Eur Radiol (2006) 16: 2491–2504
DOI 10.1007/s00330-006-0235-0

CARDIAC

Ružica Maksimović
Thorsten Dill
Arsen D. Ristić
Petar M. Seferović

Imaging in percutaneous ablation for atrial fibrillation

Received: 2 November 2005
Revised: 20 February 2006
Accepted: 3 March 2006
Published online: 20 May 2006

R. Maksimović (✉)
Department of Radiology,
Erasmus Medical Center,
40, Doctor Molewaterplein,
3015 GD Rotterdam, The Netherlands
e-mail: rmaksimovic@yahoo.com
Tel.: +31-10-4634044
Fax: +31-10-4634033

T. Dill
Department of Cardiology,
Kerckhoff-Heart Center,
Bad Nauheim, Germany

R. Maksimović · A. D. Ristić ·
P. M. Seferović
Institute for Cardiovascular Diseases
of the University Medical Center,
Belgrade, Serbia and Montenegro

Abstract Percutaneous ablation for electrical disconnection of the arrhythmogenic foci using various forms of energy has become a well-established technique for treating atrial fibrillation (AF). Success rate in preventing recurrence of AF episodes is high although associated with a significant incidence of pulmonary vein (PV) stenosis and other rare complications. Clinical workup of AF patients includes imaging before and after ablative treatment using different noninvasive and invasive techniques such as conventional angiography, transoesophageal and intracardiac echocardiography, computed tomography (CT) and magnetic resonance imaging (MRI), which offer different information with variable diagnostic accuracy. Evaluation before percutaneous ablation involves assessment of PVs (PV pattern, branching pattern, orientation and ostial size) to facilitate position and size of catheters and reduce procedure time as well as examining the left atrium (presence of thrombi, dimensions and volumes). Imaging after the percutaneous ablation is important for assessment of overall success of the procedure and revealing potential complications. Therefore, imaging methods enable depiction of PVs and the anatomy of surrounding structures essential for preprocedural management and early detection of PV stenosis and other ablation-related procedures, as well as long-term follow-up of these patients.

Keywords Atrial fibrillation · Ablation · Imaging

Introduction

Atrial fibrillation (AF) is one of the most frequently encountered arrhythmias in the clinical settings and as such has raised a lot of attention among scientists in evaluation of incidence, mechanisms, consequences and treatment as well as quality of life and cost of health care for these patients [1, 2]. Paroxysmal and permanent AFs are associated with an increased risk of cerebral and systemic thromboembolic accidents, cardiac failure and mortality, and therefore, adequate diagnosis and treatment is of major importance. Since antiarrhythmic drugs have shown to be of limited value, nonpharmacological treatment using catheter ablation has been developed in the last decade for selected patients. Most arrhythmogenic foci in patients with AF refractory to medical therapy are located within pulmonary veins (PVs) [3]. Discovery by Haissaguerre et al. of the importance of radiofrequency catheter ablation in PVs that can eliminate AF by electrical disconnection of arrthymogenic foci represented a major therapeutic advance, which has prevented recurrence of AF in 70–80% of patients during the first year of follow-up [4, 5]. However, radiofrequency ablation in the vicinity of the ostia is associated with significant incidence of stenosis after the procedure and during short- and long-term follow-up [6, 7]. Although usually asymptomatic, PV stenosis could progress to complete occlusion, which could cause segmental pulmonary hypertension, venous infarction of the corresponding lobe or even a fatal outcome [8–10].

Several imaging modalities are being used to depict PV anatomy and the left atrium, such as conventional pulmonary venography [11], transoesophageal echocardiography

[12], intracardiac ultrasound [13], spiral and multidetector-row computed tomography (MDCT) [14, 15], and magnetic resonance imaging (MRI) [16].

Clinical considerations

Atrial fibrillation

The prevalence of AF has been estimated to be 0.4% in the general population, but due to replacement of the muscle with fibrotic tissue at the rate of 1% each year after the age of 50, it increases to about 5% in patients over 65 years [17]. Focal arrhythmogenic triggers may be found in the superior vena cava, crista terminalis, coronary sinus, vein of Marchall (v. obliqua atrii sinistri - Marshalli), interatrial septum or left atrial posterior wall, but several studies have suggested that most AFs are related to the existence of arrhythmogenic foci in PVs [18, 19]. The study by Jais et al. [20] demonstrated that PVs in patients with AF have distinctive electrophysiological properties, which could be explained by extension of atrial myocardium in the veins. The atrial myocardial sleeves have different lengths, 10–20 mm in the superior veins and 5–10 mm in the inferior PVs, and are the thickest in the inferior wall of the superior veins and superior wall of the inferior veins, thinning out or disappearing as the veins divide into segmental branches [21]. In addition to this, dilatation of the venous orifices presumably stretches the myocardium, thus changing its electrophysiological characteristics [22].

Antiarrhythmic drugs have shown inadequate efficacy and can paradoxically lead to life-threatening arrhythmias, and therefore, other therapeutic options have been considered, such as application of implantable devices and ablation therapy. In the last 15 years, percutaneous catheter ablation techniques have become a preferred therapeutic option in patients with paroxysmal AF who do not respond to at least 1–2 antiarrhythmic drugs, but future technical improvements will possibly widen the clinical spectrum for ablative treatment [23].

Radiofrequency ablation

Radiofrequency ablation is performed by using an electric current with alternating frequencies that creates myocardial lesions (Fig. 1). Different ablative techniques have been developed with various clinical efficacy and safety, such as focal ablation within PVs, segmental ablation and application of circumferential lesions. Successful PV isolation is reached in 89–97% of patients and is associated with a risk of PV stenosis in up to 42% of patients after the procedure and during the follow-up period [24, 25]. Frequency of PV stenosis depends on the technique and method of assessment, but overall major complication rate in high-volume electrophysiology laboratories is acceptably low and varies between 1% and 2% [4, 26].

Cryothermal ablation and other techniques

Cryothermal energy ablation is a relatively new technique for treatment of AF that preserves the basic underlying tissue architecture and integrity of the endocardial structure and therefore produces less risk of thrombus formation [27]. Long-term follow-up studies have shown the procedure is not associated with PV stenosis and stroke although clinical outcome is controversial and has not fulfilled initial high expectations [28–30]. Ultrasound [31], microwave [32] and diode laser ablation are alternative procedures and are undergoing preclinical and clinical evaluation, with great potential in clinical application.

Imaging

Detailed anatomical considerations of PVs and the left atrium are very important for effectiveness of PV ablation and clinical success of the procedure. The technique has been increasingly performed in electrophysiology laboratories, and therefore, radiologists are encountering more requests to assess anatomy of PVs and the left atrium both before and after the procedure.

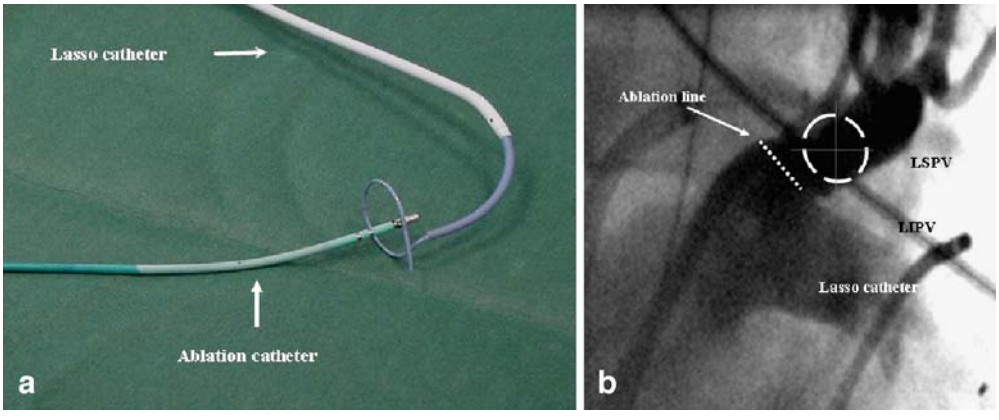

Fig. 1 Catheters for percutaneous ablation. **a** Lasso and ablation catheter; **b** circumferential catheter is positioned for mapping in left superior pulmonary vein through separate transseptal access (pulmonary venography). *LSPV* left superior pulmonary vein, *LIPV* left inferior pulmonary vein

Preprocedural imaging

Percutaneous ablation is based on complete electrical disconnection of PVs from atrial tissue, and detailed morphological information of PVs, including their relationship with the left atrium, are essential as the anatomic roadmap for the procedure [33]. Comprehensive knowledge of PV anatomy before the procedure allows size selection and positioning of mapping/ablation catheters and reduces overall procedure and radiation time. Also, preprocedural imaging includes measurement of PV ostial diameter, a mandatory parameter for assessment of potential postprocedural PVs stenosis. Different imaging modalities have been used for assessment of PVs. Conventional angiography is an invasive method that exposes a patient to radiation although it does not add invasiveness to the whole procedure in this particular case. Furthermore, it requires iodine contrast and does not allow detailed visualisation of all PVs due to structure overlap. Transoesophageal echocardiography frequently omits detailed visualisation of the left inferior PV [34] but is accurate in diagnosing small-branch stenosis, which produces a high velocity Doppler jet [35]. Intracardiac echocardiography provides real-time imaging of the interatrial septum and the proximal 1–3 cm of PVs, facilitating catheter guidance and accurate stent placement, but is not instructive for visualisation of the PV/left atrium relationship [36, 37]. Measurements of PV flow velocity could be obtained by both transoesophageal and intracardiac Doppler echocardiography, but these are less specific than direct measurements by conventional PV angiography [37] (Fig. 2). Conventional angiography overestimates while transoesophageal echocardiography underestimates PV ostial diameter compared with CT or intracardiac echocardiography [37].

CT and, recently, MDCT and MR angiography (MRA) have been applied to imaging PVs, with excellent spatial resolution. These techniques have low interobserver and intraobserver variability and provide accurate imaging of PVs and left atrial anatomy [38]. The major advantage of these methods is measurement of lumen diameter and visualisation of not only superior and inferior, but also anterior and posterior walls of the PVs. Reconstructions of the acquired images could be performed in three planes (transversal, sagittal and coronal) using different postprocessing techniques of the very thin axial slices as maximum intensity projection (MIP) and multiplanar reformation. Improved three-dimensional (3D) volume-rendering technique enables panoramic visualisation of PV anatomy and assessment of anatomical relationships of PVs and neighbouring structures. Virtual flythrough endoscopic images can also be reconstructed, allowing endoluminal evaluation of the venoatrial junction and PV branches. Furthermore, CT and 3D MRI morphological information has been used for stereotactic guidance during anatomically targeted ablations as well as to navigate and stabilise an ablation catheter [39, 40].

In comparison with MRI, MDCT scanning is fast, is completed during one breath hold in 20 s, is easy to perform and is well tolerated. However, CT and MDCT exposes patients to considerable amounts of radiation, 3.1–4.1 mSy, which is a dose that is likely to cause one fatal radiation-induced cancer every 1,240–1,640 examinations [41]. This calculation was based on estimated carcinogenic risk of 0.0004 per 1 mSy according to the International Commission on Radiological Protection [42]. MDCT with electrocardiogram (ECG) gating techniques exposes a patient to radiation of approximately 8 mSv [43]. Furthermore, MDCT could miss significant information and requires 100 ml of potentially nephrotoxic iodine contrast [44]. A bolus test or bolus tracking with triggering could be used to reduce the amount of contrast media [46] although it may not be absolutely necessary for analysing PV anatomy [45].

Image acquisition using MRI is ECG gated, with breath hold for about 10 s. After the correct image planes are defined, fast-precession steady-state sequence (True-FISP) images can be obtained for anatomical and functional assessment of PVs. For 3D MRA, nongated FISP sequence

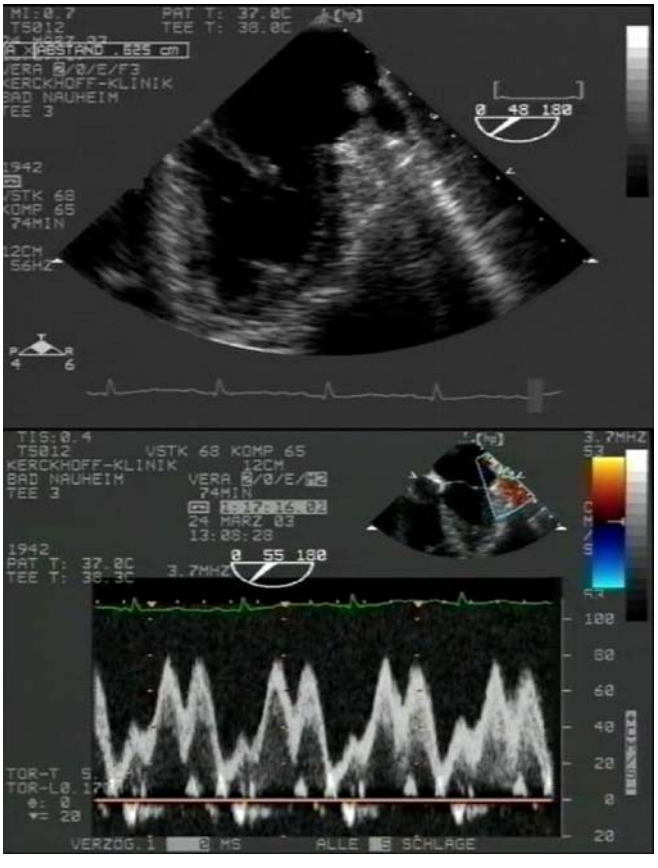

Fig. 2 Normal pulmonary vein. Doppler flow image of the left upper pulmonary vein shows no stenosis of the vein

is applied in a paracoronal orientation, and after injection of contrast agent (0.1 mmol/l per kilogram of body weight, flow 3 ml/s) followed by a 20 ml saline solution (flow 3 ml/s), angiogram-like images are acquired. The contrast media bolus should be targeted for peak enhancement in the left atrium, as determined by a bolus test timing sequence. Thus, the use of MRI is not associated with radiation and application of potentially nephrotoxic iodine contrast, can quantify PV flow and is considered as a method of choice in patients without absolute contraindications, such as in electronically, magnetically, and mechanically activated implants (automatic cardioverter defibrillators, cardiac pacemakers, metallic splinters in the eye, ferromagnetic haemostatic clips in the central nervous system).

Anatomy of pulmonary veins

Pulmonary vein patterns The basic pattern of PVs with two ostia to the left and two ostia to the right has been seen with different frequency in reported studies, ranging from 57% [37, 47] to 80% of the examined population (Fig. 3), [48]. This diversity of findings may be due to lack of definition of PV ostium and different imaging techniques used [38].

An additional venous orifice could be a source of arrhythmogenic foci or share an orifice with a short main venous stem and therefore needs to be ablated [49, 50]. In general, the right PVs were found to be more divergent than left ones. The right middle PV tends frequently to be the source of atrial arrhythmias although no significant

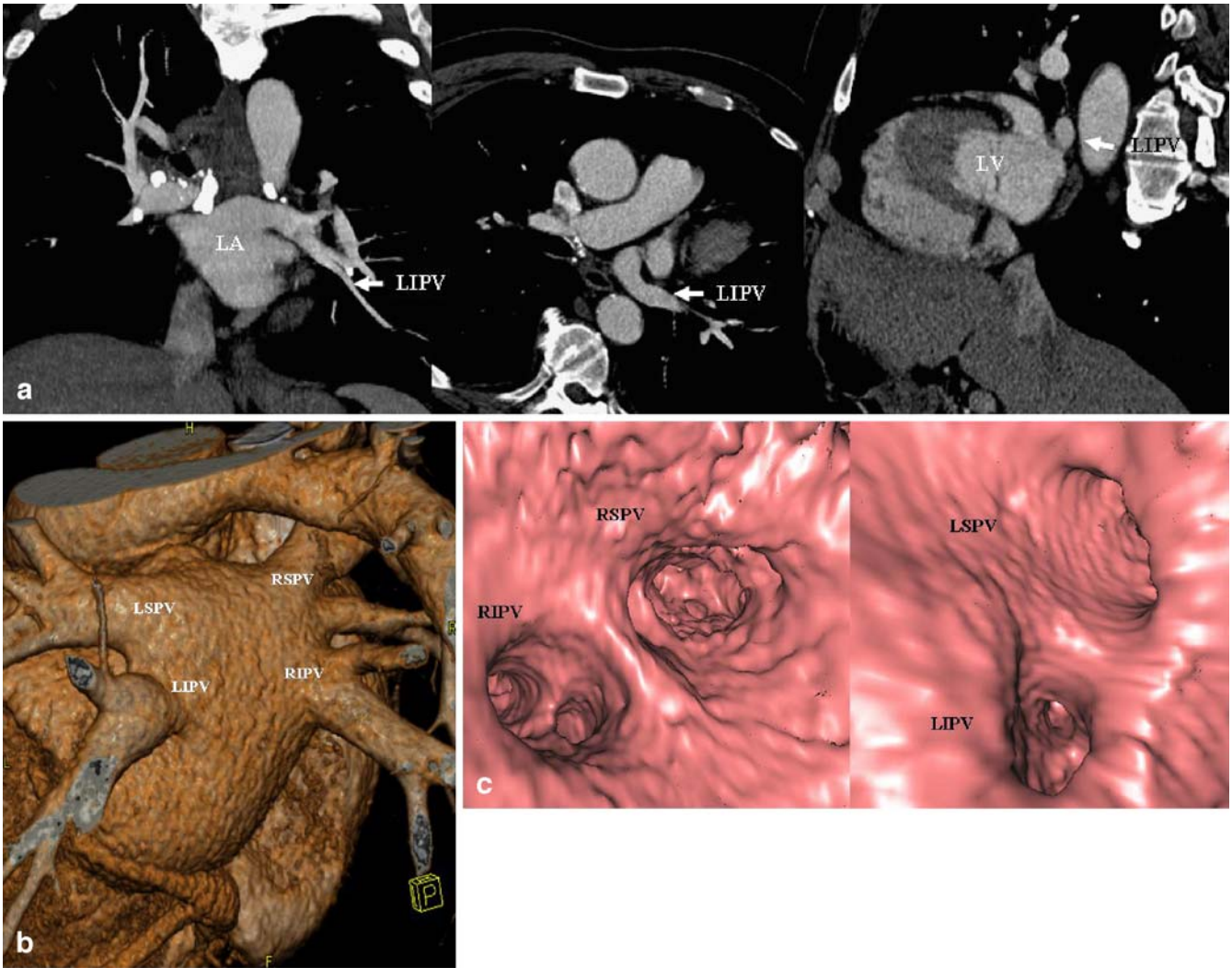

Fig. 3 Normal anatomy of pulmonary veins (PVs) as shown using contrast-enhanced multidetector-row computed tomography (MDCT) images. Separate insertion of left inferior PV in coronal, axial and sagittal plane (*from left to right panel*). Volume rendering reconstruction of the heart and PVs in the posterior view (**b**), and virtual endoscopy view of the left atrium visualising the origin of all PVs (**c**). *LSPV* left superior pulmonary vein, *LIPV* left inferior pulmonary vein, *RSPV* right superior pulmonary vein, *RIPV* right inferior pulmonary vein, *LA* left atrium, *LV* left ventricle

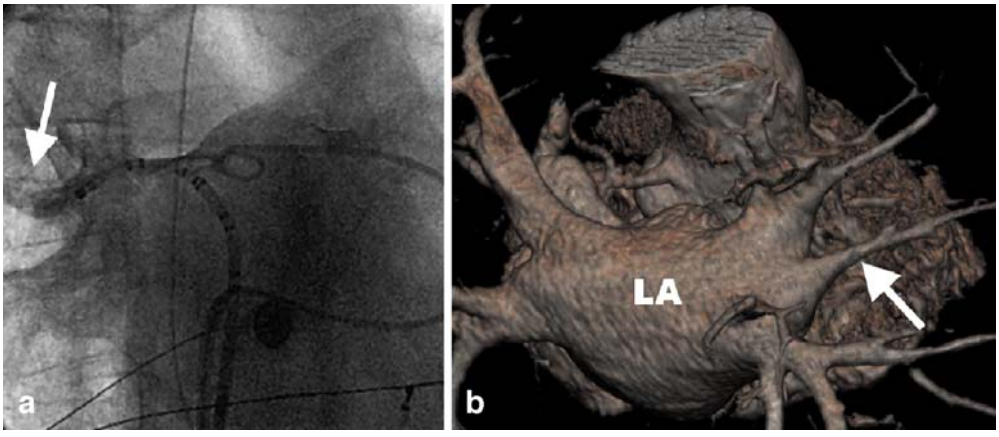

Fig. 4 Right middle pulmonary vein. Pulmonary venography (**a**) and volume rendering technique reconstruction (**b**) of images obtained using contrast-enhanced multidetector-row computed tomography (MDCT). Right middle pulmonary vein is seen as a separate additional vein

association between particular venous pattern and atrial arrhythmias has been proven [44]. Frequent presence of the right middle vein may be explained by the necessity to drain the lung area between the divergent right superior and right inferior PV [37]. Based on MRI studies, single right middle PV has been found in 4–27% of patients [37, 51], (Fig. 4) while two additional right PVs are less frequent and have been reported in 3–7% of the population [47, 51]. This vein provides sufficient blood flow if postablation stenosis of the right inferior PV occurs. Furthermore, since the ridge of atrial tissue separating the veins is narrow, unstable position of the ablation catheter in this area could potentially result in adverse application of energy inside one of the veins [37].

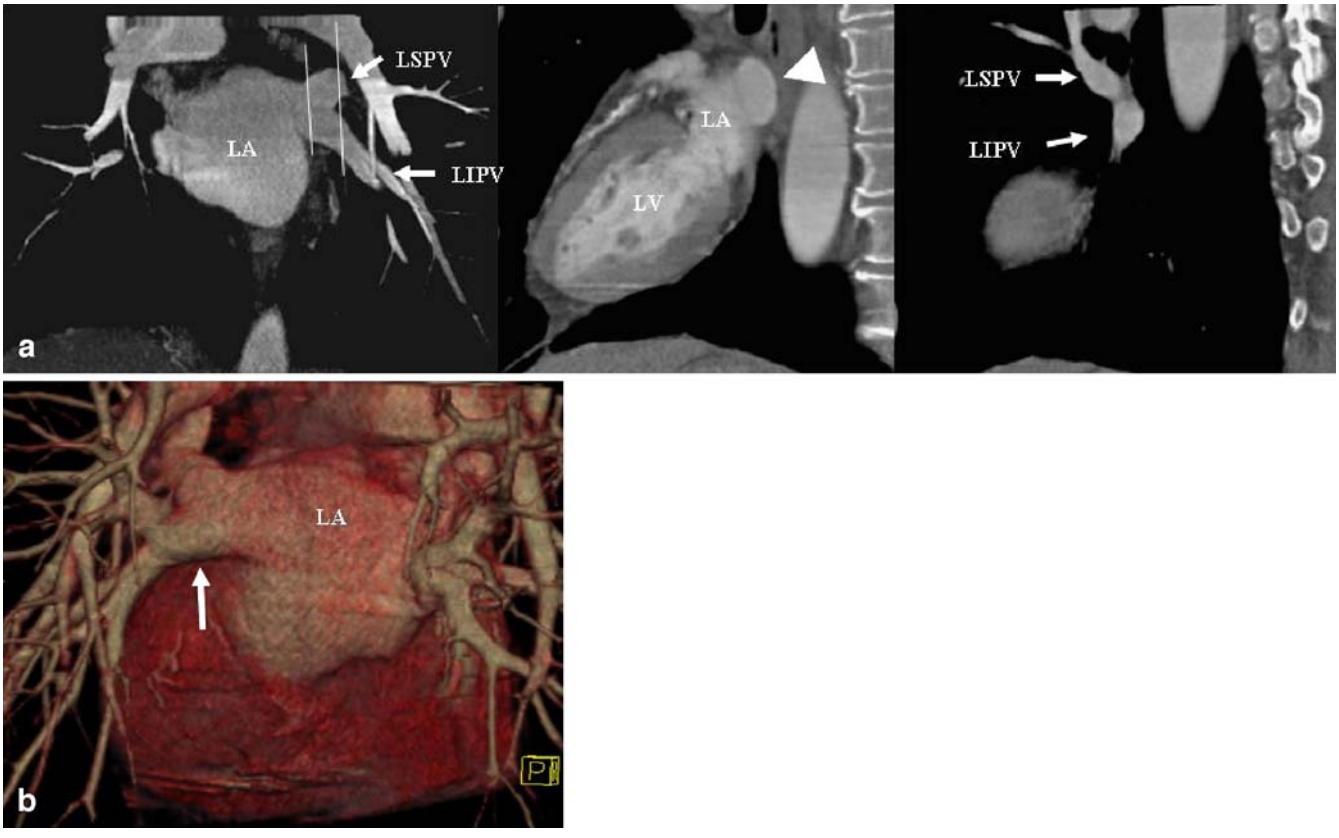

Fig. 5 Common trunk of the left superior and left inferior pulmonary vein. The superior and inferior left pulmonary veins have merged before entering the left atrium. **a** Lines on the left panel in coronal projection indicate position of slices in the sagittal plane presented in the *middle and right panels*. *Arrowhead* in the *middle panel* is pointing to the common trunk. **b** Volume rendering technique reconstruction of multidetector-row computed tomography (MDCT) images from posterior view. The *arrow* is indicating the common trunk. *LSPV* left superior pulmonary vein, *LIPV* left inferior pulmonary vein, *LA* left atrium, *LV* left ventricle

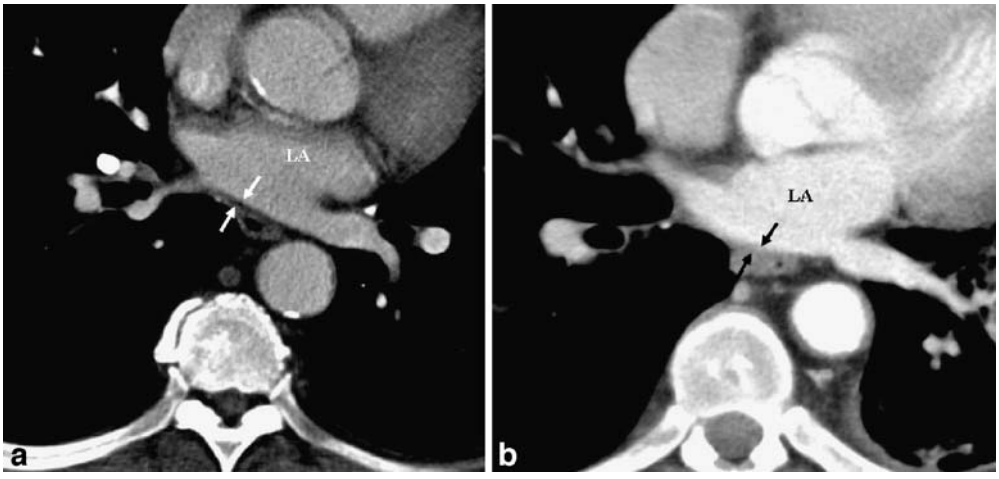

Fig. 6 Fatty tissue. Fatty tissue is seen as a radiolucent area between the posterior wall of the left atrium and anterior wall of oesophagus on axial multidetector-row computed tomography (MDCT) image (**a**). No fatty tissue could be seen in another patient (**b**)

Right top PV, reported in the MRI study of Lickfett et al. [51] in 3% of the patients, drains the right upper lung lobe, presumably the bronchopulmonary segment as well. It is too small (7±2 mm) to be a source of AF, but it should be recognised during the intraprocedural venography if it is accidentally blocked with the angiography catheter. Additional single left-sided PV, draining the lingula, was found in only 2% of the patients in the MRI study of Mansour et al. [38]. Common ostium is a confluence of PVs before entering the left atrium (Fig. 5). Right-sided single venous ostium was found in 2–39% of the cases [38, 49] while the left-sided single ostium was reported in 3–83% of patients with AF [46, 47, 52, 53]. This difference could be related to both definition of the common ostium and sensitivity of the applied imaging technique. In the study of Jongbloed et al., right-sided common ostia were observed in 31% with MDCT and in 38% with intracardiac echocardiography while left-sided common ostia were identified in 79% and in 74%, respectively [52].

Branching pattern Both cross-sectional imaging techniques, MDCT and MRI, have been extensively used in evaluation of PV branching pattern. Early PV branching was defined as either branching within 1 cm of PV bifurcation or within 5 mm from the ostium of the main PV [37, 52] and is often prone to stenosis. Early branching in the MRI study of Mansour et al. [38] was detected in 41% of patients and was more frequent in right-sided PVs, supported by the study of Jongbloed et al. using MDCT [52]. This study showed that MDCT sensitivity for detecting an early branching pattern of right PVs was 54% in comparison with intracardiac echocardiography. Topographic assessment of PVs, including second-order branches, could be successfully performed using MRI fly-through endoscopic navigation, which, although complex and time consuming, holds promise for the wider application [47, 51, 54].

Pulmonary vein orientation Different PV orientation to the left atrium might explain the difficulties in proper catheter placement [38]. MRI and MDCT have been very useful in presenting PV orientation in relation to different planes. The study of Ho et al. on 20 human heart specimens [55] revealed that superior veins enter the left atrium at an angle of 45–60° to the horizontal plane and inferior veins at an angle of 30–45°. The MRI study of Mansour et al. showed that the right superior PV was projected at 131±11° in relation to the longitudinal plane of the left atrium, right inferior PV at 206±16°, left superior at 32±13° and left inferior PV at 329±14° [38].

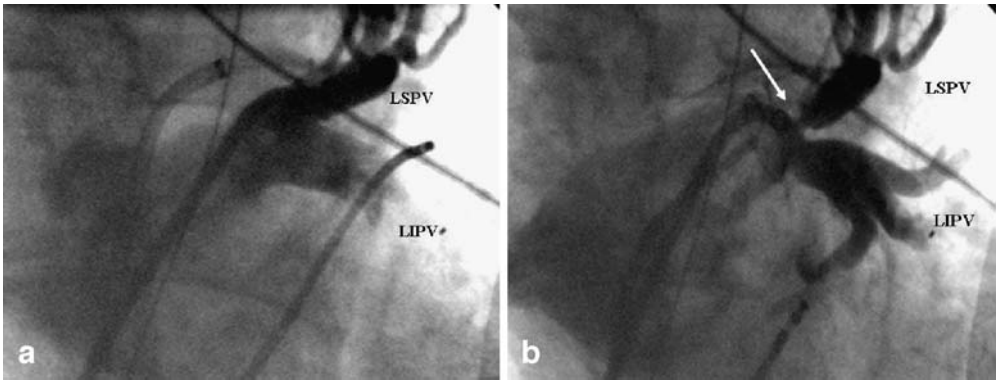

Fig. 7 Early stenosis of left superior pulmonary vein. Left superior pulmonary vein before (**a**) and after (**b**) radiofrequency ablation (*arrow*). Stenosis is remarkable immediately after the procedure on control pulmonary venography. *LSPV* left superior pulmonary vein, *LIPV* left inferior pulmonary vein

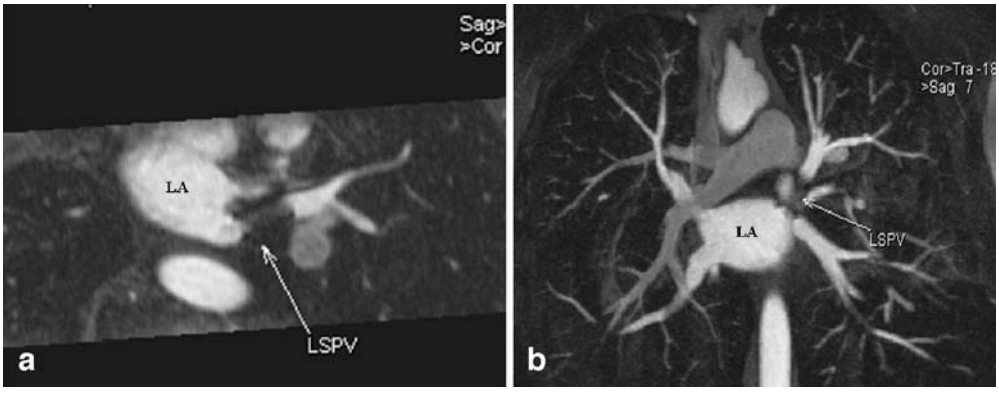

Fig. 8 Occlusion of the left superior pulmonary vein. Maximal intensity projection of magnetic resonance angiography (MRA) in axial (**a**) and coronal (**b**) orientation showing total occlusion of the vein (*arrow*). *LSPV* left superior pulmonary vein, *LA* left atrium

Pulmonary vein ostia PV ostium is defined as the distance between the upper and lower wall of the PV and the wall of adjacent left atrium [38, 52]. In preprocedural imaging, PV ostial diameter is an important factor in selection of optimal catheter size while after the procedure, a possible stenosis is a major concern. In addition, small PV ostial diameter (less than 10 mm) is more frequently prone to stenosis, and most operators avoid ablation of these veins. However, they may have a focal AF trigger or may be connected by muscle sleeves to another vein, and therefore, they needed to be electrically isolated [38].

Normal PV ostial diameter measurements depend on imaging plane and technique and cardiac cycle. Cross-sectional anatomy does not reflect true anatomic variations of PVs, and the sagittal plane is suggested as more reproducible for serial measurements [56]. Also, venography overestimates and transoesophageal echocardiography underestimates ostial diameter compared with CT and intracardiac echocardiography while MDCT and intracardiac echocardiography provide comparable measurements of PV ostia [36, 52]. Furthermore, in atrial systole, PV ostial size decreases by 32.5%, indicating the need for PV measurements in the same phase of the cardiac cycle [57].

Ostia of the superior PVs in patients with AF were larger than in healthy controls or in non-AF patients [53, 58–60]. Patients with persistent AF had larger ostia than patients with paroxysmal AF [53], which has not been confirmed in other studies [47, 60, 61]. Superoinferior diameter of PV ostia is longer than anteroposterior, and therefore, the venous ostial index calculated as their ratio has been suggested for evaluation of PV ostia [15, 52, 62]. Value of the ostial index indicates oval shape of left-sided and round shape of right-sided PVs [52, 62].

Anatomy of the left atrium

Preprocedural evaluation of patients with AF includes assessment of the left atrium for the presence of thrombus, left atrial dimensions and volumes, relationship with adjacent structures and imaging of left atrial appendage. Exclusion of atrial and left atrial appendage thrombi is essential since it is an absolute contraindication for ablation [63].

In healthy volunteers, the mean longitudinal diameter of the left atrium is 4.5±1.4 cm, the transverse dimension is 4.0±1.2 cm [51] while the volume varies from 79 to 115 ml

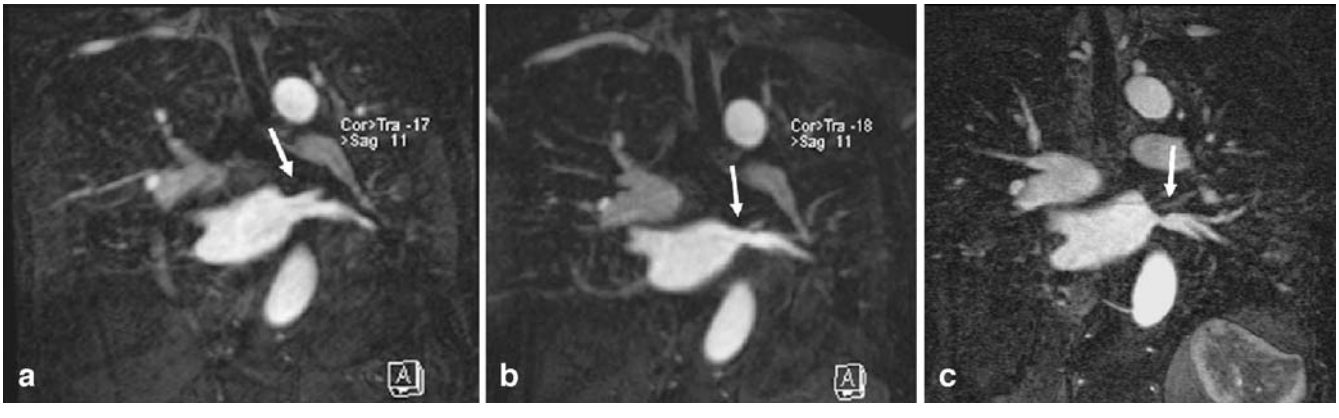

Fig. 9 Stenosis of the left inferior pulmonary vein. Multiplanar reconstruction of magnetic resonance angiography (MRA) 1 day after radiofrequency ablation (**a**), 3 months after the procedure (**b**) and after 6 months' follow-up (**c**). After 3 months' follow-up, pulmonary vein diameter at the ostium was reduced by 25% while after 6 months the vein diameter was reduced by 50% (*arrows*)

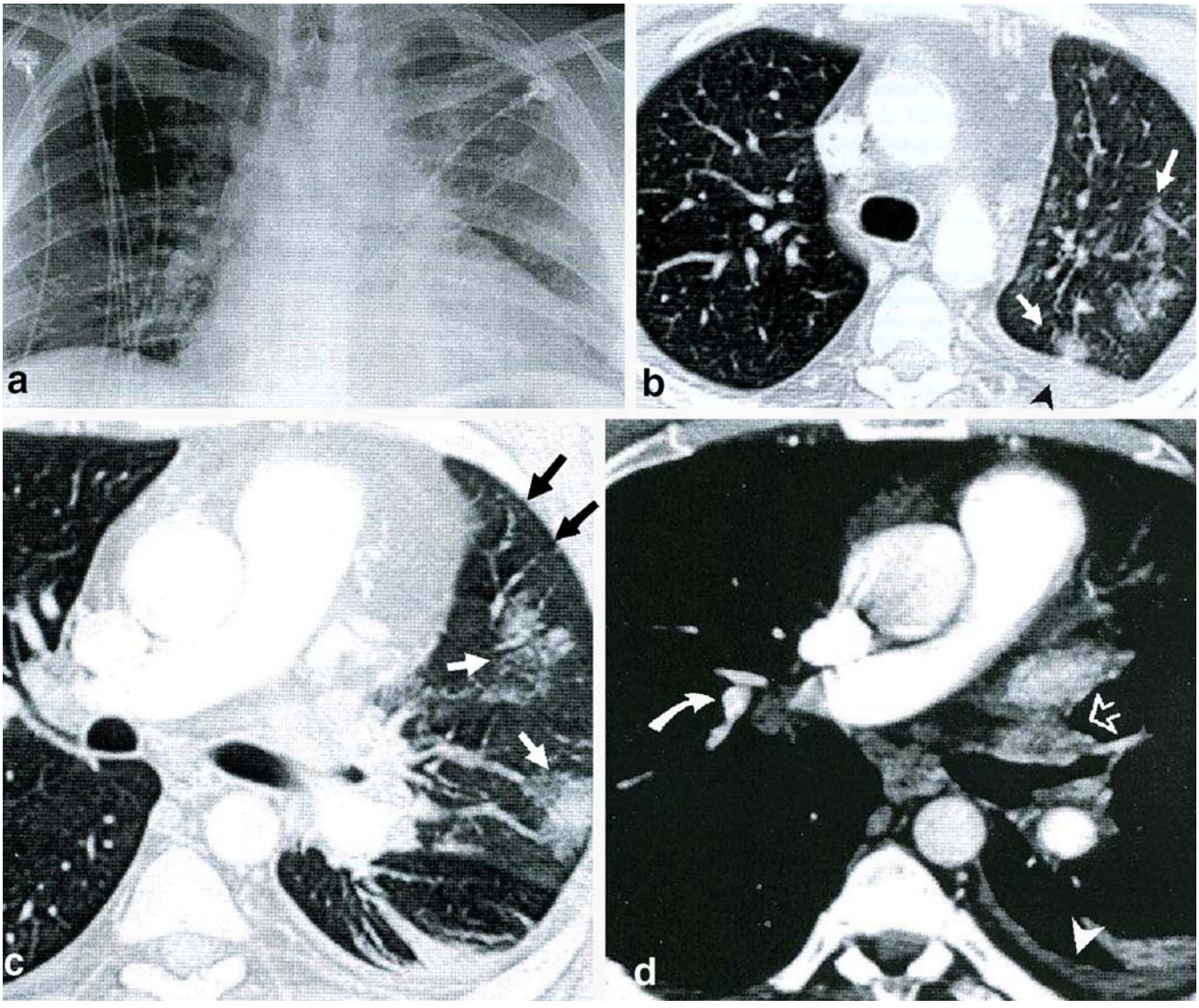

Fig. 10 Thrombosis of the left superior pulmonary vein (PV). The patient underwent ablation of the left superior PV and had hemoptysis and chest discomfort during 3 months' follow-up. **a** Chest X-ray shows heterogeneous opacity in the left upper lobe. **b**, **c** Axial contrast-enhanced computed tomography (CT) images (*lung window*) demonstrate ground-glass attenuation and focal peripheral consolidation in the left upper lobe (*white arrows* in **b** and **c**), thickened interlobular septum (*black arrows* in **c**) consistent with pulmonary venous infarction. Note also pleural effusion (*arrowheads* in **b**). **d** Axial contrast-enhanced CT scan (*mediastinal window*) presents occlusion of the left superior PV (*open arrow*) with soft tissue attenuation surrounding the expected location of the vein. Contrast is seen in the right superior pulmonary vein (*curved arrow*). Reproduced with permission from *American Journal of Roentgenology*, Ravenel JG, Duke University Medical Center, Durham, NC, USA 8

to 65 to 139 ml, depending on the technique applied, echocardiography or cardiac MRI [17, 61, 64]. Patients with idiopathic AF have longer longitudinal diameter compared with healthy controls [17, 65].

Another critical clinical issue is the relation of the posterior wall of the left atrium and the oesophagus because the known complication of catheter ablation could be atrioesophageal fistula [66]. As measured on helical CT, posterior wall of the left atrium is 2.2±0.9 mm while the anterior aspect of the oesophageal wall is 3.6±1.7 mm. Fatty tissue between these structures is 0.9±0.2 mm, which might insulate the oesophagus from thermal injury during radiofrequency ablation and could explain relatively low incidence of atrioesophageal fistula (Fig. 6). However, the fatty tissue layer is discontinuous in 98% of patients and is usually absent at the level of the mid posterior wall in average length of 18±10 mm (3–40 mm) [67].

Left atrial appendage could be assessed using different modalities: MDCT, MRI, echocardiography. Functional assessment using intracardiac echocardiography has been

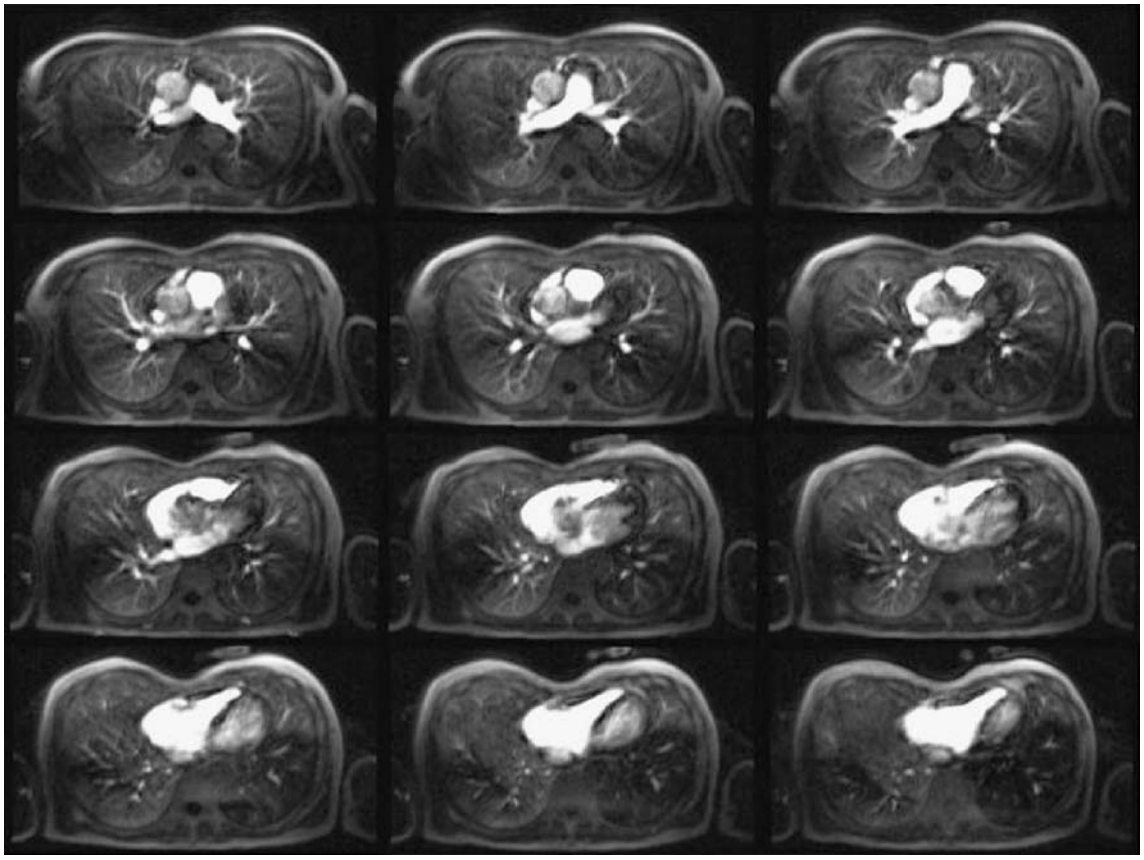

Fig. 11 Magnetic resonance imaging (MRI) perfusion study. MR perfusion images of patients with occlusion of the left superior pulmonary vein from Fig. 8. Axial plane MRI images from the pulmonary apex to the base show corresponding perfusion defects thorough the left lung

shown to be valuable in evaluation of left atrial appendage emptying velocities and was found to be a predictor of recovery of atrial booster pump function [63].

Postprocedural imaging

Imaging after ablation includes evaluation of PVs, left atrium and other structures prone to complications. Due to the increasing frequency of ablation procedures, radiologists should be aware of timing and severity of potential complications and their clinical implications. The most commonly reported complication after radiofrequency ablation is PV stenosis while others have been documented less frequently.

There is no overall accepted consensus on timing of imaging after the procedure. Usually, patients are imaged 1 day after the procedure, and then after 1, 3, 6 and 12 months, depending on study design and clinical indications [6, 63, 68]. This enables monitoring of PVs and left atrium and possible dynamics of PV narrowing. PV diameter reduction of less than 50% usually remains stable while narrowing of more than 50% after 3 months tends to progress to high-grade stenosis [68]. These results demonstrate the need for follow-up imaging even in asymptomatic patients who could develop symptoms that might be misinterpreted. Also, in a case of symptom recurrence, initial information of PV stenosis is important for planning reintervention.

Various methods have been used to screen for the presence of postprocedural complications. Keeping in mind noninvasiveness, scanning with MDCT and MRI are recommended imaging modalities. However, MDCT scanning exposes a patient to repeated radiation and application of a contrast media. In addition to previously mentioned advantages, MRI could quantify PV flow while MR pulmonary perfusion imaging has reached sensitivity of 95.2% in revealing pulmonary perfusion defect in comparison with single-photon emission CT [69]. Therefore, MRI seems to be the preferred imaging technique for follow-up.

Evaluation of the pulmonary veins

The incidence of PV stenosis after radiofrequency ablation varies depending on imaging modality applied, ablation techniques and energy delivered during the procedure [70].

Furthermore, sensitivity of various diagnostic methods is largely variable, without widely accepted criteria for PV stenosis [35, 43].

The frequency of PV stenosis reported in the literature varies between 1–42% [1, 7]. Interestingly enough, the high incidence of PV stenosis reported by Chen (42%) was based on transoesophageal echocardiography flow velocity and is considered to overestimate the incidence of this complication [7]. A later study by the same group with the same technique revealed stenosis in 33% [12] of the patients while other groups reported far lower incidence of this complication [19, 33, 71].

After the procedure, PV wall thickness significantly increases while the diameter is considerably reduced due to inflammatory oedema [72], as confirmed by increased PV ostial flow on intracardiac Doppler echocardiography, (Fig. 7). Although this morphological changes did not predict subsequent PV stenosis [73], diameter reduction of more than 25% was reported as an independent long-term predictor of severe stenosis (Fig. 8), [74]. Left inferior PV more frequently tends to develop stenosis due to its smaller size, which often causes longer operative manipulation [68] (Fig. 9).

Pulmonary hypertension is caused by significant stenosis or occlusions of one or more PVs. This complication is often latent at rest but manifests during exercise [75], and it could be identified by transoesophageal echocardiography. Transthoracic echocardiography has lower diagnostic accuracy and has not been routinely used in visualisation of PVs and PV stenosis because it usually allows evaluation of the proximal part of the right upper pulmonary vein only. Morphological alterations include septal thickening, ground-glass opacity and interlobar septal thickening and could be seen on CT. In addition, reactive regional mediastinal lymph node enlargement may be demonstrated.

Perfusion defects in the area of affected PVs could be verified by ventilation-perfusion scans or MRI perfusion study [76] (Fig. 10). In the study of Kluge et al., pulmonary perfusion partially recovered over weeks, but complete normalisation was observed in only 17% of patients [69]. PV thrombosis and infarction (Fig. 11) are rare but clinically important complications, occurring 1 day to 3 months after radiofrequency ablation. This complication may be presented on chest X-ray as an area of focal pulmonary oedema distal to the occluded vein while CT may show nodules and wedge-shaped parenchymal consolidation. PV dissection is a serious but infrequent complication [77]. Fatal outcome is rarely described, as in the case study of Nilsson et al., who reported ominous postprocedural course with alveolar damage, disseminated intravascular coagulation, multiple thrombi formation and haemorrhagic infarctions [9].

Mild or moderate PV stenosis or stenosis of a single vein is often asymptomatic [73]. Asymptomatic patients might require follow-up, with MRI technique as a method of choice due to its advantages over other methods. Even if symptoms are present, they could appear to be of respiratory origin and could improve spontaneously over time in a significant number of patients [73]. However, in patients with PV stenosis who experience persistent cough, perfusion defects and documented PV diameter less than 6 mm, treatments of choice are balloon dilatation or stenting [74, 78] (Fig. 12). These procedures offer immediate symptoms relief, observed usually within 1 hour. However, in up to 47% of patients, in-stent or in-segment restenosis can develop, caused by neointimal hyperplasia, fibrosis and thrombus formation [79].

Evaluation of the left atrium

In patients with restored sinus rhythm, left atrial size decreases while progressive left atrial dilatation was associated with late recurrence of AF [71]. Furthermore,

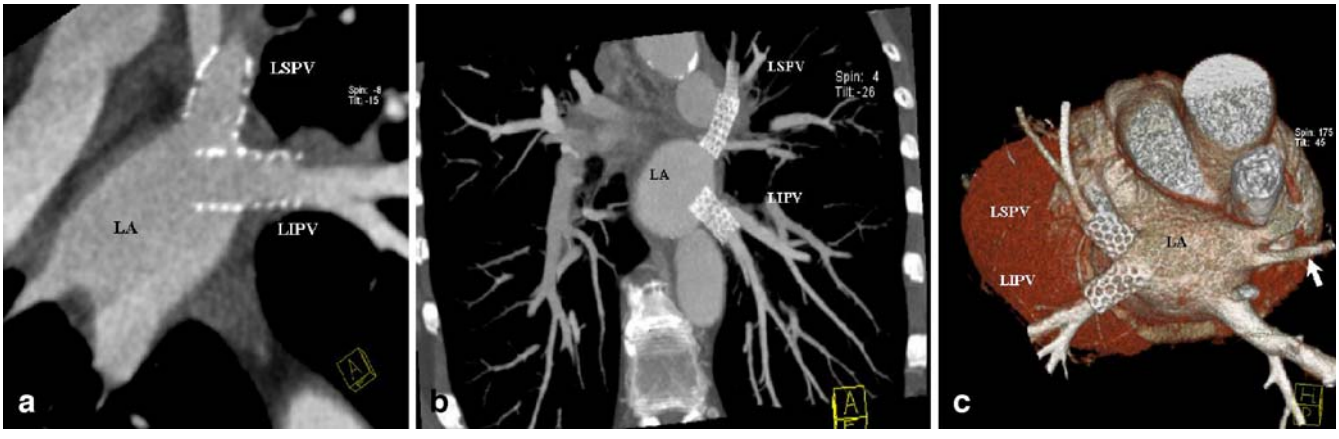

Fig. 12 Stents on left superior and left inferior pulmonary veins (PVs). Maximum intensity projection of multidetector-row computed tomography (MDCT) images in oblique axial (**a**) and coronal (**b**) projection and volume rendering technique reconstruction, posterior view (**c**), of PVs after MDCT angiography depicts stents of the left veins due to progressive diameter reduction, which resulted in complete occlusion after 6 months' follow-up. *Arrow* in **c** indicates the right middle pulmonary vein. *LSPV* left superior pulmonary vein, *LIPV* left inferior pulmonary vein, *LA* left atrium

thermal injury of the posterior wall of the left atrium and oesophagus during radiofrequency ablation bear a risk of oesophageal perforation and subsequent atrial–oesophageal fistula. This complication, the incidence of which is not reported in the literature, is caused by overlapping of ablation lines of the posterior wall of the left atrium and anterior wall of the oesophagus [80]. However, in patients who underwent intraoperative radiofrequency ablation of AF [81], it is described in 1%, with 50% mortality [82].

Evaluation of other structures

Embolic complications can occur up to 3 months after the procedure at the rate of 2% despite anticoagulant therapy [83]. Other complications include pericarditis (3–4.8%), cardiac perforation (hemopericardium, tamponade, hemothorax), valvular injury, pleural effusion and complications not directly related to the ablation procedure itself (hemopneumothorax, catheter -site haematoma, arteriovenous fistula) [84].

Conclusions

Percutaneous catheter ablation techniques using different energy sources have become frequently applied therapeutic options in many electrophysiological laboratories world wide. Comprehensive morphological information of PVs (PV pattern, branching pattern, orientation, size of the ostia), their relationship with the left atrium and assessment of the left atrium for the presence of thrombus, measurements of left atrial dimensions and volumes and imaging of left atrial appendage are essential elements in preprocedural imaging as a roadmap for the ablation. Noninvasive and invasive imaging modalities, such as conventional angiography, transoesophageal and intracardiac echocardiography, CT, MDCT and MRI have been used to provide preablation information, with different diagnostic accuracy. This information is important for appropriate sizing of a catheter and visualisation of all PVs and the left atrium. CT, MDCT and MRA have been proven to be valuable, noninvasive diagnostic tools in imaging PVs and the left atrium, with good temporal and spatial resolution and excellent interobserver and intraobserver agreement. Furthermore, MRI does not expose patients to radiation and application of potentially nephrotoxic iodine contrast and can quantify PV flow and perform pulmonary perfusion study, and it is therefore considered as a method of choice in patients without contraindications. During the follow-up period, imaging techniques enable assessment of postprocedural remodelling of PVs and the left atrium and procedure-related complications. Since repeated examinations are necessary after the procedure, the noninvasive methods of MDCT and MRI are preferred imaging modalities. Therefore, imaging methods are an indispensable part of the complete clinical workup of patients with AF that minimise risk for development of complications and are potentially leading to greater acceptance for ablation procedures.

References

1. Haissaguerre M, Shah DC, Jais P et al (2000) Electrophysiological breakthroughs from the left atrium to the pulmonary veins. Circulation 102:2463–2465
2. Scheinman MM, Morady F (2001) Nonpharmacological approaches to atrial fibrillation. Circulation 103:2120–2125
3. Haissaguerre M, Jais P, Shah DC et al (1998) Spontaneous initiation of atrial fibrillation by ectopic beats originating in the pulmonary veins. N Engl J Med 339:659–666
4. Keane D (2002) New catheter ablation techniques for the treatment of cardiac arrhythmias. Car Electrophysiol Rev 6:341–348
5. Haissaguerre M, Jais P, Shah DC et al (1996) Right and left atrial radiofrequency catheter therapy of paroxysmal atrial fibrillation. J Cardiovasc Electorophysiol 7:1132–1144
6. Dill T, Neumann T, Ekinci O et al (2003) Pulmonary vein diameter reduction after radiofrequency catheter ablation for paroxysmal atrial fibrillation evaluated by contrast-enhanced three-dimensional magnetic resonance imaging. Circulation 107:845–850 DOI:10.1161/01.CIR.0000048146.81336.1D
7. Chen SA, Tai CT, Yu WC et al (1999) Right atrial focal atrial fibrillation: electrophysiological characteristics and radiofrequency catheter ablation. J Cardiovasc Electrophysiol 10:328–335
8. Ravenel JG, McAdams HP (2002) Pulmonary venous infarction after radiofrequency ablation for atrial fibrillation. Am J Roentgenol 178 (3):664–666
9. Nilsson B, Chen X, Pehrson S et al (2004) Acute fatal pulmonary vein occlusion after catheter ablation of atrial fibrillation. J Interv Card Electrophysiol 11(2):127–130
10. Sonmez B, Demirsoy E, Zagan N et al (2003) A fatal complication due to radiofrequency ablation for atrial fibrillation: atrio-oesophageal fistula. Ann Thorac Surg 76:281–283
11. Deisenhofer I, Schneider MAE, Bohlen-Knauf M et al (2003) Circumferential mapping and electric isolation of pulmonary veins in patients with atrial fibrillation. Am J Cardiol 91:159–163
12. Yu WC, Hsu TL, Tai CT et al (2001) Acquired pulmonary vein stenosis after radiofrequency catheter ablation of paroxysmal atrial fibrillation. J Cardiovasc Electrophysiol 12:887–892
13. Ren JF, Marchlinski FE, Callans DJ (2004) Left atrial thrombus associated with ablation for atrial fibrillation: identification with intracardiac echocardiography. J Am Coll Cardiol 43 (10):1861–1867

14. Lacomis MJ, Wigginton W, Fuhrman C, Schwrzman D, Armfeld RD, Pealer KM (2003) Multi-detector row CT of the left atrium and pulmonary veins before radio-frequency catheter ablation for atrial fibrillation. Radiographics 23:S35–S48
15. Maksimović R, Cademartiri F, Scholten M, Jordaens LJ, Pattynama PMT (2004) 16-row multislice computed tomography in the assessment of pulmonary veins prior to ablative treatment: validation versus conventional pulmonary venography and study of reproducibility. Eur Radiol 14(3): 369–374
16. Vonken EP, Velthuis BK, Wittkampf FH, Rensing BJ, Derksen R, Cramer MJ (2003) Contrast-enhanced MRA and 3D visualization of pulmonary venous anatomy to assist radiofrequency catheter ablation. J Cardiovasc Magn Reson 5(4):545–551
17. Tanabe Y, Deguchi Y, Handa S et al (2001) Longer longitudinal atrial dimension in patients with idiopathic paroxysmal atrial fibrillation: a possible cause of atrial fibrillation. Am Heart J 142:669–678
18. Jais P, Sanders P, Hsu LF, Hocini M, Haissaguerre M (2005) Catheter ablation for atrial fibrillation. Heart 91:7–9 DOI 10.1136/hrt.2003.030205
19. Haissaguerre M, Jais P, Shah DC et al (2000) Electrophysiological end point for catheter ablation of atrial fibrillation initiated from multiple pulmonary vein. Circulation 101:1409–1417
20. Jais P, Hocini M, Macle L et al (2002) Distinctive electrophysiological properties of pulmonary veins in patients with atrial fibrillation. Circulation 106:2479–2485
21. Ho SY (2003) Pulmonary vein ablation in atrial fibrillation. J Cardiovasc Electrophysiol 14:156–157
22. Fynn SP, Kalman JM (2004) Pulmonary veins: anatomy, electrophysiology, tachycardia, and fibrillation. Pacing Clin Electrophysiol 27(11):1547–1559
23. Jais P, Hocini M, Sacher F, Clementy J, Haissaguerre M (2004) The place of ablation in the treatment of atrial fibrillation: where are we and where are we going? Arch Mal Coeur Vaiss 97 (11):1071–1077
24. Pappone C, Rosanio S, Oreto G et al (2001) Prospects of the treatment of atrial fibrillation. Circumferential radiofrequency ablation of pulmonary vein ostia. Recenti Prog Med 2(9): 508–512
25. Chen SA, Hsieh MH, Tai CT et al (1999) Initiation of atrial fibrillation by ectopic beats originating from the pulmonary veins: electrophysiologic characteristics, pharamacologic response, and effects of radiofrequency ablation. Circulation 100:1879–1886
26. Oral H, Knight B, Tada H et al (2002) Pulmonary vein isolation for paroxysmal and persistent atrial fibrillation. Circulation 105:1077–1081
27. Timmermans C, Rodriguez LM, Van Suylen RJ et al (2002) Catheter-based cryoablation produces permanent bidirectional cavotricuspid isthmus conduction block in dogs. J Interv Cardiac Electrophysiol 7(2):149–155
28. Tse HF, Reek S, Timmermans C et al (2003) Pulmonary vein isolation using transvenous catheter cryoablation for treatment of atrial fibrillation without risk of pulmonary vein stenosis. J Am Coll Cardiol 20;42(4):752–758
29. Wong T, Markides V, Peters NS, Davies D (2004) Percutaneous pulmonary vein cryoablation to treat atrial fibrillation. J Interv Card Electrophysiol 11(2):117–126
30. Maksimović R, Cademartiri F, Scholten M, Jordaens LJ, Pattynama PMT (2005) 16-row multi slice computed tomography of pulmonary veins: three months follow-up after treatment of paroxysmal atrial fibrillation with cryothermal ablation. Eur Radiol 15 (6):1122–1127
31. Natale A, Pisano E, Scewichik J et al (2000) First human experience with pulmonary vein isolation using a through the balloon circumferential ultrasound ablation system for recurrent atrial fibrillation. Curculation 102:1879–1882
32. Whayne JG, Nath S, Haines D (1994) Microwave catheter ablation of myocardium in vitro. Assessment of the characteristics of tissue heating and injury. Circulation 89:2390–2395
33. Pappone C, Rosanio S, Oreto G et al (2000) Circumferential radiofrequency ablation of pulmonary vein ostia. A new anatomic approach for curing atrial fibrillation. Circulation 102:2619–2628
34. Packer DL, Keelan P, Munger TM et al (2005) Clinical presentation, investigation, and management of pulmonary vein stenosis complicating ablation for atrial fibrillation. Circulation 8;111 (5):546–554
35. Arentz T, Jander N, von Rosenthal J et al (2003) Incidence of pulmonary vein stenosis 2 years after radiofrequency catheter ablation of refractory atrial fibrillation. Eur Heart J 24: 963–969 DOI: 10.1016/S0195-668x(03)00002-2
36. Cabrera JA, Sanchez-Quintana D, Farre J et al (2002) Ultrasonic characterization of the pulmonary venous wall: echocardiographic and histological correlation. Circulation 106:968–973
37. Wood MA, Wittkamp M, Henry D et al (2004) A Comparison of pulmonary vein ostial anatomy by computerized tomography, echocardiography, and venography in patients with atrial fibrillation having radiofrequency catheter ablation. Am J Cardiol 93:49–53
38. Mansour M, Holmvang G, Sosnovik D et al (2004) Assessment of pulmonary vein anatomic variability by magnetic resonance imaging: implications for catheter ablation techniques for atrial fibrillation. J Cardiovasc Electrophysiol 15:387–393 DOI:10.1046/J.1540-8167.2004.03515.x
39. Dickfeld T, Calkins H, Zwim M et al (2003) Anatomic stereotactic catheter ablation on three-dimensional magnetic resonance images in real time. Circulation 11:2407–2413
40. Solomone SB, Dickefeld T, Calkins H (2003) Real-time cardiac catheter navigation on three-dimensional CT images. J Interv Card Electrophysiol 8:27–36
41. Kalender W, Schmidt B, Zankl M, Schmidt M (1999) A PC program for estimating organ and effective dose values in computed tomography. Eur Radiol 9(3):555–562
42. 1990 Recommendation of the International Commissions on Radiological Protection (1991) ICRP Publication 60. Annals of ICRP 21
43. Jongbloed MR, Dirksen MS, Bax JJ et al (2005) Atrial fibrillation: multi-detector row CT of pulmonary vein anatomy prior to radiofrequency catheter ablation-initial experience. Radiology 234(3):702–709
44. Burgstahler C, Trabold T, Kuettner A et al (2005) Visualization of pulmonary vein stenosis after radio frequency ablation using multi-slice computed tomography: initial clinical experience in 33 patients. Int J Cardiol 10;102 (2):287–291
45. Ghaye B, Szapiro D, Dacher JN et al (2003) Percutaneous ablation for atrial fibrillation: the role of cross-sectional imaging. Radiographics S19–S33
46. Marom EM, Herndon JE, Kim YH, McAdams HP (2004) Variations in pulmonary venous drainage to the left atrium: implications for radiofrequency ablation. Radiology 230(3):824–829

47. Kato R, Lickfett L, Meininger G et al (2003) Pulmonary vein anatomy in patients undergoing catheter ablation of atrial fibrillation. Lessons learned by use of magnetic resonance imaging. Circulation 107:2004–2010 DOI: 10.1161/ 01.CIR.00000610951. 81767.4E
48. Tsao HM, Wu MH, Yu WC et al (2001) Role of right middle pulmonary vein in patients with paroxysmal atrial fibrillation. J Cardiovasc Electrophysiol 12:1353–1357
49. Grimaldi M, Pitzalis MV, Rizzon P (2002) Electrical conduction between the pulmonary veins: Electrical connection or common ostium? Circulation 105:e62
50. Takahashi A, Iesaka Y, Takahashi Y et al (2002) Electrical connections between pulmonary veins. Implication for ostial ablation of pulmonary veins in patients with paroxysmal atrial fibrillation. Circulation 105:2998–3003
51. Lickfett L, Kato R, Tandri H et al (2004) Characterization of a new pulmonary vein variant using magnetic resonance angiography: incidence, imaging and interventional implications of the "right top pulmonary vein". J Cardiovasc Electrophysiol 15:538–543 DOI:10.1046/ J.1540-8167.2004.03499.x
52. Jongbloed MR, Bax JJ, Lamb HJ et al (2005) 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 1;45 (3):343–350
53. Scharf C, Sneider M, Case I et al (2003) Anatomy of the pulmonary veins in patients with atrial fibrillation and effects of segmental ostial ablation analyzed by computed tomography. J Cardiovasc Electrophysiol 14:150–155
54. Cirillo S, Bonamini R, Gaita F et al (2004) Magnetic resonance angiography virtual endoscopy in the assessment of pulmonary veins before radiofrequency ablation procedures for atrial fibrillation. Eur Radiol 14:2053–2060 DOI:10.1007/S00330-004-2406-1
55. Ho SY, Sanchez-Quintana D, Cabrera JA, Anderson RH (1999) Anatomy of the left atrium: implications for radiofrequency ablation of atrial fibrillation. J Cardiovasc Electrophysiol 10 (11):1525–1533
56. Hauser TH, McClennen S, Katsimaglis G, Josephson ME, Manning WJ, Yeon (2004) Assessment of left atrial volume by contrast enhanced magnetic resonance angiography. J Cardiovasc Magn Reson 6(2):491–497
57. Choi SI, Seo JB, Choi SH et al (2005) Variation of the size of pulmonary venous ostia during the cardiac cycle: optimal reconstruction window at ECG-gated multi-detector row CT. Eur Radiol 5(7):1441–1445
58. Schwartzman D, Lacomis J, Wigginton WG (2003) Characterization of left atrium and distal pulmonary vein morphology using multidimensional computed tomography. J Am Coll Cardiol 41:1349–1357
59. Lin WS, Prakash VS, Tai CT et al (2000) Pulmonary vein morphology in patients with paroxysmal atrial fibrillation initiated by ectopic beats originating from the pulmonary veins - implications for catheter ablation. Circulation 101:1274–1281
60. Perez-Lugones A, Schvartzman PR, Schweikert R et al (2003) Three-dimensional reconstruction of pulmonary veins in patients with atrial fibrillation and controls: morphological characteristics of different veins. Pacing Clin Electrophysiol 26(1 Pt 1):8–15
61. Raman SV, Ng VY, Neff MA et al (2005) Volumetric cine CMR to quantify atrial strucutre and function in patients with atrial dysrhythmias. J Cardiovasc Magn Reson 7:539–543
62. Wittkampf FH, Vonken EJ, Derksen R et al (2003) Pulmonary vein ostium geometry: analysis by magnetic resonance angiography. Circulation 107:21–23
63. Ren JF, Marchlinski FE, Callans DJ, Zado ES (2002) Intracardiac Doppler echocardiographic quantification of pulmonary vein flow velocity: an effective technique for monitoring pulmonary vein ostia narrowing during focal atrial fibrillation ablation. J Cardiovasc Electrophysiol 13:1076–1081
64. Jarvinen V, Kupari M, Hekali P, Poutanen V (1994) Assessment of left atrial volumes and phasic function using cine magnetic resonance imaging in normal subjects. Am J Cardiol 73:1135–1138
65. Wu TJ, Doshi RN, Huang HLA et al (2002) Simultaneous biatrial computerized mapping during permanent atrial fibrillation in patients with organic heart diseases. J Cardiovasc Electrophysiol 13:571–577
66. Monnig G, Wessling J, Juergens KU et al (2005) Further evidence of a close anatomical relation between the oesophagus and pulmonary veins. Europace 7(6):540–545
67. Lemola K, Sneider M, Desjardins B (2004) Computed tomographic analysis of the anatomy of the left atrium and the oesophagus - implications for left atrial catheter ablation. Circulation 110:3655–3660 DOI:10.1161/01. CIR.0000149714.31471
68. Purerfellner H, Cihal R, Aichinger J, Martinek M, Nesser HJ (2003) Pulmonary vein stenosis by ostial irrigated-tip ablation: incidence, time course, and prediction. J Cardiovasc Electrophysiol 14:158–164
69. Kluge A, Dill A, Ekinci O et al (2004) Decreased pulmonary perfusion in pulmonary vein stenosis after radiofrequency ablation - assessment with dynamic magnetic resonance perfusion imaging. Chest 126:428–437
70. Yang M, Akbari H, Reddy G, Higgins CB (2001) Identification of pulmonary vein stenosis after radiofrequency ablation for atrial fibrillation using MRI. J Comput Assist Tomogr 20(5):782–785
71. Pappone C, Oreto G, Rosario S et al (2001) Atrial electroanatomic remodelling after circumferential radiofrequency pulmonary vein ablation. Efficacy of an anatomic approach in a large cohort of patients with atrial fibrillation. Circulation 104:2539–2555
72. Schwartzman D, Ren JF, Devine WA, Callans DJ (2001) Cardiac swelling associated with linear radiofrequency ablation in the atrium. J Interv Card Electrophysiol 2:159–166
73. Saad EB, Marrouche NF, Natale A (2002) Ablation of atrial fibrillation. Curr Cardiol Rep 4(5):379–387
74. Berkowitsch A, Neumann T, Ekinci O et al (2005) A decrease in pulmonary vein diameter after radiofrequency ablation predicts the development of severe stenosis. Pacing Clin Electrophysiol 28(Suppl 1):S83–85
75. Arentz T, Weber R, Jander N et al (2005) Pulmonary haemodynamics at rest and during exercise in patients with significant pulmonary vein stenosis after radiofrequency catheter ablation for drug resistant atrial fibrillation. Eur Heart J 26(14):1410–1414
76. Ley S, Kreitner KF, Fink C, Heussel CP, Borst MM, Kauczor HU (2004) Assessment of pulmonary hypertension by CT and MR imaging. Eur Radiol 14:359–368 DOI:10.1007/ s00330-003-2208-x
77. Wu CC, Tai CT, Lin YK, Tsao HM, Yu WC, Chen SA (2001) Pulmonary vein dissection during mapping of atrial fibrillation. J Cardiovasc Electrophysiol 12(4):505

78. Vance MS, Bernstein R, Ross BA (2002) Successful stent treatment of pulmonary vein stenosis following atrial fibrillation radofrequency ablation. J Invasive Cardiol 14:414–416
79. Querishi A, Prieto LR, Latson LA et al (2003) Transcatheter angioplasty for acquired pulmonary vein stenosis after radiofrequency ablation. Circulation 108:1336–1342
80. Pappone C, Oral H, Santinelli V et al (2004) Atrio-oesophageal fistula as a complication of percutaneous transcatheter ablation of atrial fibrillation. Circulation 109:2724–2726
81. Doll N, Borger MA, Fabricius A et al (2003) Esophageal perforation during left atrial radiofrequency ablation: Is the risk too high? J Thorac Cardiovasc Surg 125(4):836–842
82. Lemola K, Sneider M, Desjardins B et al (2004) Effects of left atrial ablation of atrial fibrillation on size of the left atrium and pulmonary veins. Heart Rhythm 1(5):576–581
83. Thakur RK, Klein GJ, Yee R, Zardini M (1994) Embolic complications after radiofrequency ablation. Am J Cardiol 74(3):278–279
84. Cronin P, Kazeroni EA, Kelly AM, Scharf C, Oral H, Morady F (2004) MDCT o the left atrium and pulmonary veins in planning radiofrequency ablation for atrial fibrillation: a how to guide. Am J Radiol 183:767–778