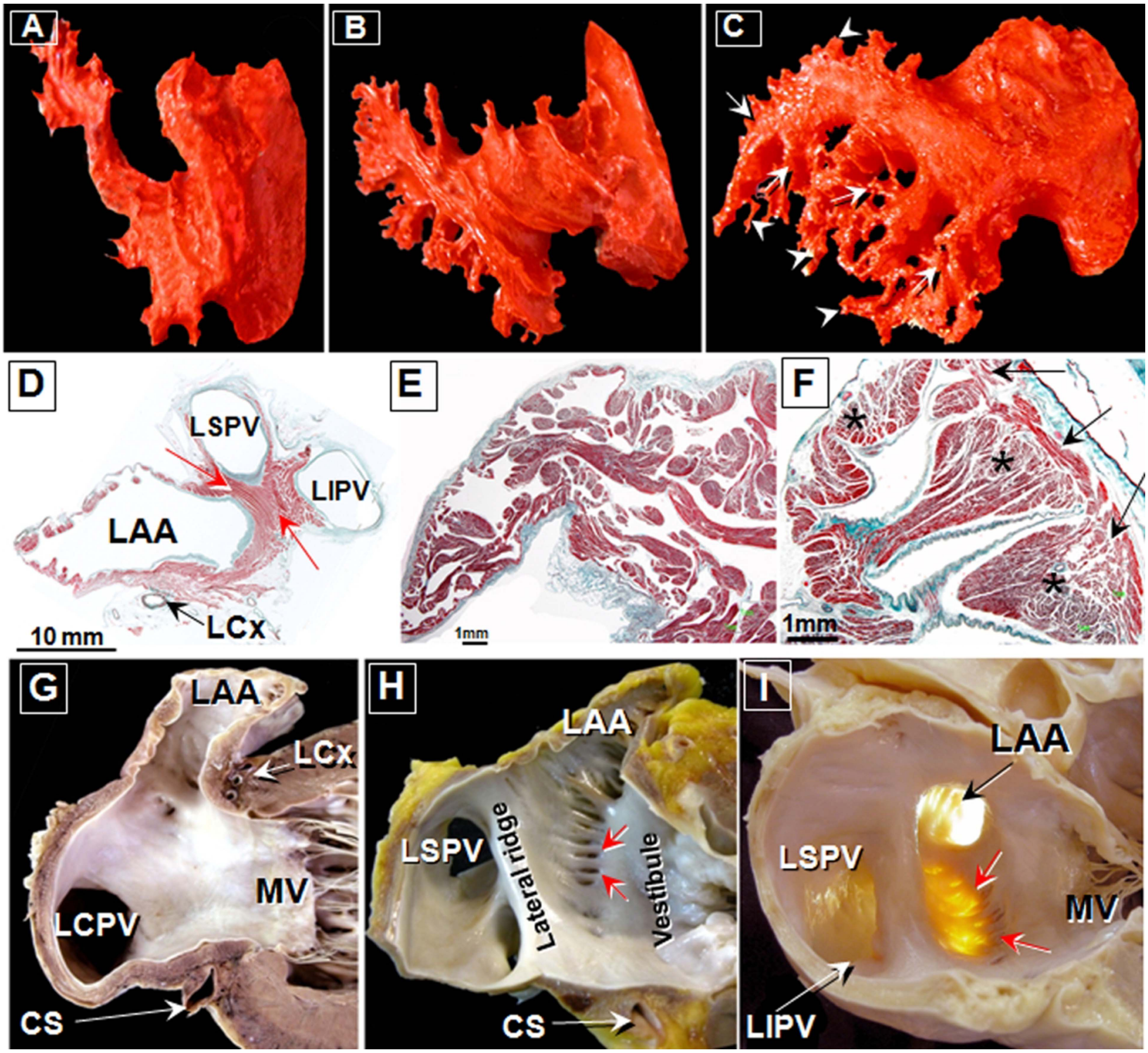

Figure 12 (A–C) Resin casts showing the density of the endocardial trabeculations of the left atrial appendage (LAA), which may be classified into three types: (A) mild trabeculations (chicken wing morphology); (B) moderate trabeculations (cactus morphology); (C) extensive trabeculations (cauliflower morphology). Note in panel C the extensive branches (arrows) and twigs (arrowheads) of the pectinate muscles. (D) Sagittal section through the left pulmonary veins and the LAA. Note the relationship of the myocardium of the left pulmonary veins with the LAA through the lateral ridge (red arrows). (E, F) Sagittal sections stained with Masson trichrome through the pectinate muscles of the LAA. Note in panel E the non-uniform arrangement of the pectinate muscles within the LAA. In higher magnification (F) the myocytes of the pectinate muscles are arranged in two layers: a thin epicardial layer (arrows) and thick endocardial layers (asterisks). Within each layer the myocytes are irregularly arranged. (G–I) Endocardial visualisation of the left posterolateral wall. Note in panel G the absence of the lateral ridge between the LAA and the left common pulmonary veins orifice (LCPV), while in panels H and I exist a prominent lateral ridge and extrapectinate muscle trabeculations (red arrows) extending inferiorly from the appendage to the vestibule of the mitral valve. Transillumination in panel I shows the atrial wall becoming exceptionally thin. CS, coronary sinus; LCx, left circumflex artery; LIPV, left inferior pulmonary vein; LSPV, left superior pulmonary vein; MV, mitral valve annulus.

from patients in sinus rhythm. Furthermore, in most patients (73%) with chronic AF, the LAA showed significant endocardial thickening with fibrous and elastic tissue (endocardial fibroelastosis) compared to those without AF.[17] Such features may contribute to the increased risk of thrombus formation and systemic embolism (figures 8, 13). Additionally, the information may have relevance in interpreting TOE images of the LAA in patients with chronic AF.[9]

MUSCULAR ARCHITECTURE OF THE LAA

Structurally, the LAA has a very fine and a non-uniform myocardial wall thickness.[3] As can be seen in figure 14, the posterior wall of the LAA shows a notably thinner myocardial content (<1 mm). Detailed transmural dissections of the LA wall and LAA have shown a complex architecture of overlapping cardiomyocytes, with different orientations giving the false impression of layers, as these are not separated by sheaths of insulating fibrous tissue.

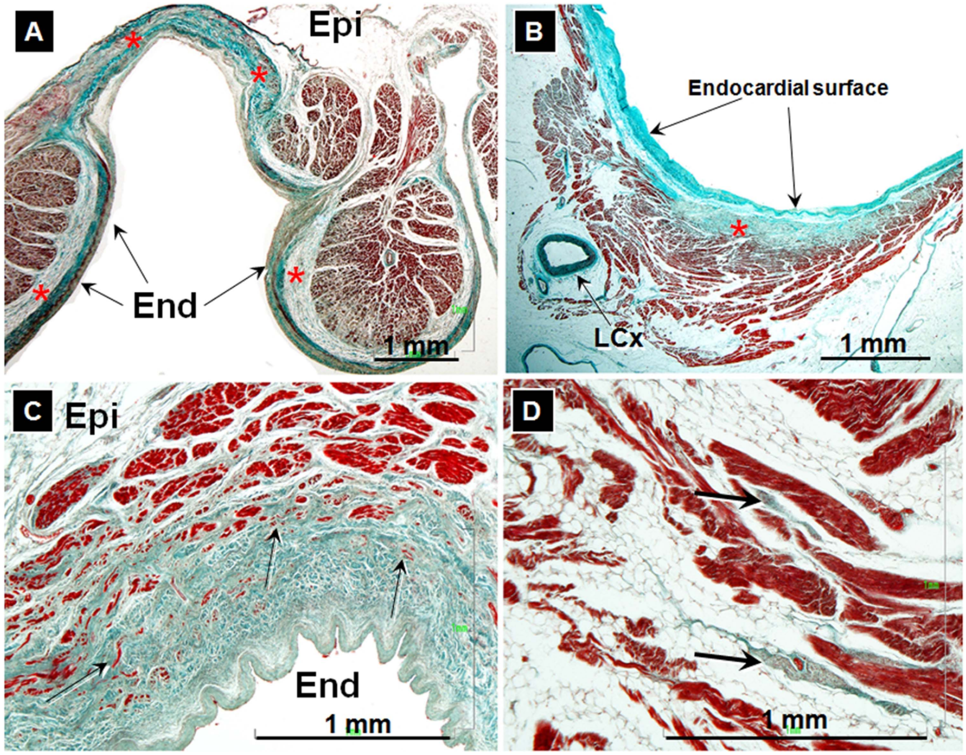

Figure 13 Histological sections of the left atrial appendage (LAA) stained with Masson trichrome, from two patients with chronic atrial fibrillation. In panels A and B the LAA shows significant endocardial thickening (arrows) with fibrous and elastic tissue (endocardial fibroelastosis) (asterisks). Note in panel C at the junction between the endocardium and myocardium a degeneration of the myocytes with adipose cell infiltration and fibrosis (arrows). In panel D the increase in collagen and elastic fibres of the endocardial surface may extend to the epicardium, affecting the autonomic nerves (arrows). End, endocardium; Epi, epicardium; LCx, left circumflex artery.

There are individual variations from heart to heart, but in general the myoarchitecture conforms to the pattern first shown so elegantly in human hearts by Papez in 1920.[18] From the epicardial aspect, it is common to find a broad muscular bundle that runs along the anterior atrial wall known as the Bachmann or interatrial bundle. This bundle is composed of myocytes that are aligned in parallel fashion relative to the plane of the AV junction, and extends from the right superior cavoatrial junction towards the lateral wall of the left atrium.[w11] The leftward extension of the Bachmann bundle bifurcates around the neck of the LAA (figure 14), and then reunites to form a broad band that runs circumferentially around the vestibular wall of the posterior surface of the LA to enter the posterior septal raphe.

Another important bundle described by Papez[18] is the septopulmonary bundle, which is composed of longitudinally to obliquely arranged myocytes. The myocytes of this bundle fan out around the insertions of the pulmonary veins to join the venous muscular sleeves.[w10] The bundle also extends to fuse with the myocytes arriving from the roof and anterior wall of the LAA. The septopulmonary bundle also forms part of the subepicardial myocytes at the LLR. Deeper than the septopulmonary bundle is the septoatrial bundle[18] which forms the subendocardium. It arises from the anterior and inferior parts of the IAS, and divides into three bands. The first band fans out towards the orifices of the right PVs and combines with the oblique myocytes from the anterior vestibule. The second band combines with leftward myocytes of the septopulmonary bundle at the orifices of the left PVs to form muscular loops around the venoatrial junctions. Some myocytes of the third band run leftward and anteriorly around the opening of the LAA, while other myocytes continue into the fine trabeculations of the pectinate muscles lining the cavity of the appendage (figure 14). The last two bands contribute to the deep myocytes of the LLR.[w11]

ANATOMIC RELATIONSHIPS OF THE LAA

Vascular structures

The LAA ostium is situated above the left AV groove which contains the left circumflex artery and the great cardiac vein together with their branches.[w1] The distance of the LAA ostium from the AV groove is variable, but in some cases close approximation of the left circumflex artery (LCx) to the ostium can make it vulnerable to injury during implantation of occluder devices, especially when devices are sized to be larger than the ostium. The lower end of the anchoring lobe is usually just distal to the artery and attention should be paid to avoid compression of the LCx between the lobe and the disc during ACP implantation. The potential for LCx injury is also present when occlusion is performed by an epicardial approach using snare devices (box 1). In patients after coronary artery bypass surgery, the

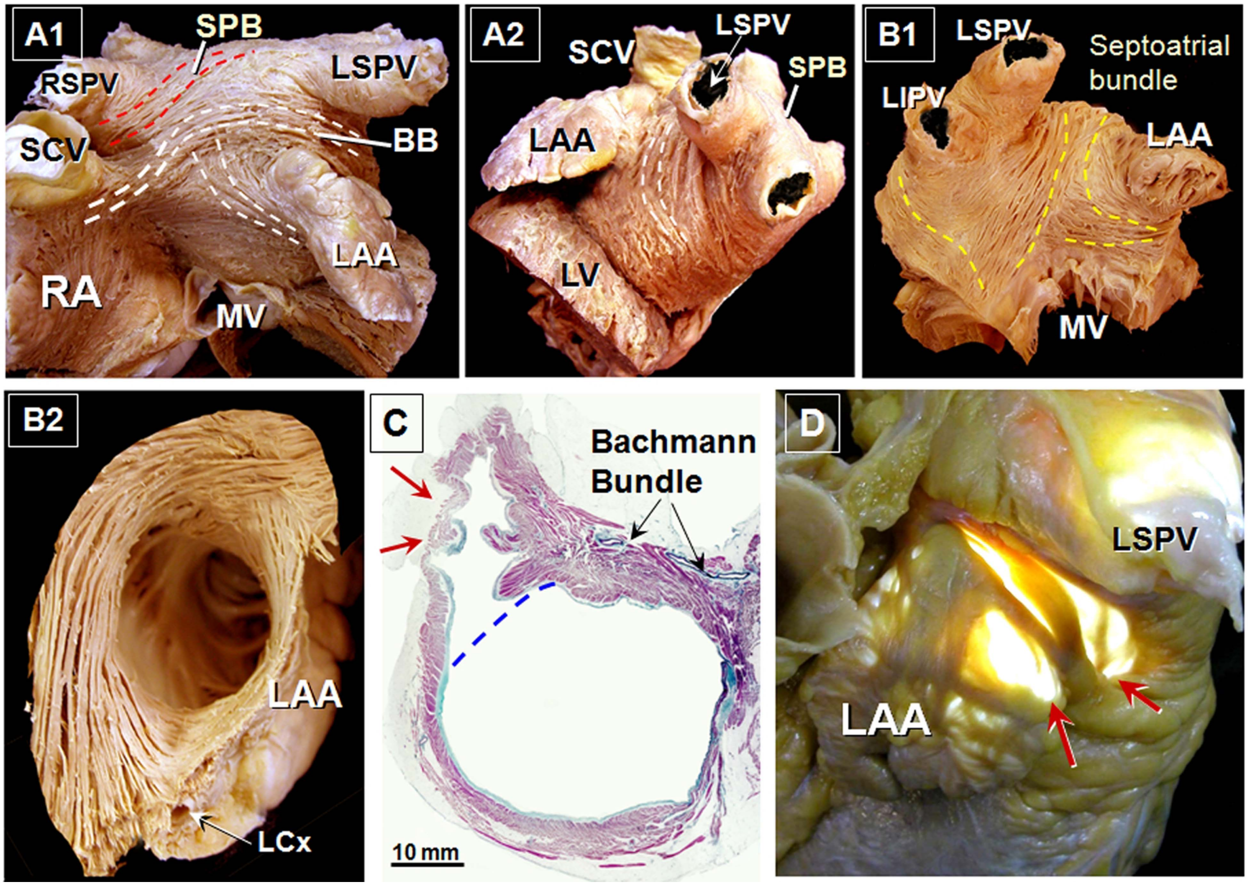

Figure 14 (A1, A2). Dissections of the subepicardial fibres viewed from the anterior and left lateral aspects. Bachmann bundle (BB, white broken lines) crosses the septal raphe, blends into the circumferential fibres of the anterior wall (dotted lines), to pass either side of the neck of the left atrial appendage (LAA) to run in parallel fashion to the lateral aspect (A2) of the left atrium. Oblique fibres of the septopulmonary bundle (SPB, red broken lines) become longitudinal as they cross the roof between the left superior and inferior pulmonary veins. (B1) The left lateral wall is everted to show the subendocardial fibres and the fibre arrangement of the septoatrial bundle and its three major fascicles (yellow dotted lines). Note in panel B2 the circular arrangement of the endocardial fibres around the neck of the LAA. In panels C and D note a non-uniform myocardial wall thickness (red arrows) at the level of both the left atrium and LAA. Transillumination in panel D shows the LAA with an exceptionally thinned wall. LCx, left circumflex artery; LIPV, left inferior pulmonary vein; LSPV, left superior pulmonary vein; MV, mitral valve annulus; RA, right atrium; RSPV, right superior pulmonary vein; SCV, superior cava vein.

anatomic passage of the venous graft targeted at obtuse marginal or diagonal branches can be very close to the tip of the appendage, making it vulnerable to injury in the percutaneous epicardial approach (figure 15).

It is well established that the sinoatrial node (SAN) artery can originate from the left coronary system in 30–40% of patients. In postmortem dissection and angiographic studies the left SAN artery was seen to arise from the LCx in 30% of the cases and from the left lateral atrial artery in 8%.[w12] The latter arises from the proximal to the mid portion of the LCx and demonstrates an S-shaped course between the LAA and the LSPV to reach the transverse pericardial sinus. This artery has been detected in 14% of coronary CT angiographies.[19] The S-shaped SAN artery can be at risk of injury during placement of LAA exclusion devices.

CT is the modality of choice to demonstrate the relationship of the vessels with the LAA ostium. Other vessels that can be seen in the ridge between the LAA and LSPV are the persistent left superior vena cava and the vein of Marshall[4] (figure 15). The vein or ligament of Marshall is located at the epicardial aspect of the ridge in close proximity to the endocardial surface, at a distance of 3 mm from the superior level of the ridge in almost 75% of the specimens, along with abundant autonomic nerves bundles.

Left phrenic nerve

The phrenic nerves lie along the lateral mediastinum, and run from the thoracic inlet to the diaphragm[w13] (box 1). In our study of cadavers, the left phrenic nerve and its accompanying pericardiophrenic vessels passed in the fibrous pericardium that was overlying the tip of the appendage in 59% of hearts and over the neck of the appendage in 23%[20] (figure 16). CT angiography demonstrated the left phrenic neurovascular bundle and its relationship to the LAA as it passes over the pericardium in almost two-thirds of studies[w14] (figure 16).

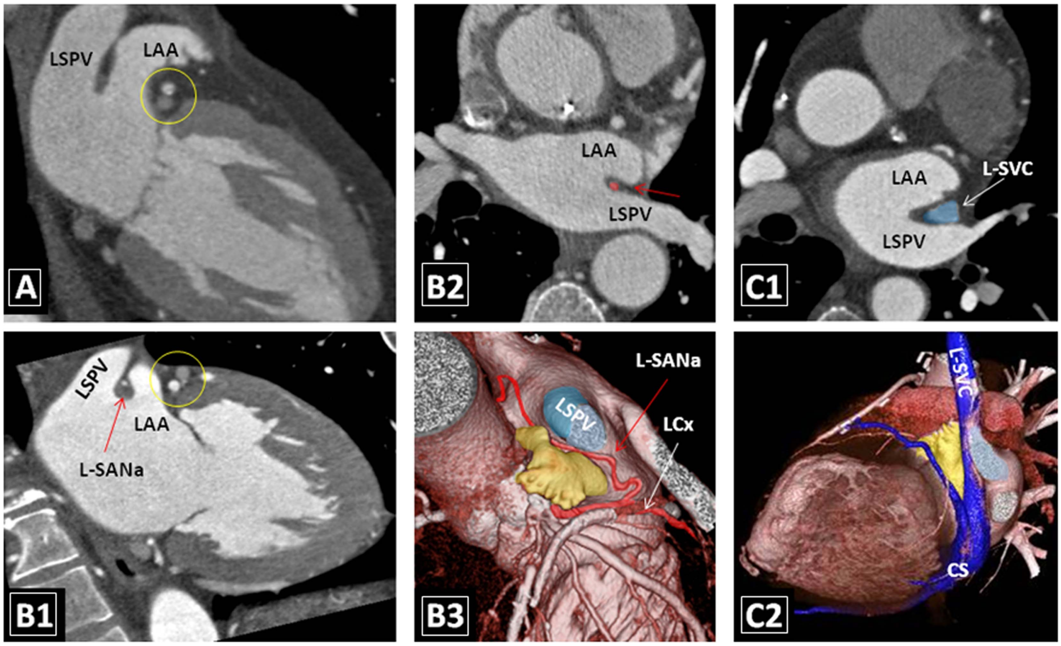

Figure 15 Relationship of vessels with the left atrial appendage (LAA). (A, B1) Left two chamber CT images showing the anatomic course of the left circumflex artery and great cardinal vein (within the yellow circle) in the atrioventricular groove and inferior to the neck of the LAA. (B1–3) In order, axial, two chamber, and left lateral volume rendered CT images showing the anatomic course of the S-shaped left sinoatrial node artery (L-SANa) in the groove between the LAA and the left superior pulmonary vein (LSPV). The S-shaped variant of the left SANa is seen in 14% of individuals and comprises 30% of the left SANa. (C1, C2) Axial and left lateral volume rendered CT images showing a persistent left superior vena cava (L-SVC) passing between the LAA and LSPV until it connects to the coronary sinus (CS). This variant is seen in <1% of the population but is more common in congenital heart disease.

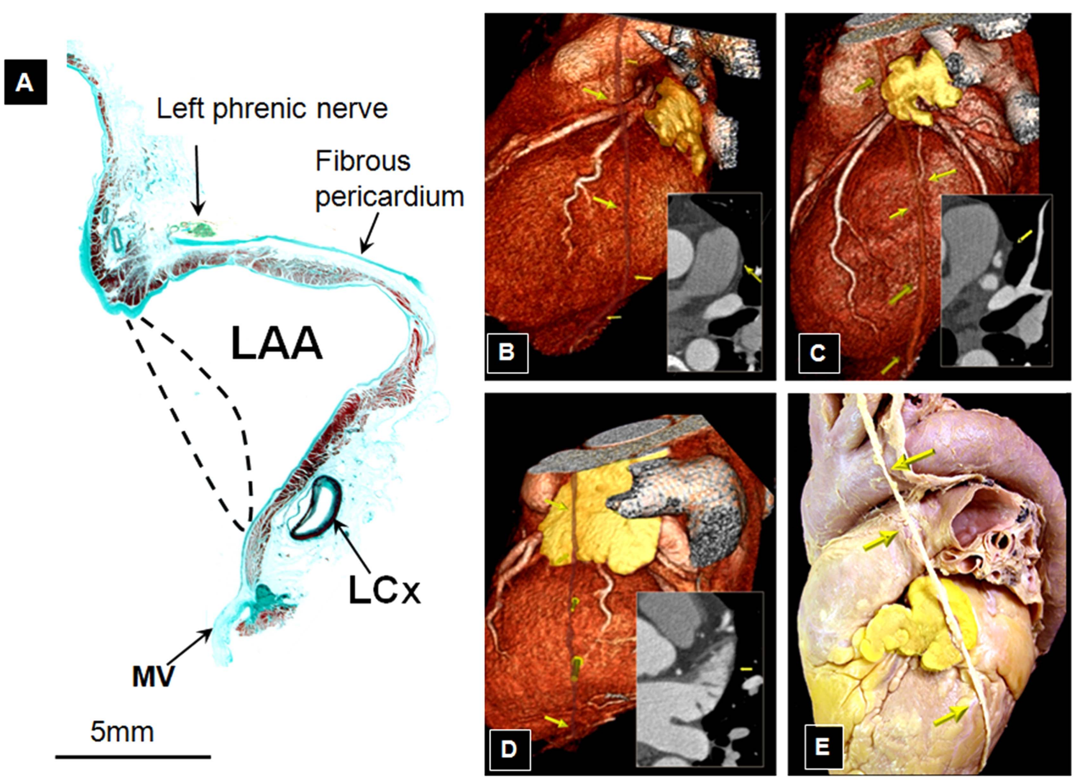

Figure 16 Anatomic relationship of the left circumflex artery and left phrenic nerve with the left atrial appendage (LAA). (A) Sagittal section stained with Masson trichrome through the LAA showing the arrangement of the left circumflex artery (LCx) in the fat tissue of the atrioventricular groove and inferior to the neck of the LAA. (B–D) Left lateral volume rendered CT images of the heart show variations of the anatomic course of the left phrenic neurovascular bundle (yellow arrows) in relation to the LAA in three different individuals. Corresponding 2D axial CT images at the level of the LAA are also shown (inlay images). (E) Postmortem specimen. In this case the left phrenic nerve (arrows) or neurovascular bundle is usually seen as a single trunk anterior or over the body of the LAA. In 23% of individuals the nerve moves over the neck of the LAA (A). MV, mitral valve annulus.

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Funding This project was supported by the Ministerio de Economía y Competitividad (Spain), grant no. TIN2012–37546-C03-02.

Competing interests In compliance with EBAC/EACCME guidelines, all authors participating in Education in *Heart* have disclosed potential conflicts of interest that might cause a bias in the article. The authors have no competing interests.

Ethics approval Bioethics Committee of the University of Extremadura.

Provenance and peer review Commissioned; externally peer reviewed.

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Heart

Left atrial appendage: anatomy and imaging landmarks pertinent to percutaneous transcatheter occlusion

José Angel Cabrera, Farhood Saremi and Damián Sánchez-Quintana

Heart 2014 100: 1636-1650 originally published online March 6, 2014
doi: 10.1136/heartjnl-2013-304464