Anatomy of the Left Atrium and Pulmonary Veins – Lessons Learned from Novel Imaging Techniques

a report by

Josef Kautzner, **Hanka Micochova** *and* **Petr Peichl**

Department of Cardiology, Institute for Clinical and Experimental Medicine, Prague

During the last decade, catheter ablation has become a highly effective treatment option for the cure of symptomatic, drug-resistant atrial fibrillation (AF).[1–3] Despite the diversity of individual ablation strategies, all of them have something in common: the ablation is performed either within or around the ostia of the pulmonary veins (PV). This practice focused the authors' attention on anatomy of the PVs and the left atrium. Multiple studies have shown that PV anatomy is highly variable, emphasising the need for imaging before or during the procedure. This has resulted in the development of sophisticated image integration strategies that integrate 3-D anatomy obtained by cardiac magnetic resonance imaging (MRI) or computed tomography (CT) with datasets obtained during 3-D intracardiac mapping. This process may even be guided by an intracardiac echocardiography (ICE). The aim of this article is to discuss what has been learned in recent years about the anatomy of the left atrium and PVs, and to illustrate its impact on the practice of catheter ablation.

Anatomical Studies

Reflecting the need of electrophysiologists for detailed knowledge of PV anatomy, Ho et al. performed a thorough investigation of the arrangement and dimensions of the PVs in postmortem hearts.[4–5] They identified four distinct PV ostia in 77% of cases, while the rest of the specimens showed significant variance in anatomy of the PVs. Most often, a common vestibule of the left PVs was described. Approximately the same occcurrence of common ostia of PV (25%), mainly on the left side, was reported in the study by Moubarak et al.[6] Thus, the concept of four PVs with distinct ostia originating from the left atrium was debated for the first time in these early anatomical studies.

Pulmonary Venous Angiography

Contrast PV angiography has been used since the beginning of the era of curative catheter ablation for AF. It is employed by many operators to estimate the location and size of the PVs and/or to detect possible PV stenosis after the procedure. Using this imaging strategy, some studies even suggested that AF patients present with larger PV diameters proportional to the enlarged left atrium.[7] Yet, reported diameters were quite small (ranging between 8mm and 14mm) as viewed by current experience. More realistic values of PV ostial dimeters (ranging between 16.9mm and 19.4mm) were reported by Vasamreddy et al,[8] who defined PV ostium angiographically as the junction of PV with left atrium and measured from both projections with a correction for a degree of magnification. The study revealed an excellent correlation of angiographic measurements with MR angiography (MRA) analysed from 2-D maximum intensity projections and multiplanar reformations. Surprisingly, ostial diameters were found to be similar in both perpendicular planes, implying that PV ostia are of circular shape. In contrast, Wittkampf et al.[9] demonstrated clearly how contrast angiography can be misleading in description of PVs. Comparing this method with 3-D reconstruction of MRA images, they showed that the majority of the PV ostia are oval in shape with longer superoinferior than anteroposterior dimensions.

The above experience underlined the need for more detailed *in vivo* studies of PV anatomy and for development of more sophisticated imaging methods for guidance of catheter ablation for AF.

Intracardiac Echocardiography

One such technique appears to be (ICE). The most widely used imaging modalities are either a mechanical system with rotating transducer obtaining images in 360° radial fashion (Boston Scientific, Natick, MA) or a phased-array system (Acuson, Mountain View, CA) with steerable 90° longitudinal imaging. The latter system offers a greater depth of penetration and the possibility of Doppler imaging including colour coding.

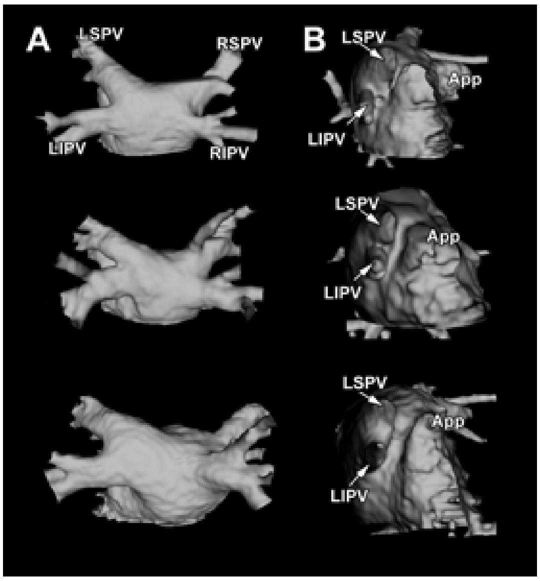
Given high variability in PV arrangement, ICE has the potential to provide very accurate information about the catheter tip position around the PV ostia and allow exact positioning of the circular mapping catheter

Josef Kautzner has been Head of the Department of Cardiology, Institute for Clinical and Experimental Medicine in Prague since 2001, and is a Professor of Medicine at Charles University Medical School I in Prague. He is internationally recognised as a Fellow of the European Society of Cardiology (ESC) and a regular member of Heart Rhythm Society and European Heart Rhythm Association. His current clinical and research activities are predominantly focused on non-pharmacological treatment of arrhythmias and cardiac resynchronisation therapy.

Hanka Micochova is is a Cardiology Fellow at the Department of Cardiology, Institute for Clinical and Experimental Medicine in Prague. She underwent part of her research training at the Cleveland Clinic Foundation in Cleveland, OH. Her contemporary research is focused on 3-D imaging of the heart and image integration.

Petr Peichl is a Cardiology Fellow at the Department of Cardiology, Institute for Clinical and Experimental Medicine in Prague. He underwent part of his research training at San Fillippo Neri Hospital in Rome. His PhD thesis was focused on intraventricular conduction abnormalities. Current clinical research activities cover predominantly electroanatomical mapping and its clinical applications.

Figure 1: Different Types of PV Branching Patterns as Assessed by 3-D Reconstructions of MRA Imaging Including Virtual Endoscopic Images of the Left PVs



App = left appendage, MRA = magnetic resonance angiography, PV = pulmonary vein, LIPV = left inferior PV, LSPV = left superior PV, RSPV = right superior PV, RIPV = right inferior PV.

(Lasso, Biosense Webster, Diamond Bar, CA) at the very level of the ostium. It has been shown to visualise PV ostia better than angiography and to ensure proper electrode alignment and contact.[10] Monitoring of microbubble formation can reveal tissue overheating[11,12] and, thus, minimise the risk of thrombus formation and other complications such as atrio-oesophageal fistulae. At the same time, ICE navigation minimises the risk of PV stenosis.[11] Based on previous experience with 'one size fits all' devices for PV isolation, such as ultrasound balloon, ostial anatomy and resulting misalignment of the catheter were identified as the main reason for ineffective energy delivery and failure.[13]

The main advantage of ICE is on-line imaging that allows monitoring of the ablation catheter or tool. At present, the main disadvantage reflects the 2-D nature of the imaging, which prevents full evaluation of the complex shape of PV vestibules. However, proper placement of the circular catheter at the level of the PV vestibule may help to ablate circumferentially under fluoroscopic guidance only.

Modern 3-D Imaging Techniques

The advent of modern 3-D imaging techniques such as MRI and/or multidetector CT has enabled detailed angiography-based anatomical studies of the PVs and non-invasive assessment of PV stenosis after catheter ablation.[14–17] PV ostia were found to be oval in shape with the anteroposterior dimension less than the superoinferior dimension. AF subjects appeared to have more complex branching patterns, especially in the inferior PVs.[15] However, individual authors identified variant PV ostial anatomy in variable proportions of patients. For instance, the occurrence of a common left vestibule of PVs ranged from 3% to 32%. Even the largest study by Mansour et al.[17] suggested that only 17% of cases presented with common left trunk and 29% with an additional right-sided PV. The authors' experience suggests that the above inconsistency could be explained by the fact that the majority of the studies used a 2-D data format for analysis instead of true 3-D reconstructions. Using special software for digital subtraction of arterial and venous phase and subsequent 3-D reconstruction of the data (see *Figure 1*), the authors have demonstrated that the majority of patients (75%) present with common left vestibule of variable length.[18] Such a high occurrence of common left antrum suggests that this pattern may be labelled as a 'normal' PV arrangement. Comparison of 2-D and 3-D formats in individual patients confirmed that the true PV ostial arrangement is often misunderstood from 2-D maximum intensity projections. Thus, only 3-D reconstructions of the segmented MRA data revealed true anatomy of the left atrium, appendage and PVs from different views.

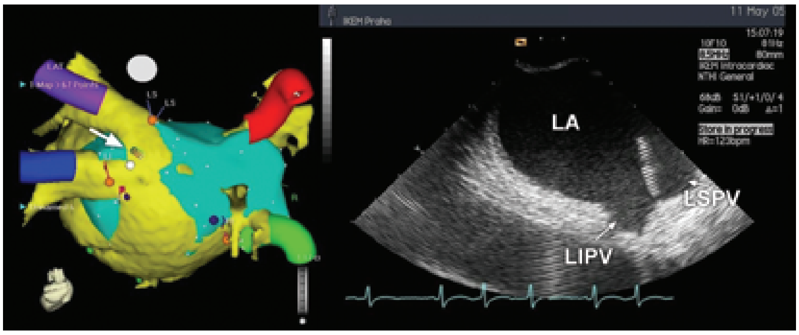
A similar observation was made by Jongbloed et al[19] using 3-D reconstructions of CT images and correlations with ICE. They confirmed frequent occurrence of common vestibules on the left side.

The use of 3-D imaging techniques has significantly changed understanding of PV ostial anatomy and helped to identify PV vestibules or antra that compose real PV–left atrial junctions. Their shape is predominantly oval and they tend to extend to the posterior wall of the left atrium, especially on the left side. As a result, both left- and right-sided antra or vestibules are in many patients close to each other on the posterior wall. This was confirmed clinically by the Cleveland group, which advocated PV antrum isolation using ICE and circular mapping catheter for navigation.[11]

Intra-procedural Image Integration

Reflecting the need for intra-procedural navigation, various techniques of image integration are being developed. One that is ready for clinical use (CARTO Merge, Biosense Webster, Diamond Bar, CA) integrates pre-procedural 3-D images (either CT angiography (CTA) or MRA) with the virtual electroanatomical map constructed during the procedure.[20] After the initial process of registration, an imported 3-D anatomical map of the left atrium and PVs is integrated with the actual mapping dataset and could be used for further catheter navigation. On-line ICE guidance could be used to improve the registration process (see *Figure 2*). According to the authors' experience with this technique, reliable correlation between between anatomical reconstructions and realtime CARTO maps of the left atrium and PVs can be obtained in a decent proportion of patients. Image integration with other mapping modalities, such as NAVx (St Jude Medical, Minneapolis-St Paul, MN), are under development. At present, side-by-side integration of images is used to compare the true anatomy with the virtual map obtained with the mapping system.

Figure 2: CT Angiographic 3-D Image Integrated with Electroanatomical Map Based on Registration Using ICE



The left panel depicts alignment of both 3-D images with an arrow pointing to the icon of catheter tip localised at the carina between left superior and inferior PV. The right panel shows the corresponding position of the catheter tip as seen by ICE. CT = computed tomography, ICE = intracardiac echocardiography, LA = left atrium, LIPV = left inferior pulmonary vein, LSPV = left superior pulmonary vein.

Conclusions

Lessons learned from sophisticated imaging techniques such as MRA or CTA suggest that the anatomy of the left atrium and PVs is very complex and individually highly variable. The most important discovery appears to be the fact that left-sided PVs merge in a large proportion of patients into the common vestibule or antrum. This variability explains why it is difficult to use one-size-fits-all devices for catheter ablation of PVs and actually puts this concept *per se* into question. On the contrary, recent evidence suggests that ablation at the level of the true common antrum may have better efficacy and lower risk of PV stenosis. This emphasises the need for pre-procedural 3-D imaging (and image integration) and/or intra-procedural imaging using ICE to improve spatial orientation.

References

1. *Haïssaguerre M, Jais P, Shah D C et al., "Spontaneous initiation of atrial fibrillation by ectopic beats originating in the pulmonary veins",* N Engl J Med *(1998);98: pp. 1,769–1,775.*
2. *Pappone C, Rosanio S, Oreto G et al., "Circumferential radiofrequency ablation of pulmonary vein ostia: a new anatomic approach for curing atrial fibrillation",* Circulation *(2000);102: pp. 2,619–2,628.*
3. *Nademanee K, McKenzie J, Kosar E et al., "A new approach for catheter ablation of atrial fibrillation: mapping of the electrophysiologic substrate",* J Am Coll Cardiol *(2004);43: pp. 2,044–2,053.*
4. *Ho S Y, Sanchez-Quintana D, Cabrera J A et al., "Anatomy of the left atrium: implications for radiofrequency ablation of atrial fibrillation",* J Cardiovasc Electrophysiol *(1999);10: pp. 1,525–1,533.*
5. *Ho S Y, Cabrera J A, Tran V H et al., "Architecture of the pulmonary veins: relevance to radiofrequency ablation",* Heart *(2001);86: pp. 265–270.*
6. *Moubarak J B, Rozwadowski J V, Strzalka C T et al., "Pulmonary veins-left atrial junction: anatomic and histological study",* Pacing Clin Electrophysiol *(2000);23: pp. 1,836–1,838.*
7. *Lin W S, Prakash V S, Tai C T et al., "Pulmonary vein morphology in patients with paroxysmal atrial fibrillation initiated by ectopic beats originating from the pulmonary veins: implications for catheter ablation",* Circulation *(2000);101: pp. 1,274–1,281.*
8. *Vasamreddy C R, Jayam V, Lickfett L et al., "Technique and results of pulmonary vein angiography in patients undergoing catheter ablation of atrial fibrillation",* J Cardiovasc Electrophysiol *(2004);15: pp. 21–26.*
9. *Wittkampf F H M, Vonken E J, Derksen R et al., "Pulmonary vein ostium geometry: analysis by magnetic resonance angiography",* Circulation *(2003);107: pp. 21–23.*
10. *Cooper J M, Epstein L M, "Use of intracardiac echocardiography to guide ablation of atrial fibrillation",* Circulation *(2001);104: pp. 3,010–3,013.*
11. *Marrouche N, Martin D, Wazni O et al., "Phased-array intracardiac echocardiography monitoring during pulmonary vein isolation in patients with atrial fibrillation: impact on outcome and complications,"* Circulation *(2003);107: pp. 2,710–2,716.*
12. *Wood M A, Shaffer K M, Ellenbogen A L et al., "Microbubbles during radiofrequency blation: composition and formation",* Heart Rhythm *(2005);2: pp. 397–403.*
13. *Saliba W, Wilber D, Packer D et al., "Circumferential ultrasound ablation for pulmonary vein isolation: analysis of acute and chronic failures",* J Cardiovasc Electrophysiol *(2002);13: pp. 957–961.*
14. *Dill T, Neumann T, Ekinci O et al., "Pulmonary vein diameter reduction after radiofrequency catheter ablation for paroxysmal atrial fibrillation evaluated by contrast-enhanced three-dimensional magnetic resonance imaging",* Circulation *(2003);107: pp. 845–850.*
15. *Kato R, Lickfett L, Meininger G et al., "Pulmonary vein anatomy in patients undergoing catheter ablation of atrial*

fibrillation: lessons learned by use of magnetic resonance imaging", Circulation *(2003);107: pp. 2,004–2,010.*

16. *Scharf C, Sneider M, Case I et al., "Anatomy of the pulmonary veins in patients with atrial fibrillation and effects of segmental ostial ablation analyzed by computed tomography",* J Cardiovasc Electrophysiol *(2003);14: pp. 150–155.*
17. *Mansour M, Holmvang G, Sosnovik D et al., "Assessment of pulmonary vein anatomic variability by magnetic resonance imaging: implications for catheter ablation techniques for atrial fibrillation",* J Cardiovasc Electrophysiol *(2004);15: pp. 387–393.*
18. *Mlcochova H, Tintera J, Porod V et al., "Magnetic resonance angiography of pulmonary veins: implications for catheter ablation of atrial fibrillation",* Pacing Clin Electrophysiol *(2005);28: pp. 1,073–1,080.*
19. *Jongbloed M R, Bax J J, Lamb H J et al., "Multislice computed tomography versus intracardiac echocardiography to evaluate the pulmonary veins before radiofrequency catheter ablation of atrial fibrillation: a head-to-head comparison",* J Am Coll Cardiol *(2005);45: pp. 343–350.*
20. *Tops L F, Bax J J, Zeppenfeld K et al., "Fusion of multislice computed tomography imaging with three-dimensional electroanatomic mapping to guide radiofrequency catheter ablation procedures",* Heart Rhythm *(2005);2: pp. 1,076–1,081.*