

The architecture of the left lateral atrial wall: a particular anatomic region with implications for ablation of atrial fibrillation

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Aims

We examined the left lateral ridge (LLR) between the orifices of the left pulmonary veins and the left atrial appendage for a better understanding of its structural composition relevant to ablations for atrial fibrillation (AF).

Methods and results

The LLR and its surrounding areas were studied in 40 heart specimens by dissection and histological sections. The LLR is a fold of the atrial wall with a mean width that was narrower superiorly than inferiorly ($P < 0.001$). Its myocardial thickness at the antero-superior level was thicker than at the postero-inferior level (2.8 ± 1.1 vs. 1.7 ± 0.8 mm, $P < 0.001$). Transmurally from subepicardium to subendocardium, the LLR comprises myofibres from the leftward extension of Bachmann's bundle together with the inferior branches of the septopulmonary bundle and the septoatrial bundle. The vein or ligament of Marshall is located on the epicardial aspect of the LLR. The Marshall structures and autonomic nervous system are in close proximity (< 3 mm) to the endocardial surface at the superior level of the ridge in 70% of specimens.

Conclusion

The variability in width and thickness of the LLR, its proximity to Marshall structures and autonomic nerves, and myofibre arrangement may be significant in the fibrillatory process and spread of AF activity.

Keywords

Anatomy • Atrial fibrillation • Bachmann's bundle • Left atrium

Introduction

Catheter ablation techniques are being used increasingly to treat paroxysmal and persistent atrial fibrillation (AF).¹ Modification of the atrial substrate by targeting maintaining structures in the left atrium (LA) appears to increase success rate.^{2,3} Electrophysiologists recognize the presence of several endocardial ridges that may make positioning of catheters for ablation difficult resulting in incomplete ablation lines.^{4–6} The most prominent ridge in the LA is the left lateral ridge (LLR) between the orifices of the left pulmonary veins (PVs) and the os of the left atrial appendage (LAA).⁴ Previous morphologic studies in post-mortem hearts and recent reports have shown considerable anatomic variations of the LAA^{7,8} and the LLR^{4,5} emphasizing that a better understanding of this atrial structure and its vicinity may facilitate ablation

procedures and prevent serious complications during PVs isolation. Recent electrophysiological and surgical investigations also demonstrated extra-PV atrial foci after PV isolation originating from the LAA and that the junctional area between the left appendage and the LA body impacts upon the fibrillatory process acting as a source of activity spreading to the rest of the atrium during AF.^{9,10} As the composition of this critical region of the LA has not been investigated previously, our study aims to provide an insight into the structure of the LLR and associated structures in this region.

Methods

This study has been approved by the bio-ethical committee on human research (University of Extremadura). We examined 40 formalin-fixed

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hearts from patients who died of non-cardiac causes (29 males, mean age 49 ± 20 years). Five of the patients had a history of coronary artery disease and two had chronic AF constituting a group with structural heart disease. The mean heart weight was 375 ± 25 g (range 330–488 g). The LA walls were dissected to display the lateral region of the LA between the roof of the atrium, the left PVs and the mitral valve (MV) (Figure 1).

In describing the veins, ‘proximal’ and ‘distal’ were used with reference to the direction of blood flow. A common vestibule, or venous antrum, was present when the left superior (LS) and left inferior (LI) PVs coalesced proximal to the junction with the LA body. It was classified as *short* when the distance between the level of the left PV intervenous ridge at its narrowest part to the level coinciding with the middle of the LR was within 5–15 mm and *long* when the distance was >15 mm. Measurements were made on the endocardial surface using callipers. We also measured the longitudinal axis of the ostium of the left common PV or individual left PVs, the distance between superior and inferior veins (intervenous ridge), the longitudinal and transverse axes of the orifice of the LAA and noted the relative positions of the LAA and LSPV (left pulmonary veins, superior) orifices. Subsequently, we examined the endocardial contour of the ridge and measured its length from the antero-superior border of the LSPV orifice to the inferior border of the LIPV (left pulmonary veins, inferior) orifice. The maximal widths between its anterior and posterior edges were measured at two levels perpendicular to its long axis – superiorly corresponding to the superior margin of the LSPV

orifice and inferiorly corresponding to the inferior margin of the LIPV orifice (levels ‘a’ and ‘b’ in Figure 1A). The maximal transmural myocardial thickness of the LLR was measured at the two levels perpendicular to the endocardium in both macroscopical and histological sections (Table 1).

Histological study

Twenty-two hearts selected to represent the spectrum of morphological features identified by gross inspection were prepared for light microscopy. Blocks of tissue encompassing the left PVs, LLR, LAA, mitral vestibule and annulus were processed and serially sectioned at 12 or 15 μ m in sagittal (13 hearts) and frontal planes (nine hearts) (Figures 1 and 2). Sections at 1 mm intervals were stained with Masson’s trichrome. On the histological sections, we measured the minimal distance from the endocardial surface to the oblique vein (VOM) or ligament of Marshall (LOM), and the distribution and relative density of ganglia and fibres of the autonomic nervous system from endocardium to epicardium along the LLR. To analyse LLR innervation, we took digital photographs at $\times 40$ magnification and superimposed a grid of vertical and horizontal lines with 121 intersection points representing 100%. Autonomic nerve density (AND) was defined as the proportion of intersection points overlying nerve fibres and ganglia within the grid. AND was estimated in four different chosen fields for each specimen (one of each pulmonary ostium and the other in the LLR at 0.5 cm distal to each ostium) and the values were then averaged. Altogether, 10 samples were examined in each heart.

Dissection technique

In 12 hearts, we studied the alignment of the myocardial fibres by peeling away the epicardium and the endocardium to reveal the arrangement of the major muscular bundles. We used the term ‘myofibre’ to refer to the macroscopic appearance of slender muscle bundles, which can be revealed after removing the endocardium or epicardium. For simplicity, we distinguished three orientations: circumferential, longitudinal, and oblique. Circumferential fibres were those

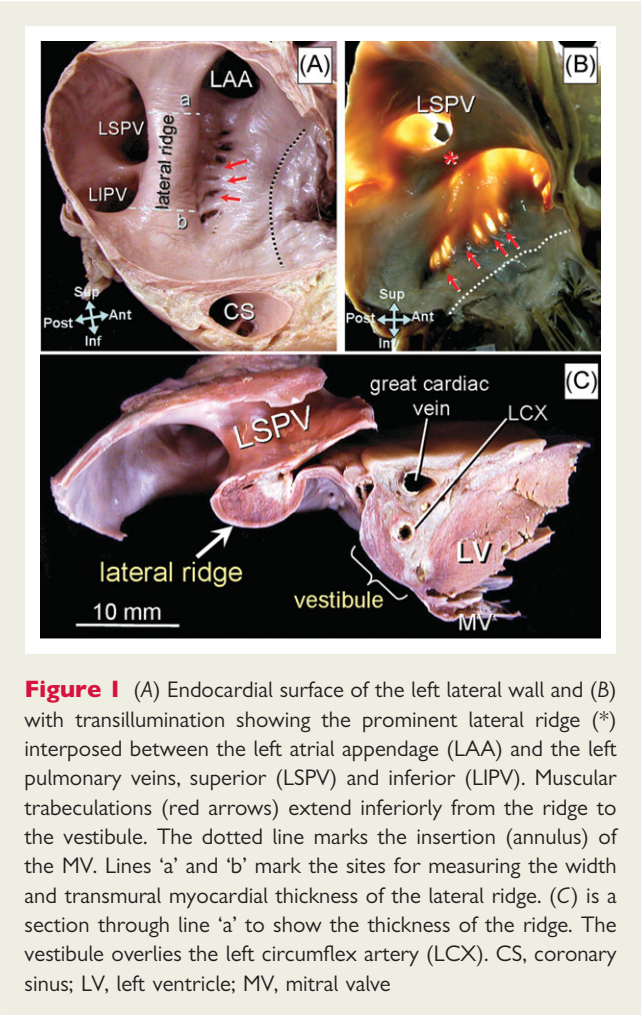


Figure 1 (A) Endocardial surface of the left lateral wall and (B) with transillumination showing the prominent lateral ridge (*) interposed between the left atrial appendage (LAA) and the left pulmonary veins, superior (LSPV) and inferior (LIPV). Muscular trabeculations (red arrows) extend inferiorly from the ridge to the vestibule. The dotted line marks the insertion (annulus) of the MV. Lines ‘a’ and ‘b’ mark the sites for measuring the width and transmural myocardial thickness of the lateral ridge. (C) is a section through line ‘a’ to show the thickness of the ridge. The vestibule overlies the left circumflex artery (LCX). CS, coronary sinus; LV, left ventricle; MV, mitral valve

| Table 1 Dimensions of the left lateral ridge (LLR), pulmonary veins (PVs), and left atrial appendage (LAA) | | |
|--|----------------|------------|
| | Mean (mm) | Range (mm) |
| Left common PVs (major axis) | 31.4 ± 4.5 | 22.5–37.6 |
| Left superior PV (major axis) | 19.3 ± 2.5 | 13.1–24.3 |
| Left inferior PV (major axis) | 17.3 ± 1.5 | 12.5–22.3 |
| LLR width (superior level) | 5.6 ± 0.4 | 2.2–6.5 |
| LLR width (inferior level) | 10.2 ± 0.5 | 6.2–12.5 |
| LLR length | 25.3 ± 5.5 | 14.2–33.5 |
| LLR myocardial thickness (superior level) | 2.8 ± 1.1 | 1.5–4.2 |
| LLR myocardial thickness (inferior level) | 1.7 ± 0.8 | 0.5–3.5 |
| Longitudinal axis of LAA | 24.5 ± 3.5 | 18.3–28.5 |
| Sagittal axis of LAA | 19.4 ± 2.5 | 12.5–23.2 |
| Longitudinal axis of LAA in structural heart disease | 33.8 ± 4.5 | 26.4–41.5 |
| Sagittal axis of LAA in structural heart disease | 26.5 ± 3.5 | 17.5–34.5 |

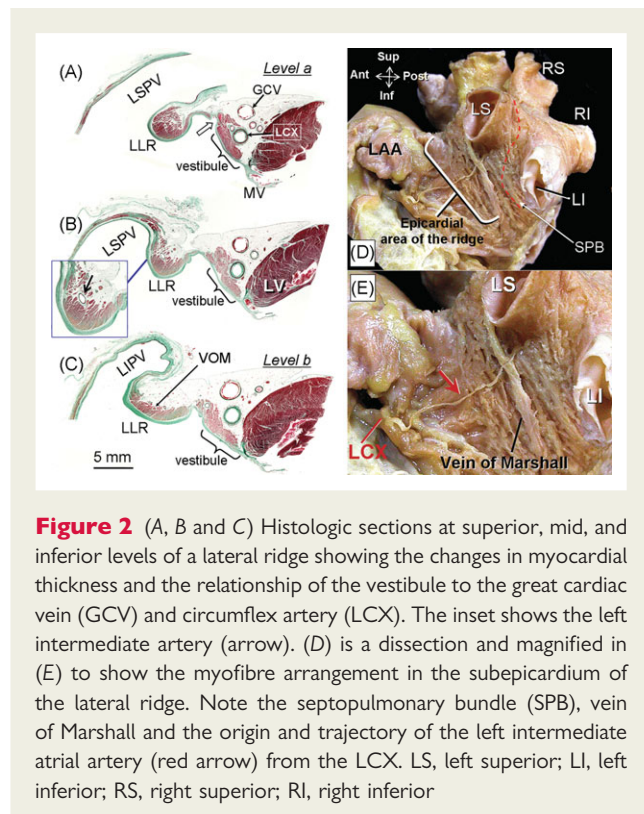


Figure 2 (A, B and C) Histologic sections at superior, mid, and inferior levels of a lateral ridge showing the changes in myocardial thickness and the relationship of the vestibule to the great cardiac vein (GCV) and circumflex artery (LCX). The inset shows the left intermediate artery (arrow). (D) is a dissection and magnified in (E) to show the myofibre arrangement in the subepicardium of the lateral ridge. Note the septopulmonary bundle (SPB), vein of Marshall and the origin and trajectory of the left intermediate atrial artery (red arrow) from the LCX. LS, left superior; LI, left inferior; RS, right superior; RI, right inferior

parallel to the insertion of the MV; longitudinal fibres were perpendicular to the circumferential fibres, and oblique fibres were at angles to both.

Statistical analysis

Data are expressed as mean \pm standard deviation. Quantitative data were compared using an unpaired *t*-test. *P*-values <0.05 were considered significant.

Results

Dimensions and relationship between the left lateral ridge, left pulmonary vein orifices, and the left atrial appendage

The muscular fold lying between the orifices of the left PVs and the LAA forms the LLR that is visible as a ridge on the endocardial surface (Figures 1 and 2). It extends obliquely along the lateral LA wall from antero-superior to postero-inferior. Immediately inferior to the ridge and the LAA is the vestibule to the MV.

Two well-defined left PVs ostia were found in 27 specimens (67%). Variant anatomy consisted of the presence of the left common vestibule in 13 specimens (33%); 10 (25%) presented a short vestibule measuring a mean of 8.3 ± 2.5 mm and three (8%) a long common vestibule. The mean distance between both left PVs orifices was 2.8 ± 0.5 mm (range 1–4.5 mm). We found a narrower separation of the orifices in those hearts with common vestibule (range 1–2.5 mm). Morphologically, the individual PV ostia or common vestibule were oval-shaped with the longitudinal axis longer than the transverse axis. The mean

measurement for the major axis (sagittal) of the left common vestibule was significantly smaller ($P < 0.05$) than the mean total for separate superior and inferior PVs.

The mean width of the LLR was narrower at the superior level when compared with the inferior level ($P < 0.001$) (Table 1) and <5 mm wide in 30 specimens (75%). The cross-sectional contour of the ridge at its narrowest part was rounded in 30 hearts (75%) (Figure 1A), pointed in four hearts (10%), and flat in six hearts (15%). The length of LLR varied from 14.2 to 33.5 mm (mean 25.3 ± 5.5 mm) with a constant superior insertion at the lateral roof of the LA extending inferiorly to reach the postero-inferior margin of the inferior PV in 34 specimens (85%). In the remaining six hearts we found a shorter ridge extending from the superior portion of the LSPV orifice to the intervenous ridge. The myocardium at its antero-superior level was thicker than at its postero-inferior level (2.8 ± 1.1 vs. 1.7 ± 0.8 mm, $P < 0.001$) (Figure 2). The length and width of the LLR was similar in hearts with and without common vestibule. However, the myocardial thickness tended to be thicker in specimens with common vestibule (3.1 ± 0.8 mm and 2.1 ± 0.5 mm at the superior and inferior level respectively). No significant differences were found in the length, width and thickness of the LLR between hearts with and without structural heart disease. The oval-shaped orifice of the LAA showed significant increase in both diameters in hearts with structural heart disease ($P < 0.001$) (Table 1). The superior portion of the LAA orifice was located adjacent to the anterior border of the ridge and superior to the LSPV orifice in 27 specimens (67%) (Figures 1 and 3). It was at the same level in the remaining 13 specimens (33%). The length of the ridge was not related to the dimensions of the LAA orifice but those hearts with a more inferior location of the LAA orifice had a shorter LLR (mean 17.2 ± 2.5 mm).

Muscular architecture of the left lateral ridge

On the anterior subepicardial aspect of the LA, the most prominent bundle is Bachmann's bundle.¹¹ This broad band of circumferential interatrial myofibres can be traced rightward to the junction between the right atrium and the superior caval vein, and leftward to either side of the neck of the LAA reuniting posteriorly to run on the epicardial aspect of the lateral wall (Figure 3). After encircling the LAA the bundle forms the subepicardial myofibres of the LLR in close relationship with the VOM or its ligament (Figure 3). Deeper than Bachmann's bundle, arising from the atrial septum is another subepicardial band, named by Papez¹² as the 'septopulmonary bundle'. This comprises of obliquely arranged myofibres that cover the superior and posterior surfaces of the LA and encircle the orifices of left PVs to form part of the subepicardial myofibres at the postero-inferior level (Figure 3A and B). Deeper still, in the subendocardium, the myofibres in the anterior wall form a broad flat bundle, termed the 'septatrial bundle'.¹² It rises from the anterior and inferior part of the atrial septum, and divides in three bands. One band fans out towards the orifices of the right PVs. Another band combines with leftward fibres of the septopulmonary bundle towards the orifices of the left PVs. A third band runs leftward to go anteriorly around the

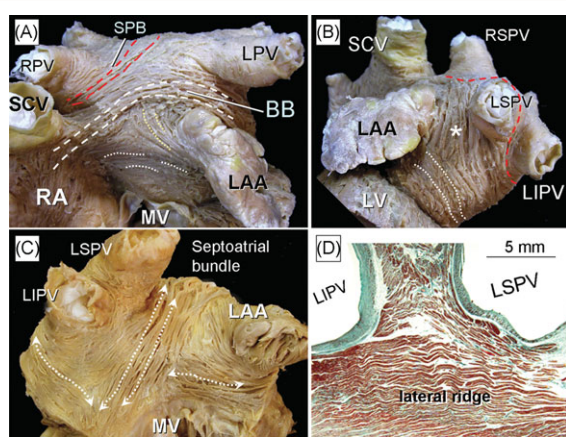


Figure 3 (A and B) Dissections of the subepicardial fibres viewed from the anterior and left lateral aspects. Bachmann's bundle (BB, white broken lines) crosses the septal raphe, blends into the circumferential fibres of the anterior wall (dotted lines), to pass to either side of the neck of the atrial appendage to run in parallel fashion to the lateral aspect (*) 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. (C) The left lateral wall is everted to show the subendocardial fibres and the fibre arrangement of the septoatrial bundle and its three major fascicles (double-headed arrows). The subendocardial myofibres of the lateral ridge (parallel arrows) are continuations of leftward fibres from the septoatrial bundle. (D) Sagittal section through the left superior and inferior pulmonary veins and the lateral ridge to show intervenous myofibres intersecting myofibres of the ridge. Abbreviations as before

mouth of the LAA (Figure 3C). The last two bands contribute to the deep myofibres of the LLR (Figure 3C and D).

The LA wall in close vicinity to the orifice of the LAA and inferior to the LLR showed a marked variability. In most hearts (22 specimens, 55%) the wall was smooth. However, in 12 specimens (30%) we found near-parallel muscle bundles separated by crevices of thin atrial wall between the anterior margin of the ridge and the vestibule of the MV, giving the area a ladder-like appearance on transillumination (Figure 1). In another six specimens (15%) the bundles were less obvious but the endocardial surface was indented with crevices and pits of various sizes and shapes. Histology confirmed the atrial myocardium in the pits and crevices was extremely thin (mean 0.5 ± 0.2 mm). Anterior to the orifice of the LAA the myocardial thickness of the smooth vestibule ranged between 1.8 and 3.2 mm (mean 2.6 ± 0.4 mm). The left circumflex artery (LCX) ran epicardially and the mean distance between the endocardium and the LCX was 4.2 ± 0.5 mm (range 2.8–6.2 mm) (Figures 1 and 2).

Structural content of the left lateral ridge

The VOM/LOM course obliquely and superficially in the ridge (Figures 2 and 4) at variable distances from the endocardial surface of the ridge (range 1.7–3.5 mm). In 28 specimens (70%)

the distance was <3 mm at the superior level. Smaller fibromuscular subepicardial bundles in the ridge crossed the VOM into the left PVs and the LA free wall (Figure 4). These bundles increased in density around the vein at the coronary sinus juncture. The epicardial fat pad of the LLR adjacent to the left PVs contained numerous parasympathetic ganglia and fibres of the autonomic nervous system (Figure 4). A higher density of nerve elements was found in the epicardial region, sparse elements within the muscle layer and none in the subendocardium. Average estimated AND was significantly higher at the anterosuperior level of the LLR at the ostium of the LSPV ($8.5 \pm 1.5\%$; range 4–12.6%) than at the inferior level ($6.3 \pm 1.5\%$; range 3–10.6%) ($P < 0.001$). No significant differences were found between hearts with and without structural heart disease.

In 27 specimens (67%) we observed an arterial branch termed left intermediate atrial artery that originated from the LCX next to the inferior border of the LAA orifice (Figure 3B, D, E). This artery ran on the epicardial aspect of the left lateral wall, over the LLR and VOM. Its external diameter within the ridge was 1.1 ± 0.3 mm (range 0.5–1.6 mm) and the distance from the endocardial surface of the left PLR ranged between 1.8 and 3.7 mm (mean 2.5 ± 0.5 mm).

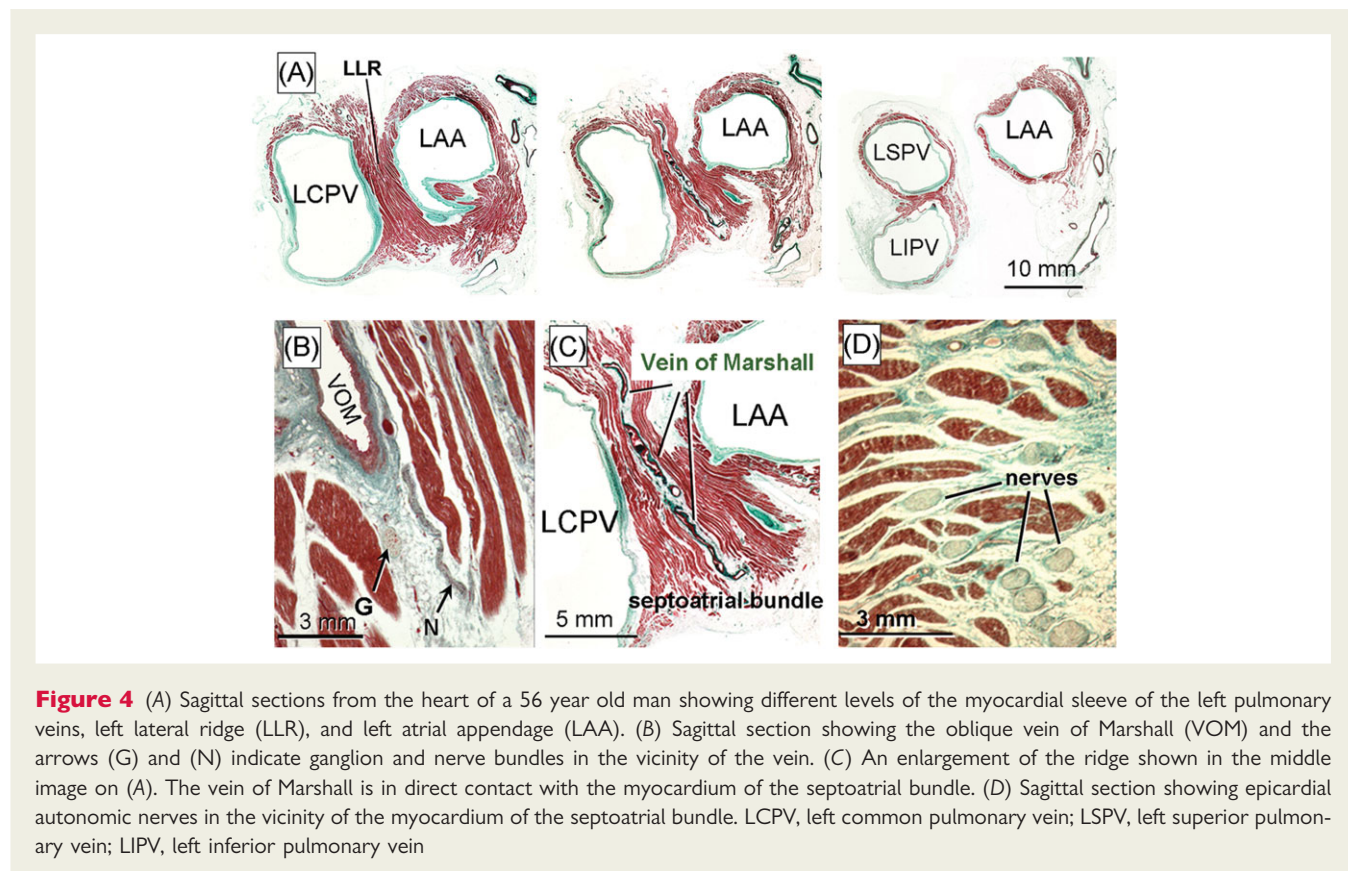
Discussion

Our findings revealed that (i) the LLR is not of uniform width or muscular thickness being narrower and thicker at the anterosuperior level; (ii) from subepicardium to subendocardium, the ridge comprises the leftward extension of Bachmann's bundle, the inferior branches of the septopulmonary bundle and the septoatrial bundle providing marked crossover arrangements of the myocardial fibres transversally; (iii) in 30% of hearts there are extra-appendicular muscular trabeculations connecting the ridge to the vestibule of the mitral annulus; (iv) in most hearts (70%) the VOM/LOM is <3 mm from the endocardium of the ridge and has muscular connections to the PVs; and (v) the ridge contains more autonomic nerves at its superior level close to the LSPV than at the inferior level.

Gross morphological features of the left lateral ridge: relevance during catheter ablation of atrial fibrillation

Although described in 1907 by Arthur Keith¹³ as the 'left tænia terminalis' and 13 years later by James Papez¹² as the 'left posterior crest', the LLR actually is a fold of the lateral left atrial wall protruding into the endocardial LA surface. Its shape and size is of relevance during catheter ablation of AF when encircling the orifices of the left PVs or during ablation of extrapulmonary vein triggers arising around or inside the LAA. It is also the site that is most challenging for accomplishing a complete ablation line.¹⁴

Anatomic information can be obtained with current multislice CT and MR imaging reconstructions of the endocardial aspect of the LA.^{4–6} Our anatomic study demonstrated good morphologic correlations with imaging studies. A recent CT study showed a prominent ridge in all subjects and found no significant differences in length and width of the ridge between patients with AF and



controls.⁶ However, limitations of both spatial and temporal resolution inherent in the imaging techniques did not allow detailed measurements of wall and myocardial thickness. Our anatomical study confirmed a narrow ridge of <5 mm in majority, and the ridge had thicker myocardium superiorly than inferiorly. No significant differences were found between hearts with and without structural heart disease. In consideration of constructing continuous circumferential lesions around ipsilateral veins ~1 cm from the PV orifice on the posterior wall and ~0.5 cm on the anterior wall, ablating within the common vestibule may allow a smoother drag for the catheter. In contrast, when a common vestibule is very short or absent, the anterior line will need to be placed on the crest of the LLR or in its vicinity. In cases with narrow or pointed ridge and no vestibule, it may be safer to stay on the LAA side of the ridge to avoid accidentally ablating inside the PVs. In so doing, ablationists should be mindful of the potentially thin atrial wall and crevices that may entrap catheters (Figure 1B).¹⁵

The myoarchitecture of the left lateral ridge and its adjacent structures

Our dissections revealed the subepicardial and subendocardial muscular arrangement of the PLR with abrupt changes of myofibre orientation transmurally through the atrial wall. Clinical studies that showed the contribution of different atrial regions to the fibrillatory process and to the maintenance of AF, emphasized the role of structural discontinuities and heterogeneous fibre orientation in favouring anatomic re-entry or in anchoring rotors.^{16–18} The

crossover arrangements deep in the wall of the ridge may provide three-dimensional structural heterogeneity and destabilize re-entry. Recent electroanatomic findings showed that the left atrial muscular bundles can provide lines of conduction block line and barrier and may play a role in the formation of LA flutter and AF recurrences after PV isolation.¹⁹ Electrophysiological data on chronic AF found that most of the patients had the 'highest' dominant frequency in a part of the LA corresponding to the region now described as the LLR.²⁰ Studies by Jalife and co-workers²¹ on the isolated sheep heart demonstrated the presence of a small number of stable ongoing circuits generating high frequency waves located in the PV orifices or at the contiguous posterior left atrial region.

In the LA, the pectinate muscles are mostly confined within the LAA, where they form a complicated network lining the endocardial surface. The role of the LAA as a source of activity during AF has been suggested in studies using endocardial mapping.^{9,22,23} In 30% of our human heart specimens the posterior ostial margin of the LAA does not present as a clear-cut border and muscular trabeculations can be found extending inferiorly connecting the ridge with the vestibule of the MV. These could provide preferential conduction pathways between ridge and mitral vestibule.

The left lateral ridge and Marshall structures

The VOM, or LOM, can be traced on the epicardial aspect of the LLR. The Marshall structures are in close proximity to the

endocardial surface, at a distance of <3 mm at the superior level of the ridge in 73% of specimens. In clinical studies, electrical activity originating from the LOM can be recorded from the endocardial aspect of the LA in or around the orifices of the left PVs. By cannulating the vein, Hwang *et al.*,²⁴ were able to record electrical activity in patients with focal AF arising from the VOM. Kim *et al.*²⁵ demonstrated multiple myocardial 'tracts' present within the LOM that insert directly into the coronary sinus musculature or more distally into the posterior free wall of the LA. In all our specimens examined histologically, we found small muscular bundles that crossed the oblique vein to connect with the LA free wall. The LOM and its adjacent epicardium are richly innervated by autonomic nerve fibres as demonstrated in a previous anatomic study.²⁶ Cholinergic nerve fibres arising from the LOM contribute to the electrophysiological profile of surrounding LA structures.²⁷ Our study also showed that the epicardial aspect of the ridge displays a higher nerve density at its superior level in relationship to the ostium of the LSPV than at the inferior level. In addition to Marshall structures, we found an atrial artery in the ridge in majority of specimens (67%). Previous anatomical studies had shown sinus nodal arteries taking this course in 8–22% of hearts.²⁸

Limitations

This anatomic study on structurally normal hearts and several with structural heart diseases is without electrophysiological correlates. Owing to previous fixation of tissues over a long period, we were restricted to routine histological techniques that did not allow us to study the subtypes of autonomic nervous fibres. Our study, nevertheless, serves to provide anatomical details relevant to clinical practice.

Conclusions

Our anatomic findings revealed a non-uniform myocardial thickness and width of the left-lateral ridge, new information on the muscular arrangement, and AND distribution. The region of the LLR sets the scene for close anatomic relationship between the Marshall structures, the subepicardial interatrial Bachmann bundle and the deeper septoatrial bundle that may have implications in the fibrillatory process and spread of AF activity between both atria.

Conflict of interest: none declared.

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