Translational Research in Anatomy 23 (2021) 100102

Contents lists available at ScienceDirect

Translational Research in Anatomy

journal homepage: www.elsevier.com/locate/tria

# The clinical anatomy of the left atrial structures used as landmarks in ablation of arrhythmogenic substrates and cardiac invasive procedures

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ARTICLE INFO

*Keywords:*
Pulmonary veins
Myocardial sleeves
Left atrial appendage
Mitral isthmus
Left atrial medial isthmus
Left atrial ridge

ABSTRACT

*Background:* The clinical anatomy of the left atrium is of special interest since many invasive procedures are performed within this chamber. Pulmonary vein isolation, linear transcatheter ablations, transcatheter mitral valve repair procedures and left atrial appendage occlusions are examples of highly effective procedures done within the left atrial chamber.
*Methods:* This narrative literature review seeks to discuss the latest articles about the anatomy of left atrial structures.
*Results:* This article reviews recent morphological studies about the pulmonary venous ostia, the myocardial sleeves of the pulmonary veins, the mitral isthmus, the left atrial appendage isthmus, the left atrial medial isthmus and the other left atrial isthmuses together with spatial relationships of blood vessels within the isthmus lines. This review touch upon the clinical relevance of the left lateral ridge and the left atrial appendage.
*Conclusion:* A thorough understanding of local anatomy is essential for safe electrophysiologic invasive procedures. Clinical anatomy of the left atrium is treacherous, difficult and its unfamiliarity can cause serious intraoperative complications. Some anatomical features of the left atrium may significantly impede invasive transcatheter interventions, especially ablation procedures.

## 1. Introduction

There is a renewed interest in the study of the morphology of the heart due to recent developments in cardiac invasive procedures. Novel treatments for arrhythmias such as transcatheter ablations and structural heart diseases are at the forefront of this revival [1–6]. The anatomy of the left atrium is of particular interest since many popular and effective procedures such as pulmonary vein isolation, linear transcatheter ablations, transcatheter mitral valve repairs and occlusion of the left atrial appendage are executed within this cardiac chamber [7,8]. However, the anatomical variability of left atrial structures may have a profound negative impact on the course, duration, and safety of various invasive procedures [9]. It is therefore recommended to have a better understanding of this region.

There have been several instances when novel invasive procedures were performed without a thorough understanding of the anatomy of the targeted region. This was mainly due to the shortage of comprehensive morphological cardiac studies [10,11]. Fortunately, over the past decade, dozens of high-quality studies have emerged. The extensive amount of studies performed on autopsied material and clinical imaging have allowed clinicians to better understand the local anatomy relevant for clinical medicine [12–18]. This narrative review reviews the key discoveries made about left atrial structures and points out their clinical significance for invasive electrophysiologists and cardiologists. It discusses recent morphological studies about the pulmonary venous ostia, the myocardial sleeves of pulmonary veins, the left atrial isthmuses, the left lateral ridge, and the left atrial appendage and elaborates on their clinical significance.

## 2. Pulmonary venous drainage to the left atrium

Pulmonary veins are an important culprit in the pathophysiology of supraventricular tachyarrhythmias, especially in atrial fibrillation. The myocardial sleeves of the pulmonary veins (thin extensions of the left

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https://doi.org/10.1016/j.tria.2020.100102
Received 19 November 2020; Received in revised form 10 December 2020; Accepted 11 December 2020
Available online 19 December 2020

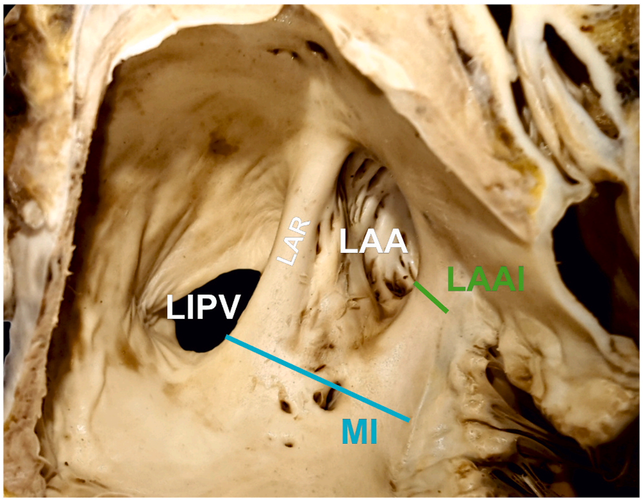


**Fig. 1.** Photograph of cadaveric heart specimen showing the postero-inferior region of the lateral left atrial wall. The mitral isthmus (MI) and left atrial appendage isthmus (LAAI) are marked. LAA – left atrial appendage, LAR - left atrial ridge, LIPV – left inferior pulmonary vein.

atrial myocardium with pacemaker-like cells that cover the distal part of the pulmonary veins), are a recognized arrhythmogenic substrate responsible for initiating and supporting atrial fibrillation [19]. Although myocardial sleeves are present in each pulmonary vein, their physical characteristics can vary significantly [16]. Several studies have examined the morphometric characteristics of pulmonary venous ostia and myocardial sleeves. The anatomical variants present within these structures may increase the likelihood of developing arrythmias or influencing the course of ablation procedures [16,20–22].

The classic pattern of pulmonary venous drainage in the left atrium consists of two separate ostia on each side (each contains a superior and inferior ostium). Previous studies have demonstrated that this arrangement of venous flow is present in 70.8% of all hearts [22]. Analyses of classic pulmonary venous patterns indicate that the left superior pulmonary vein has the longest trunk (15.1 ± 4.6 mm), the longest myocardial sleeves (9.4 ± 4.6 mm), and the largest percentage of myocardial sleeve coverage (60.1 ± 19.4%) [16]. It is postulated that the length of myocardial sleeves may be the main contributing factor in the pathogenesis of atrial fibrillation [23]. Consequently, it is plausible to assume that the superior pulmonary veins (which have significantly longer myocardial sleeves) are more arrhythmogenic than the inferior pulmonary veins [24].

The second most common venous drainage pattern observed in the left atrium consists of an accessory middle right pulmonary vein which drains directly into the atrium. This arrangement is present in 19.2% of hearts (right middle lobe vein draining not to the superior pulmonary vein, but directly to the left atrium). In this variant, the additional ostium of the pulmonary vein has the smallest mean diameter (8.2 ± 4.1 mm) when compared to the diameters of the other ostia [22]. Isolating this small pulmonary vein ostium may be difficult. Moreover, there is an increased risk of postprocedural pulmonary vein stenosis, and the supplementary myocardial sleeves are another risk factor for arrhythmias. Clinicians should be particularly wary of this variant, since it is easy to omit this small accessory vein during preprocedural imaging testing [22]. Moreover, the length of trunk of the additional vein is significantly shorter than the right superior vein (7.8 ± 3.2 vs. 11.8 ± 4.0 mm) and the right inferior vein (7.8 ± 3.2 vs. 11.0 ± 3.7 mm). The lengths of the myocardial sleeves are also significantly shorter than the right superior pulmonary vein and the right inferior pulmonary vein (2.7 ± 1.1 vs. 6.0 ± 2.7 mm and 2.7 ± 1.1 vs. 5.0 ± 2.8 mm, respectively). A study by Marom et al. showed that individuals with an accessory middle right pulmonary vein have a higher frequency of atrial fibrillation than those with other pulmonary venous drainage patterns [25].

The third most common variant of pulmonary venous drainage is one with a single common ostium for the left superior and left inferior pulmonary veins. This arrangement is present in approximately 4.4% of hearts. The diameter of the common ostium has an average dimension of 19.6 ± 6.7 mm, which is significantly larger than the diameters of other pulmonary vein ostia seen in the classic venous pattern ($p < 0.05$) [22]. Hearts with a single common pulmonary vein have significantly longer myocardial sleeves (13.7 ± 4.4 mm) than hearts with a classic venous drainage. The percent trunk coverage of their myocardial sleeves is also larger (79.7 ± 4.9%) when compared to the classic venous drainage arrangement ($p < 0.05$) [16].

## 3. Mitral isthmus

To improve the efficiency of pulmonary venous ostia isolation and to prevent recurrence of atrial fibrillation, there have been several adjuvant linear ablation lines proposed inside the left atrium [26]. The most common one is the mitral isthmus line located between the mitral annulus and the ostium of the left inferior pulmonary vein (Fig. 1) [27]. The length of the isthmus is 28.8 ± 7.0 mm, and its size is not affected by anatomical variants of left-sided pulmonary veins [28]. This line is mostly concave (69.5–80.0% of hearts) and it sometimes has an additional pouch (4.4–20% of hearts) [8]. In most cases, the area of the mitral isthmus is completely smooth (65.6% of hearts). The remaining hearts have additional muscular and/or membranous structures such as crevices, diverticula, intertrabecular recesses or trabecular bridges. The concave shape and the presence of additional structures within the mitral isthmus may decrease catheter stability and could be a reason for poor tissue contact. This in turn could lower the rate of achieving a complete block [29]. It has been suggested that the thickness of the myocardial layer could also affect the ablation success rate. The thickness of the mitral isthmus line varies significantly, although its thickest section lies in the middle (thickness of upper section = 1.9 ± 1.0 mm, middle = 3.0 ± 1.5 mm, lower = 2.7 ± 1.3 mm) [13]. The presence and location of blood vessels may also have an impact on ablation procedures. Within the mitral isthmus line, the great cardiac vein is present in 98.0%, while the left circumflex artery in 57.0%, and the Marshall vein in 35.0% of all hearts. Intramural blood flow can behave as a heat sink that eliminates the heat from the ablation site, which could in turn lower the efficacy of mitral isthmus ablation. Furthermore, myocardial sleeves present around the coronary veins may behave as connection bridges. Finally, the vicinity of blood vessels may require a decrease in energy levels to avoid damage to blood vessel walls [13,30].

Recently, the superolateral mitral isthmus line has been suggested as an alternative ablation site. Located within the region of the mitral isthmus, it lies parallel to the mitral isthmus and it is located immediately below the posterior base of the orifice of the left atrial appendage, linking the left pulmonary veins with the lateral aspect of the mitral valve annulus. The length of the superolateral mitral isthmus is similar to that of the mitral isthmus line (28.9 ± 6.9 vs. 28.8 ± 7.0 mm) [31]. However, in 55.3% of hearts, there is also an interposed artery located between the cardiac vein and the endocardial surface. Its presence can make epicardial and endocardial access difficult [13].

## 4. Left atrial appendage isthmus

The next clinically important line lies adjacent to the mitral isthmus. It connects the margin of the orifice of the left atrial appendage and the lateral aspect of the mitral annulus (Fig. 1) [28]. The isthmus of the left atrial appendage is significantly shorter than the mitral isthmus (14.2 ± 4.8 vs. 28.8 ± 7.0 mm). It also has different macroscopic features. In 95.5% of hearts, the endocardial surface of the appendage is smooth, although the remaining 4.5% of hearts has some crevices [28]. There is variability in the thickness of the myocardial wall within the isthmus. It is thickest at the left atrial appendage end of the isthmus (2.4 ± 0.7 mm).

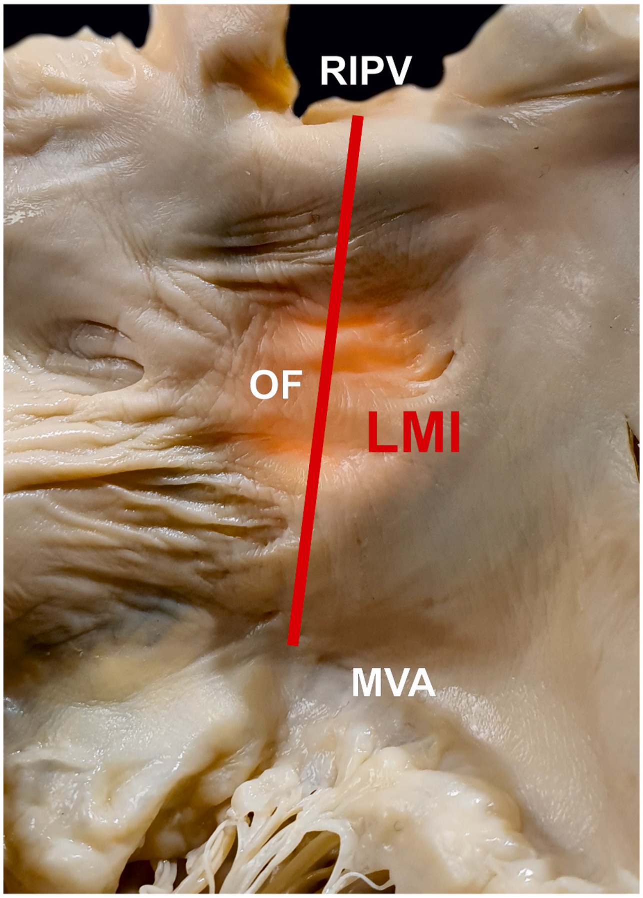


**Fig. 2.** Photograph of cadaveric heart specimen showing left atrial medial isthmus (LMI) with transluminated oval fossa (OF). The oval fossa is transected by the isthmus line. MVA – mitral valve annulus, RIPV – right inferior pulmonary vein.

The middle section is slightly thinner (2.1 ± 0.7 mm) and the mitral annulus end of the isthmus is the thinnest (1.8 ± 0.6 mm) [14]. A thinner myocardial wall may be associated with better outcomes in ablation procedures. However, thinner walls require lower energy levels, so if no adjustments are done prior to the procedure, there is an increased risk of perforation of the left atrial wall [32]. Blood vessels within the isthmus line are also important risk factors for determining the outcome of ablation procedures. In 96.5% of all samples, at least one artery coursed through this region. This was usually one branch (89.5% of cases) or two branches (7%) of the left circumflex coronary artery. In 77.0% of all hearts, there was also at least one coronary vein present. The most undesirable spatial arrangement found in 31.5% of hearts was that of a coronary artery interposed between the endocardium and the vein [14]. This anatomical organization increased the probability of coronary artery injury in procedures with epicardial coronary venous access [29].

## 5. Left atrial medial isthmus

The line connecting the right inferior pulmonary vein with the medial part of the mitral annulus is called the left atrial medial isthmus (or the septal isthmus) [10] (Fig. 2). It has a mean length of 42.4 ± 8.6 mm. Due to its septal location, the medial isthmus line lies adjacent to the oval fossa. Three distinct spatial arrangements are observed: type I has an oval fossa located outside the medial isthmus line (54.5% of cases); type II has an oval fossa crossed by the medial isthmus line (32.5% of cases) (Fig. 2); and type III has its oval fossa rim located tangentially to the isthmus line (13.0% of cases) [17]. It is postulated that ablations may be more difficult in type II and type III. Moreover,

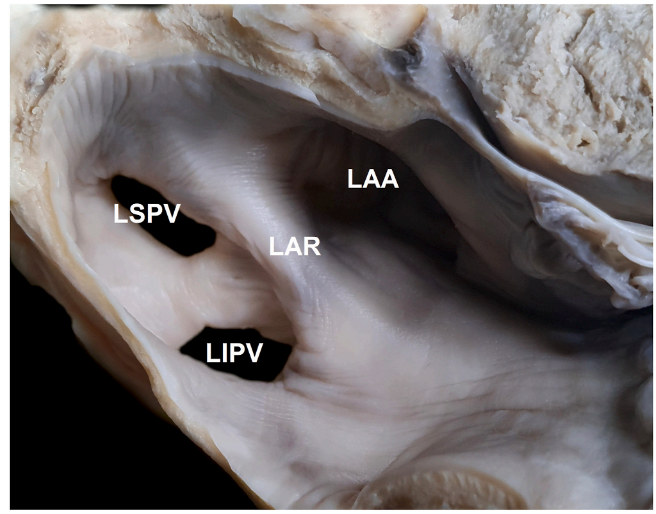


**Fig. 3.** Photograph of cadaveric heart specimen showing the left atrial ridge (LAR) located between the left-sided pulmonary veins (LSPV and LIPV) and the orifice of the left atrial appendage (LAA).

different macroscopic traits of the endocardial surface of the septal region may also have adverse outcomes on ablation procedures in this area [33]. In 31.5% of hearts, other additional structures were present such as diverticula, recesses and tissue bridges [17].

## 6. Roof and anterior lines

Besides the abovementioned isthmuses, often referred to as posterior lines, there are several other attractive ablation locations. These are bound by easily identifiable anatomical structures within the left atrium. The roof line is located at the most cranial part of the left atrium and links the contralateral ostia of the superior pulmonary veins. It has a mean length of 33.3 ± 5.3 mm [10]. Lines that cross the left atrial roof but connect the anterior aspects of the mitral annulus with the pulmonary venous ostia are called the anterior lines or anterior isthmuses. The two most common lines are the anteromedial line (which begins at the ostium of the right superior pulmonary vein and extends to the 10 o'clock position of the mitral valve annulus, mean length of 46.7 ± 7.6 mm) and the anterolateral line (which spans from the medial aspect of the left superior pulmonary vein ostium to the 12 o'clock position of the mitral valve annulus, mean length of 43.9 ± 6.2 mm) [18]. These anterior lines may cross Bachman's bundle and therefore ablation procedures near them can cause undesired interatrial blocks [34].

## 7. Left atrial ridge

The left atrial ridge is a little-known structure situated between the left-sided pulmonary veins and the orifice of the left atrial appendage (Figs. 1 and 3). It is also known as the left lateral ridge, the warfarin ridge, the coumadin ridge, or the endocardial ridge [35,36]. The left atrial ridge is present in 59.5% of hearts and absent in the remaining 40.5% [35]. The mean length of the ridge is 22.4 ± 5.1 mm. It is wider in the inferior sector and thinner in the superior sector (9.1 ± 5.0 vs 7.9 ± 3.2 mm). The wall of the left atrial ridge is significantly thicker at the level of the left inferior pulmonary vein than at the level of the left superior pulmonary vein (6.2 ± 3.5 vs 4.3 ± 1.8 mm). However, the opposite is true with respect to the thickness of the myocardial layer which is significantly thicker at the level of superior ostium and thinner at the inferior ostium (3.1 ± 1.4 vs 1.9 ± 0.9 mm) [35]. The left atrial ridge is a common source of supraventricular arrhythmias and due to its unique morphological characteristics, it can sometimes be mistaken for a tumour or a thrombus [37]. The left atrial ridge has several features

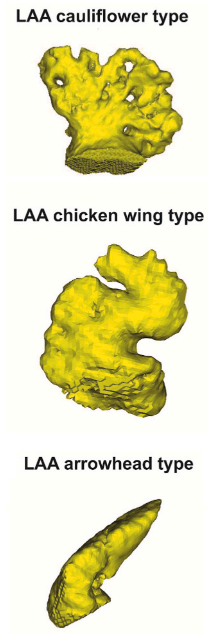


**Fig. 4.** Three-dimensional reconstructions segmented from contrast enhanced computed tomography of the heart showing representative for each left atrial appendage (LAA) type (Mimics Innovation Suite 22, Materialise).

that make it a poor site for cardiac invasive procedures. There is the issue of the overlying vein of Marshall and that of the autonomic nerve bundles it contains. It also has direct connections with surrounding cardiac structures [38,39]. For these reasons, the ridge is considered the most difficult ablation site in the left atrium [40].

## 8. Left atrial appendage

The left atrial appendage is a remnant of the primitive atrium that protrudes from the postero-lateral aspect of the left atrium. It is important for heart rate control and maintaining atrial pressure. Furthermore, it also plays an important role in cardiac thrombogenesis and arrhythmogenesis [41]. Several morphological factors are responsible for the increased thrombogenicity of the left atrial appendage. Firstly, it is a multi-lobular structure with rich trabeculations, a small orifice and a narrow neck – ideal for thrombus formation [42]. Secondly, the appendage may have electrical activity which contributes to atrial fibrillation [43]. The left atrial appendage comes in different shapes and sizes and its thrombogenic potential is closely related to its morphology [44,45]. Wang et al. have developed a classification system that divides the appendages into four types: a chicken wing type, a cauliflower type, a cactus type and windsock type [46]. Some shapes are less pathogenetic than others. For example, the chicken wing morphology is significantly less likely cause thromboembolic events than other shapes [47]. On the other hand, the cauliflower type is an independent predictor for stroke [48].

Unfortunately, Wang's classification has a lot of discrepancies in both imaging and cadaveric studies. It is believed that the classification system is not well replicable and cannot accurately predict the correlation between different types of appendages and their risk factor for stroke [49]. Recently, a simple classification system was designed to help estimate different thrombogenic properties based on the left atrial appendage shape. Three different appendage body types were distinguished: type I – the cauliflower (present in 36.5% of cases); type II – the chicken wing (present in 37.5% of cases) and type III – the arrowhead (present in 26.0% of cases) (Fig. 4) [49]. Interestingly, the total volume and the orifice sizes were similar between appendage types. It was shown that age significantly affects the size of the left atrial appendage. It causes appendage enlargement through the progressive transformation of the orifice geometry from a round to a more oval-shaped opening [49]. Changes in the shape of the orifice may have negative implications for interventions. The irregular appendage openings can complicate transcatheter procedures targeted since there may be a device mismatch and residual leaks [50].

## Financial support and disclosure statement

None.

## Ethical statement

N/a.

## Declaration of competing interest

None.

## Acknowledgements

The authors wish to sincerely thank those who donated their bodies to science so that anatomical research could be performed. Results from such research can potentially improve patient care and increase mankind's overall knowledge. Therefore, these donors and their families deserve our highest gratitude.

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