CLINICAL RESEARCH
Electrophysiology and ablation

Right atrial appendage and vestibule: further anatomical insights with implications for invasive electrophysiology†

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Received 20 July 2012; accepted after revision 23 October 2012; online publish-ahead-of-print 23 November 2012

Aims
Despite recognition that understanding gross anatomy of the right atrium is important in the era of invasive electrophysiology, areas such as the right atrial appendage (RAA) wall or the vestibule are not fully appreciated. The aim of this study was to conduct an anatomical assessment focusing on these structures to gain further insights into electrophysiological procedures.

Methods
Forty-four normal human hearts were examined macro- and microscopically.

Results
Inside the RAA, two prominent muscle bundles; the crista terminalis (CT) and the sagittal bundle (SB) were identified. The medial wall at which the CT originated from and its surrounding area was the thickest part adjacent anteriorly to the thin aortic mound, suggesting non-uniform wall thickness of this area. Histological sections revealed that myocardial strands of the SB connected the CT and RAA tip, implying preferential anterior conduction of the sinus impulse. The vestibule had a thin myocardium with extensive fat covering along the epicardial side of the tricuspid annulus. The proximal portion of the right coronary artery (RCA) was relatively distant from the annulus, followed by gradual shortening of the distance from the endocardium to the RCA, which led to a very close relationship (<3.0 mm) at the inferior annulus.

Conclusion
Non-uniform wall thickness and muscle fibre orientation in the RAA should be taken into consideration during lead/catheter positioning. The RCA proximity in the inferior portion of the vestibule and the deeper fatty plane of the anterior atrioventricular groove are important anatomical features relevant to accessory pathway ablation.

Keywords
Anatomy • Right atrial appendage • Crista terminalis • Sagittal bundle • Vestibule • Right coronary artery

Introduction
The importance of understanding the gross anatomy of the right atrium (RA) became widely recognized in recent decades for successful and safer interventional procedures in the field of electrophysiology. Various studies reviewing the human RA structure have been reported, especially pertaining to the cavotricuspid isthmus and the crista terminalis (CT).1–6 but there remain areas that have not been fully appreciated. For instance, there are scarce descriptions on spatial variation of wall thickness in the RA appendage (RAA), its medial wall, or the proximity of the coronary artery (CA) to the parietal vestibule which are all features of particular importance in the setting of device lead implantation or catheter ablation for accessory pathways. We conducted an anatomical study on the RAA and the RA vestibule to provide more insights into these features, focusing on the relevance to interventional electrophysiology.

Methods

Subjects
This study has been approved by our institutional ethics committee. From the archives of the Cardiac Morphology Unit, Royal

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Apex of the right atrial appendage (RAA) had two prominent muscle bundles termed as the precaval part of the crista terminalis (CT) and the sagittal bundle (SB) that showed several types of ramifications distally.

- The SB connected the CT and tip of the RAA, implying preferential conduction of the sinus impulse towards the anterior part of the appendage.
- Thickness of the medial part of the RAA adjacent to the aortic root is non-uniform, with minimal median thickness of 2 mm (range 1–4 mm).
- The right atrial vestibule has a thin muscle layer with thicker epicardial fat in the superoanterior to anterior atrioventricular groove and with a thinner deposit of fat in the inferior groove.
- The distance between the right coronary artery and vestibule endocardium is very short in the inferior portion.

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Brompton Hospital, we retrieved anatomically normal adult human heart specimens that had been fixed by immersion in 10% formalin solution. Hearts with macroscopically visible structural abnormalities such as valvar stenosis or ventricular hypertrophy were excluded although we included hearts with minimal myocardial scarring.

**Investigation of the right atrial appendage**

We defined the RAA as the entire anterolateral triangular part of the RA which is demarcated on the endocardial surface by the CT (terminal crest) distinguishing it from the smooth-walled venous portion. Its distal border is the smooth-walled vestibule around the tricuspid orifice. The RAA investigation was carried out macro- and microscopically with particular attention to muscle structures inside the RAA, medial wall thickness, and arrangement of the muscle bundles.

The lateral wall was opened with the incision from the inferior vena cava to the RAA anterior towards the tip, which allowed us an adequate window for inspection of the muscle structures inside the RAA. Initially, we performed gross examination of the RAA apex inside in order to define and categorize features of the RAA tip into anteromedial and posterolateral parts. Subsequently, we performed morphometrical analysis, focusing on the medial wall and these two prominent muscle bundles. We measured the width and/or transmural thickness from the endocardium to the epicardium using callipers at the following points (Figure 1A):

- width × thickness of the CT origin just proximal to the SB origin (point A);
- width × thickness of the CT just distal to the SB origin (point B);
- width × thickness of proximal site of the SB (point C);
- thickness of the RA medial wall at 10 and 15 mm distant from the point A (points D and E);
- length of the SB from point C to the point where the SB branches become indistinguishable, mingling with surrounding pectinate muscles, or branch, or insert into the vestibule.

We also measured the surface area of the thickest part in the medial wall. After taking pictures with a ruler, the surface area in each image was quantified by using an image analyser (ImageScope®; Aperio Technologies, Inc.) with calibration.

In addition, histological examination was conducted in order to address the orientation of the myocardial strands that make up the CT and the SB. After routine processing, tissue blocks of this area from five hearts were serially sectioned at a thickness of 10 μm transmurally in longitudinal and transverse planes (parallel and perpendicular to the length of the CT) from anterior to posterior. Every 10th section was stained with Masson’s trichrome technique and examined under light microscopy. We also made cross sections for the lateral wall in the same manner.

**Investigation of the right atrial vestibule**

We initially measured the thickness of the mid-point of the RA vestibule from the endocardium to the epicardium including the epicardial fat pad at three points along the tricuspid circumference: superoanterior, anterior, and inferior segments in attitudinal parlance (described as anterolateral, lateral, and posterior segments in older terminology), since right accessory pathways are predominantly distributed in these areas (Figure 1B). Subsequently, we measured the thickness of the myocardium and the transmural distance from the endocardium to the nearest right coronary artery (RCA) wall in each point to determine the proximity of the RCA to the vestibule.

**Statistics**

All measured data were expressed as median and range. Data of wall thickness in different portions in the RAA medial wall and the vestibule were compared using the Mann–Whitney test. A P value < 0.05 was defined as significant.

**Results**

**Study subjects**

Forty-four specimens were examined; 39 specimens were used for macroscopic study and 5 were used for histological analysis. Eleven specimens were from men, 19 were from women, and 9 were unknown. The median age at death was 51.1 years (range 16.0–66.0). The records on cause of death were available from 23 subjects and none of them were cardiac related except for two (acute myocardial infarction).

**The right atrial appendage**

In all of the 39 specimens, the CT was clearly recognisable on the endocardial surface as a C-shaped bundle arising from the superior aspects of the medial wall, an area which lies between the anterosegmental portion of the rim of the oval fossa and the aortic mound.
Thirty-five (89.7%) out of 39 cases had distinguishable SB running towards the RAA tip anterosuperiorly (Figure 2). The most common pattern of the SB bifurcation from the CT was that the single SB originated from the proximal medial site of the CT (31 out of 35 subjects, 88.6%). Two of 35 subjects (5.7%) had two distinctive bundles arising in parallel from the CT and 2 other subjects (5.7%) had a single SB originating directly from the medial wall (Figure 2E). The distal part of the SB had variable morphology. It branched into a leash of fine muscular strands towards the tricuspid vestibule in 20 hearts (Figure 2A). In other hearts, one of its initial branches continued as a robust bundle (2 hearts, 5.1%) or several narrower bundles (17 hearts; 43.6%) to insert into the vestibule (Figure 2D–F). In these arrangements, depending on the trajectory of the SB being directly anterior or slightly anterolateral, the resulting muscular ‘ring’ comprising SB and vestibule was of variable sizes as was the encircled anteromedial tip of the appendage. On the endocardial aspect, the gross arrangement of the myocardial strands encircled the RAA tip (Figure 2F). On the lateral wall of the appendage, bundles of branching and interconnecting pectinate muscles arose from the CT to form struts joining with the vestibule.

The RA morphometric measurements in each point are shown in Figure 1. The superior part of the medial wall from which the CT originated (point A) was thick (median 4.0, range 1.8–7.5 mm) and then gradually became thinner towards the aortic mound, the area overlying the aortic non-coronary sinus and the adjoining ascending aorta. The wall thickness in point D (median 3.0, range 1.0–6.1 mm) was significantly thinner than in point A (P < 0.001) and thicker than in point E (median 2.0, range 1.0–4.0 mm, P < 0.001). Accordingly, the surface area of the relatively thick area in the RAA medial wall, delineated by the anterosuperior rim of the oval fossa posteriorly and by aortic mound anteriorly, was relatively limited (median 13.0, range 7.7–20.0 mm²). The distance from point A to aortic mound was ~20 mm.
Serial histological sections of the RAA demonstrated that the atrial musculature in contact with the sinus node was confined to the CT which continued in an anterosuperior arch (the precaval bundle) towards the medial side to connect with the SB as well as Bachmann’s bundle (Figure 3A). The myocardial strands of these distinctive muscle bundles were aligned along the long axis of...
the bundles. In contrast, the posterior atrial wall was thinner and without a clear pattern of the myocardial strands. The SB coursed predominantly anteriorly or slightly laterally and connected near to the very tip of the RAA. Histological sections of the RAA lateral wall showed that the wall between pectinate muscles was mostly covered with very thin muscle strands comprising one or few myocytes thickness and in some areas it was devoid of myocardium (Figure 3B).

**The right atrial vestibule**

The morphometrical measurements of the vestibule are shown in Figure 1B depicted in the left anterior oblique orientation. Although the measurements were taken at the middle part of the vestibule, the muscle wall of the vestibule tended to taper to \(\sim 1\) mm thick towards the annulus. The atrioventricular groove was filled with extensive fat deposits particularly in the superior to anterior aspects that were confluent with the periaortic and right coronary fat pads, accounting for the thick transmural wall in these areas (median thickness 9.0 mm in the superoanterior portion, 12.1 mm in the anterior portion, respectively; the anterior was significantly thicker than the superoanterior, \(P = 0.046\)). The transmural wall in the inferior portion was significantly thinner as compared with those of other portions (\(P = 0.043\) in both superoanterior vs. inferior portion and in anterior vs. inferior portion).

The origin of the RCA related to the superior paraseptal aspect of the tricuspid annulus, although at this site the orifice of the RCA was distant from the annulus. Then the RCA gradually tracked rightward and inferiorly, reaching the annulus at the level of the superoanterior (median distance from the nearest adjacent RCA to the endocardium 3.9, range 2.3–8.2 mm) to anterior (median 6.8, range 5.9–11.0 mm) segments and traversed alongside the annulus until it reached the cardiac crux. Accordingly, the distance between endocardium and RCA gradually decreased and became less than 3 mm at the posterior aspect (median 2.1, range 2.0–4.0 mm, \(P < 0.001\) both in superoanterior vs. inferior segments and in anterior vs. inferior segments).

**Discussion**

**The right atrial appendage structure**

Although previous reports including those from our group have described the inner structure of the RA, our study provides further information on the thickness of the medial wall, the predominant muscle distribution in the anterior RAA particularly the relationship between the CT, Bachmann’s bundle, and the SB. In clinical imaging studies, variations of the wall thickness are often overlooked and identifying the CT and SB can be difficult. Although the SB can be a particularly prominent ridge in some hearts, the concept of it being a partition dividing the RAA into supero/anteromedial and supero/posterolateral compartments is probably misleading.7 Our present study adds to the understanding of anatomical structures relevant to interventional electrophysiologists for improving procedural efficacy and safety.

We previously reported a detailed anatomy of the CT and the pectinate muscle in the RAA through an examination of 97 human normal hearts.3 The width and thickness of the CT origin in that study were 9.1 and 5.4 mm, respectively, which were almost equivalent to that of this study. A report by Loukas et al.,6 examining 300 human normal hearts, showed the most frequent pattern of the SB ramification to be single SB (65%) followed by multiple (20%) and absent SB (15%), which was again almost comparable with this study. Although the SB was examined in detail by Loukas and colleagues, their study made no mention of the distal insertions of the bundle. Our observation of the SB forming a potential ring around the tip of the RAA might suggest a potential reentry pathway involving propagation of the sinus node impulse. Variations in thicknesses of the bundle such as from thick to fine and back to thick again might produce different conduction properties resulting in arrhythmogenic sites such as those reported by Killu et al.7 Sinus node reentrant tachycardia could also be related to the ring where bundles running in one direction join with others in oblique or transverse directions causing conduction to slow down. The examination of the RA wall in our series further revealed non-uniform thickness in multiple sites in the medial portion, although there was a tendency for the thickest sites to be in the limited area of the medial wall, located superior to the aortic mound and anterior to the true atrial septum.

**The vestibule**

Reports on the detailed anatomy of the RAA vestibule and its relation to the adjacent CA in adult heart are scarce. Al-Ammouri and Perry10 reported the distances between the vestibule endocardium and the RCA at the multiple sites in the right and left atrioventricular groove in paediatric heart specimens, demonstrating that the shortest distance was in the coronary sinus ostium, which is close to the RA inferior, and the greatest distance was seen in the right superior region. Our examination showed similar trends, with the distance from the endocardium to the CA diminishing as one goes anti-clockwise from the superoanterior position to the inferior position, down to <3 mm in the normal adult hearts.

**Potential clinical implications**

Understanding of site-dependent wall thickness in the RA might provide some implications for catheter(s)/lead(s) insertion and implantation. Although the thick portion in the medial wall is limited, this area might be safer as compared with other areas such as the lateral wall which consisted of ridges of pectinate muscles that were separated by membrane-like walls with sparse myocardium, particularly when active-fixation leads are selected. Although there is no golden rule for preventing perforations, operators should be aware of this risk and confirm the direction of the lead(s)/catheter(s) by fluoroscopy in multi-angles. In addition, the amplitude of a sensed electrogram should also be reviewed prior to the screw extension. Having anatomical images of the RA wall in mind may also enable electrophysiologists to perform safer manoeuvres in the setting of ablation energy delivery not only in this chamber but also in the non-coronary sinus of the aortic root. Unsuccessful mapping and ablation of focal atrial tachycardia in the perinodal or perihisian region in the RA could be successfully carried out in the aortic sinus.11

Although electrophysiological data were unavailable in this series, our histological examination supports the findings of a
Figure 3 (A) Gross specimen of the inside of the RAA apex viewed from the left-anterior oblique perspective and a series of histological sections of the specimen cut transversely from the atrium towards the superior vena cava (SVC). The red broken line on the gross specimen represents the location of the sinus node while the red ovals on the sections mark the nodal artery and surrounding nodal tissues. Bachmann’s bundle crosses the fatty tissues of the interatrial groove as a fairly distinct bundle. Its rightward extension blends into the right atrial wall at the plane where the CT becomes recognizable. The blue arrows indicate the thin lateral wall between the pectinate muscles (PM). L, posterolateral tip; LA, left atrium; M, anteromedial tip. (B) Endocardial surface of strips of the lateral wall from the RAA with corresponding transmural histological sections show at low magnification (×16) the variability in extent of pectinate muscle vs. membrane-like wall. High magnification (×200) of three sites shows the paucity and even absence of myocardium at the thin parts. Masson’s trichrome stain colours myocardium red and fibrous tissue green.
study reporting endocardial sinus node impulse propagation. The study using a non-contact mapping system showed that sinus node impulse propagated preferentially in cranial, caudal directions as well as anteriorly in the RAA. Like Bachmann’s bundle and the CT, the SB has a well-aligned arrangement of the myocytes along the length of the bundle that would facilitate preferential conduction anteriorly.

Moreover, connection of the major muscle bundles in the RAA might be one of the possible explanations for the controversies over the selective-site pacing such as Bachmann’s bundle, low atrial septal, or dual-site pacing instead of ordinary RAA over the selective-site pacing such as Bachmann’s bundle, low atrial septal, or dual-site pacing instead of ordinary RAA pacing. Although these alternative approaches aim to minimize atrial conduction time in order to prevent atrial arrhythmias, the effects have not been fully established. From our histological examination, the RAA medial wall, lateral wall, and wall near the tip interconnect via rather prominent muscle bundles suggesting that the impulses could preferentially propagate to each other. Accordingly, the ‘RAA-pacing’ sites might include sites both close to and non-close to the preferential muscle bundles, which may lead to short and long conduction times even in the same category of ‘RAA-pacing’. Also, the various thicknesses and widths of muscle bundles in the appendage could cause impedance mismatch resulting in different conduction velocities.

We demonstrated the spatial relationship between vestibule endocardium and CA. This is the first report describing distances between these two structures in adult hearts, which is again important in the setting of accessory pathway ablation. Currently, it is difficult to predict coronary damage from the standpoint of mechanisms or energy sources but, by taking heed of the spatial relationships, caution can be given when delivering ablation energy and setting its power or temperature when approaching the posterior(inferior) part relating to the tricuspid orifice.

Several studies have reported the existence of non-annulus accessory pathways, of which atrial insertion is far from the annulus. A clinical study showed that all of the atrial insertions of these atypical pathways were located at the superior to anterior wall. A deep atrioventricular groove filled with extensive epicardial fat in this part of the annulus, as observed in our study, could allow the accessory pathway muscle bundle to cross the fatty tissues much further from the annulus, i.e. more epicardially than anticipated. Although the accurate delineation of anatomical structures in three-dimensional image modalities is still challenging due to the relatively dynamic heart motion in this area, future improvement of anatomic–electronic correlation could provide more information to identify the exact insertion sites of these bundles and allow a better understanding to this variant of the accessory pathway.

Conclusions

Non-uniformity of the wall thickness in the RAA, fibre arrangement of the muscle bundles in the RAA in relation to the Bachmann’s bundle, and the spatial relationship between the CA to the RA vestibule are further anatomical features relevant to lead implants and ablative procedures.

Acknowledgements

This project was supported by the NIHR Cardiovascular Biomedical Research Unit at the Royal Brompton and Harefield NHS Foundation Trust and Imperial College.

Conflict of interest: none declared.

Funding

A.U. is supported by a fellowship from Fukuda-denshi and St Jude Medical, Japan.

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