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The role of imaging to support catheter ablation of atrial fibrillation

Josef Kautzner, Petr Peichl

Klinika kardiologie, Institut klinické a experimentální medicíny, Praha, Česká republika

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ABSTRACT

Atrial fibrillation (AF) ablation is a complex procedure that requires transseptal puncture and extensive manipulation with catheter(s) in the left atrium and pulmonary veins. Individual anatomy of these structures contributes to a challenge of AF ablation. The proximity of surrounding structures, such as oesophagus, further increases risk of complications of this procedure. Increased risk of intracardiac thrombosis associated with AF is another factor that may complicate management of these patients. For all these reasons, imaging techniques play increasingly important role. Preprocedural imaging becomes important not only to rule out thrombus but also for assessment of anatomy of the PVs and left atrium, left atrial size and the extent of a substrate. Various forms of imaging help significantly during the procedure both with identification of anatomy and with catheter navigation. Many studies have shown increased efficacy, safety and decreased fluoroscopy times. After the procedure, imaging techniques such as echocardiography, CT or MR imaging are useful to diagnose potential complications. This paper briefly reviews clinical utility of different imaging tools for ablation of AF.

SOUHRN

Katetrizační ablace fibrilace síní (FS) je komplexním výkonem, který vyžaduje transseptální punkci a extenzivní manipulaci s katetrem (nebo katetry) v levé síni a plicních žilách. Individuální anatomie těchto struktur přispívá ke složitosti výkonu. Blízkost okolních struktur, jako je například jícen, dále zvyšuje rizika komplikací této procedury. Dalším faktorem, který může komplikovat léčbu, je zvýšené riziko intrakardiální trombózy, které je spojeno s FS. Ze všech výše uvedených důvodů hrají stále větší úlohu zobrazovací metody. Před výkonem je potřeba zobrazovacích metod nejen k vyloučení trombózy, ale také k posouzení anatomie plicních žil a levé síně, velikosti levé síně a rozsahu substrátu. Během výkonu pomáhají různé zobrazovací metody jak s ověřením anatomie, tak s navigací katetru. Mnoho studií ukázalo zvýšenou účinnost, bezpečnost a snížení skiaskopických časů. Po výkonu je možno použít zobrazovací metody, jako jsou echokardiografie, CT nebo magnetická rezonance, k diagnostice potenciálních komplikací. Tento článek stručně rekapituluje klinickou použitelnost různých zobrazovacích technik při ablaci FS.

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Introduction

Progress in the field of catheter ablation over the past decade has resulted in a paradigm shift in interventional electrophysiology. While in conventional ablation procedures (e.g. ablation of accessory pathways or AV nodal re-entry) the definition of the target site is determined primarily by electrograms and fluoroscopy is sufficient for spatial navigation of ablation catheters, the situation is different in catheter ablation of complex arrhythmias, e.g. atrial fibrillation (AF), arrhythmias after previous correction for congenital heart disease, ventricular tachycardias

Adresa: Prof. MUDr. Josef Kautzner, CSc., FESC, Klinika kardiologie, Institut klinické a experimentální medicíny, Vídeňská 1958/9, 140 21 Praha 4,
e-mail: josef.kautzner@medicon.cz
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in structural heart disease, etc. Such cases require modified approach to identification of the ablation targets. These are not anymore defined by electrophysiological recordings only (like zone of slow conduction or earliest activation) but by a complex interplay between electrograms and anatomical structures. AF ablation is a prototype of this paradigm shift. Variable individual anatomy of the left atrium and pulmonary veins (PVs) and the proximity of surrounding structures such as oesophagus emphasize the need for better imaging techniques than fluoroscopy. Increased risk of intracardiac thrombosis associated with AF is another factor that may complicate management of these patients. This paper will review clinical utility of various imaging techniques before, during and after ablation of AF.

Preprocedural imaging

Prior to an ablation procedure for AF should all patients undergo a transthoracic echocardiogram to identify or exclude significant underlying structural heart disease. Additional imaging studies, e.g. MRI or CT, could be used to demonstrate individual three-dimensional geometry and provide some quantification of atrial fibrosis. To lower the risk of thromboembolic events during any left atrial ablation procedure, a left atrial thrombus should be excluded [1].

Screening by transesophageal echocardiography. The risk of a thromboembolic event at the time of catheter ablation procedure depends on multiple factors such as the type of AF, the duration of AF, and the patient's stroke risk profile including left atrial size, left appendage velocity and $CHADS_2$ or CHA_2DS_2-VASc score. Usually, the anticoagulation guidelines pertinent to cardioversion of AF are recommended to adhere to in patients who present in AF for an AF ablation procedure. For instance, if the patient has been in AF for 48 hours or longer or for an unknown duration, three weeks of systemic anticoagulation at a therapeutic level are required prior to the procedure. Several studies have evaluated the incidence of left atrial thrombus on TEE among patients undergoing AF ablation who have been therapeutically anticoagulated [2–4]. The results have been quite consistent, demonstrating that 1.6% to 2.1% of patients will present with a thrombus or "sludge" in the left atrial appendage (Fig. 1). The probability of thrombus detection was directly related to the $CHADS_2$ score in each of these studies. Therefore, in a patient with higher $CHADS_2$ score or with long-term persistent AF, TEE is recommended to be performed to screen for thrombus.

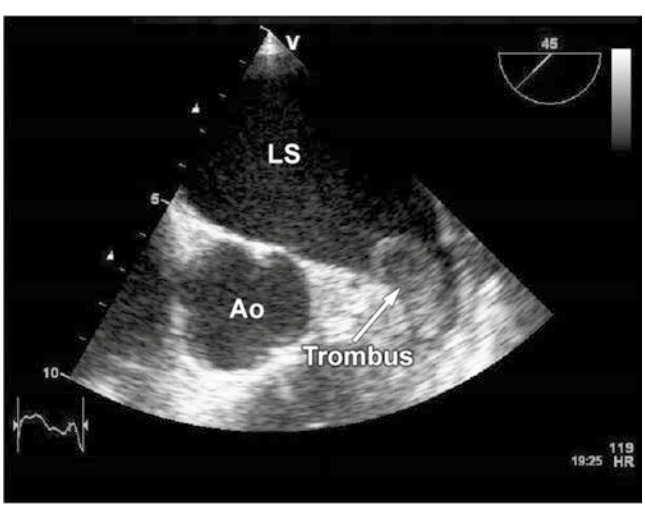

Fig. 1 – Preprocedural transesophageal echocardiogram in a patient with long term persistent AF, depicting thrombus in the left atrial appendage (arrow) despite previous anticoagulation therapy with INR above 2.
Ao – aortic valve; LS – left atrium.

Assessment of left atrial volume. Left atrial size has been determined as an important predictor of outcome after catheter ablation [5–8]. Most frequently, this parameter is evaluated echocardiographically as the end-systolic left atrial diameter in the parasternal long axis view. Although widely used in clinical practice to determine eligibility for AF ablation with cut-offs of 5 or 5.5 cm, more recent studies recommend using true left atrial volume as assessed by CT imaging. Alternative methods to assess left atrial volume include 3D echo [6], CT imaging, MR imaging [7], left atrial angiography [8], 3D electroanatomical mapping [9], and TEE [10]. Recent studies have demonstrated that assessment of left atrial volume based on three orthogonal left atrial dimensions obtained from CT, MR, or 3D echo imaging underestimates true left atrial volume as determined by the gold standard multiple slice technique by 10–20% [11–13].

Assessment of the anatomy. The anatomy of the left atrium and pulmonary veins (PVs) is quite variable. Contrary to the popular view that there are 4 PV that enter into the left atrium more or less separately, the reality is more complex [14–16]. We and others showed that the prevailing pattern of PV anatomy is a common antrum on the left side with short or long common portion between the veins and the left appendage (Fig. 2). This pattern rather than two separate ostia can be detected in approximately 80% of cases [17,18]. Anteriorly, the antrum is separated from the appendage by a carina of a various thickness. On the contrary, posterior transition into the left atrium is more gradual and often reaches to the middle of the posterior wall. Right PVs are more rounded in their shape and tend to enter the atrium separately. Especially right superior vein is practically always of rounded, funnel-shaped appearance with gradual transition into the left atrium. Supranumerary veins are more often present on right side (in about 20–30% cases) with diameter that could be less than 10 mm. A detailed understanding of this anatomy is essential for a safe and effective AF ablation procedure. Both MR and CT angiography allow to accomplish this task. In addition, preprocedural 3D reconstructions of the left atrium and PVs could be used intraprocedurally for advanced image integration. Preprocedural left atrial imaging may also assist in the detection of post-procedural complications such as pulmonary venous stenosis.

Recently, rotational angiography has been introduced to display the left atrium during the procedure [19–23]. After contrast medium injection in the right heart or pulmonary artery, the fluoroscopy C-arm rotates quickly around the patient, and images are acquired throughout

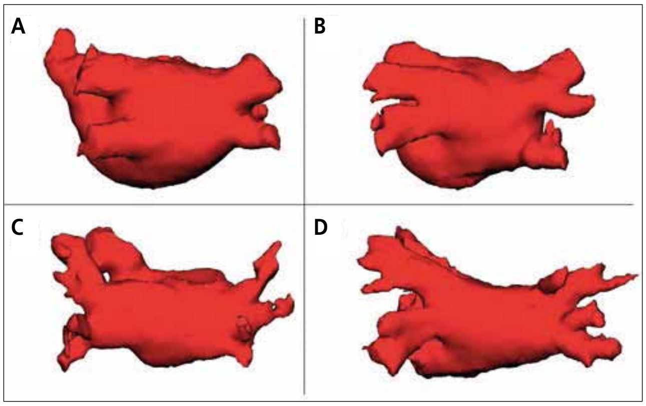

Fig. 2 – Three-dimensional reconstructions of CT angiograms of the left atrium and pulmonary veins from different patients before AF ablation (posteroanterior view). It is apparent that morphology varies from patient to patient with a prevailing pattern of short or long left common trunk of the pulmonary veins.

the rotation to generate 3D volumetric anatomical rendering of the left atrium and PVs. The result is similar to CT or MRI reconstructions and can be superimposed onto the fluoroscopic projections of the heart to help navigation during ablation. The images could also be integrated into an electroanatomical mapping system.

MR imaging of atrial fibrosis. MR imaging can be employed to visualize myocardial inflammation and fibrous tissue by using delayed clearance of gadolinium from myocardial areas with high content of fibrous tissue [24]. Recent studies, mostly from a single center, have suggested that the extent of left atrial fibrosis as assessed by special algorithms from MR images after administration of gadolinium prior to ablation can predict the outcomes of catheter ablation of AF [25–27]. However, more data are needed to determine the reproducibility of such measurements of fibrosis by different centers and also to validate the predictive accuracy of MR imaging in predicting outcomes of AF ablation (Fig. 3). Our pilot data show that although there is a good correlation between the content of the fibrosis in the left atrial wall by MR imaging and the bipolar voltage from electroanatomical mapping, MR imaging data do not seem to predict the result of catheter ablation [28].

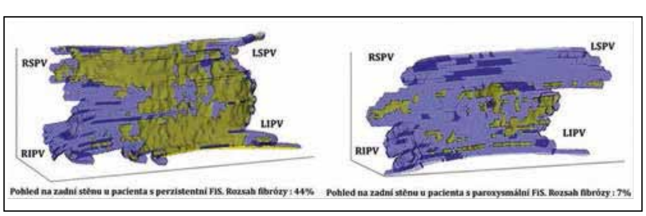

Fig. 3 – Two examples of the left atrial posterior wall processed with a special algorithm to detect and quantify the amount of fibrous tissue from late gadolinium enhanced images. Left panel shows significant fibrosis (in a patient with persistent AF), right panel depicts small amount of fibrosis (in a patient with paroxysmal AF).
LSPV and LIVP – left superior and inferior pulmonary veins, respectively; RSPV and RIVP – right superior and inferior pulmonary veins, respectively.

Intraprocedural imaging

Echocardiography

Some benefits of intraprocedural echocardiography for electrophysiologic interventions were shown nearly two decades ago. The first reports used transoesophageal echocardiography (TEE) for navigation during ablation of ventricular tachycardias [29] and/or accessory pathways [30]. More recently, TEE has been used successfully to guide balloon placements in PV ostia during catheter ablation of PVs. However, the widespread use of TEE for prolonged electrophysiologic procedures remains limited by the necessity for deep sedation or general anaesthesia.

Miniaturization of the ultrasound technology has allowed development of truly intracardiac catheters that can be introduced into cardiac chambers [31,32]. Intracardiac echocardiography (9 MHz. Intracardiac echocardiography (ICE) has significant advantage against TEE since it does not require prolonged oesophageal intubation and is not associated with the risk of oesophageal damage or discomfort for the patient. In addition, it could be performed routinely by the operator alone, without the need for other personnel for image acquisition and interpretation.

Transseptal puncture guidance. Transseptal catheterization is the first step in AF procedure. Traditional technique is based on fluoroscopic guidance in which the important anatomical structures are not displayed directly and the needle with a sheath are guided entirely by their movement during pullback from the superior vena cava and by their position within cardiac silhouette relative to catheter in coronary sinus and/or aortic root [33,34]. More recently, some modifications using nitinol thin wire for safe fossa ovalis puncture have been described [35]. However, there is a lack of data on clinical performance of these techniques in large series of patients.

Many authors use TEE to guide transseptal puncture [36]. It allows direct imaging of the needle tip within the fossa ovalis region and enables safe puncture (Fig. 4A). Even easier guidance of the transseptal puncture can be obtained by means of ICE [37]. A cross-sectional view of the fossa ovalis is best acquired with the ICE catheter placed near the septum (Fig. 4B). Using this guidance, the optimum puncture site can be subselected according to the clinical need. For catheter ablation around PVs, the preferable puncture site is more posterior and inferior. Both TEE and ICE display clearly tenting of the septum with the needle tip/dilator and advancement of the assembly into the left atrium. The main advantage of ultrasound guidance is safe navigation in case of anatomical abnormalities such as lipomatous hypertrophy of the septum, atrial septal aneurysm or double layered fossa ovalis. ICE can also help to re-navigate into the site of former puncture in cases when catheter slips back to the right atrium during manipulation. The catheter tip can be displayed and colour Doppler flow imaging can easily detect initial puncture site.

Even though the complications of traditionally guided transseptal puncture are infrequent in highly experienced centres, they occasionally occur [33,34]. They include aortic puncture, pericardial puncture or tamponade, syste-

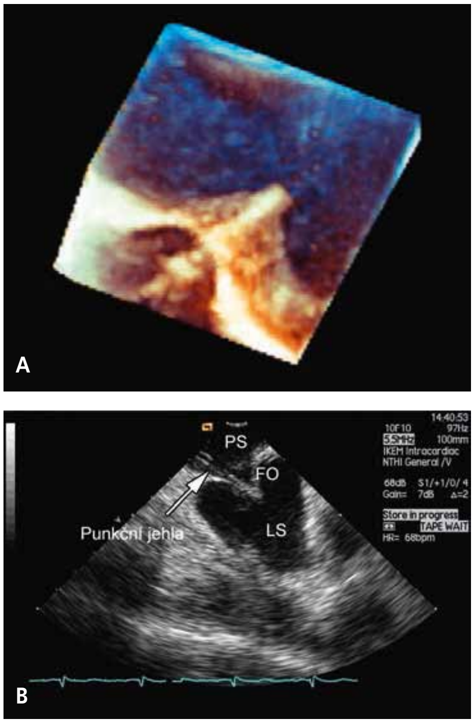

Fig. 4 – (A) Tenting of the interatrial septum in a detail using 3D TEE probe guidance during transseptal puncture. (B) Typical picture obtained during transseptal puncture using ICE with tenting of the fossa ovalis by the needle (arrow "punkční jehla").
FO – fossa ovalis; LS – left atrium; PS – right atrium.

mic embolism and perforation of the vena cava inferior. It is believed that ICE guidance would practically avoid serious complications of the transseptal puncture. In a large series of 1,692 transseptal punctures guided by ICE in our facility in last 4 years, no serious complication was observed and efficacy reached 100% [unpublished data].

Online assessment of anatomy. TEE or ICE can be used for online imaging of PV ostia and/or oesophagus and assisting accurate placement of both mapping and ablation catheter. The utility of ICE for ablation catheter navigation can be demonstrated by the fact that it enables to perform catheter ablation of AF without fluoroscopy. Ferguson et al. [38] in 21 patients undergoing catheter ablation of AF used ICE and electroanatomical mapping for procedure guidance and in 19/21 patients no fluoroscopy was used and the staff did not wear protective lead apron. This technique may be of particular benefit to the obese patients, children and pregnant women who are at the highest risk from X-ray exposure. Both TEE and ICE can be also used for accurate measurement of PV diameters and thus, assist to selection of appropriate size of circular mapping catheter and/or balloon ablation tools.

Prevention of thromboembolism. Intraprocedural TEE or ICE can minimize risk of thromboembolism during ablation of AF. The Pennsylvania group demonstrated for the first time that maintaining average level of anticoagulation with ACT around 250 s does not provide complete protection against thrombus formation in the left atrium [39]. They revealed approximately 10% rate of thrombus occurrence and ICE allowed safe removal of the catheters with thrombus. Spontaneous echocontrast was identified as the only independent risk predictor of subsequent thrombus formation. Therefore, ICE may help to identify both high risk subjects and display thrombus whenever it develops. The use of ICE for transseptal puncture guidance allows heparin administration even before the crossing of the fossa ovalis [40]. We typically administer 100 IU/kg body weight of heparin before the first transseptal puncture with adjustment of the activated clotting time around 350 s.

Monitoring of radiofrequency current delivery. As mentioned above, radiofrequency energy application may cause perforation due to tissue superheating and "crater" formation that follows "steam pop" [41]. Based on experience with observation of the tip of ablation catheter during multiple RF deliveries and on data from some experimental studies, we adapted our RF delivery protocol. We use moderate constant flow for irrigation of the ablation catheter that still allows monitoring of the tip temperature [42]. Any rise of temperature above 40–42 °C means high level of tissue heating and prompts down regulation of power. Similarly, we check tissue characteristics during RF application. Any sudden whitening of the tissue that is reflection of high temperature (close to 100 °C) due to microcavitation inside cells leads to interruption of RF delivery (Fig. 5). Using these empirical recommendations we do not experience steam pops anymore.

Early detection of complications. One of the important roles of intraprocedural online imaging in electrophysiology is early diagnosis and prevention of procedural complications during complex procedures. Damage to cardiac structures due to inadvertent manipulation of the catheter may cause damage to adjacent structures such as appendage, mitral or tricuspid valve, and atrial or ventricular wall. Monitoring of the position of the ablation catheter in relationship to specific anatomical structures

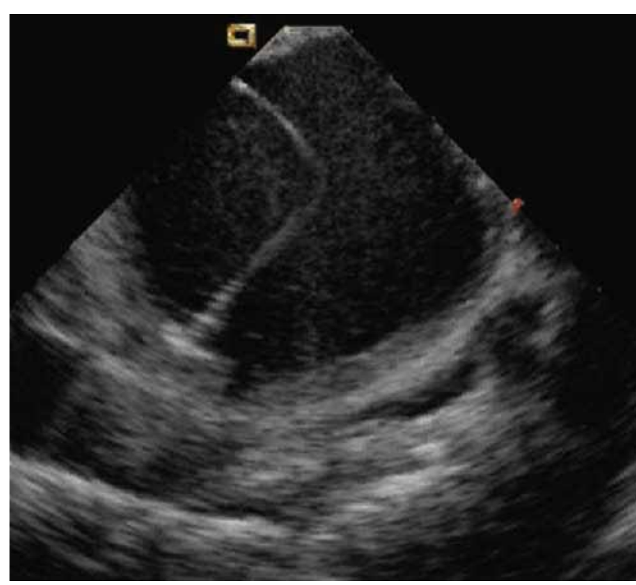

Fig. 5 – ICE image of the left atrium with ablation catheter bended against the mitral isthmus. Whitening of the tissue around the tip of the catheter reflects microcavitation within the tissue and suggests achievement of relatively high tissue temperature.

prevents inadvertent delivery of radiofrequency current in high risk regions such as proximal part of the PV. Recent experience shows that navigation by ICE can practically eliminate PV stenosis [43]. In addition, ICE allows for measurement of the diameter of the PVs and safe placement of balloon or multielectrode catheters. Doppler modality could be used anytime during the procedure to check PV velocities [44,45]. Experience shows that PV ostial peak velocity increasing to more than 150 cm/s and Doppler pattern of turbulent flow indicate a moderate narrowing effect. Significant stenoses were associated with higher peak flow velocities. Cardiac tamponade is the most worrisome complications associated with catheter manipulation and radiofrequency current delivery within the left atrium. In such cases, ICE can provide early diagnosis and thus, prevent tamponade due to early reversal of anticoagulation [46]. In case of tamponade, ICE allows online monitoring of the patient's status.

3D intracardiac echocardiography

Two-dimensional ICE imaging has several limitations. For example, curved catheter shaft often cannot be fully visualized with single plane image, thus necessitating acquisition of multiple imaging planes and image adjustments. This requires specific skills and could be time consuming and thus, distracting during an invasive procedure. In addition, it is desirable to obtain real-time non-fluoroscopic image of the cardiac structures to improve catheter navigation. Reliable 3D imaging of specific cardiac chambers may obviate the need for virtual electroanatomical mapping and make any mapping or ablation procedure more precise and faster. Over the past several years, improvements in transducer technologies have allowed the development of a full matrix-array transducer which can be used to acquire pyramidal-shaped ultrasound data sets. These data sets can be processed both online and offline to allow the display of cardiac structures and catheters as they move in time and space. Recently, a miniaturized matrix probe has been coupled with a transoesophageal probe (Fig. 6). This allows the acquisition of high-quality real-time 3D images [46]. Currently, 3D ICE probes are being developed by several manufacturers. Ongoing research focuses also on visualization of 3D echocardiographic data in the 3D space (virtual reality). Dynamic holographic imaging of the 3D echocardiographic data appears to be feasible and may help in providing a preview of cardiac anatomy for complex ablation procedures. Such imaging may be also used in the future for sophisticated simulator of complex ablation procedures [47].

Electroanatomical mapping and image integration

The advent of electroanatomical mapping allowed excellent guiding of complex ablation procedures such as for ventricular tachycardia or for AF (Fig. 7). Electroanatomical mapping was used for catheter ablation of AF already in the early days – as an alternative to fluoroscopy-guided segmental isolation of the PVs [48]. Subsequently, other studies have shown that electroanatomical mapping decreases a need for fluoroscopy without a major impact on the efficacy [49–51]. No substantial difference was found between the two existing electroanatomical mapping systems. Using a combination of electroanatomical mapping system (NAVx) together with ICE, some authors performed completely fluoroless catheter ablation, i.e. without the need for fluoroscopic guidance [52]. Importantly, no complications were observed.

More recently, possibility to fuse preprocedural CT or MR angiography of the left atrium and PVs with actual electroanatomical map has been introduced [53,54]. After registration, the operator can use only imported 3D angio-

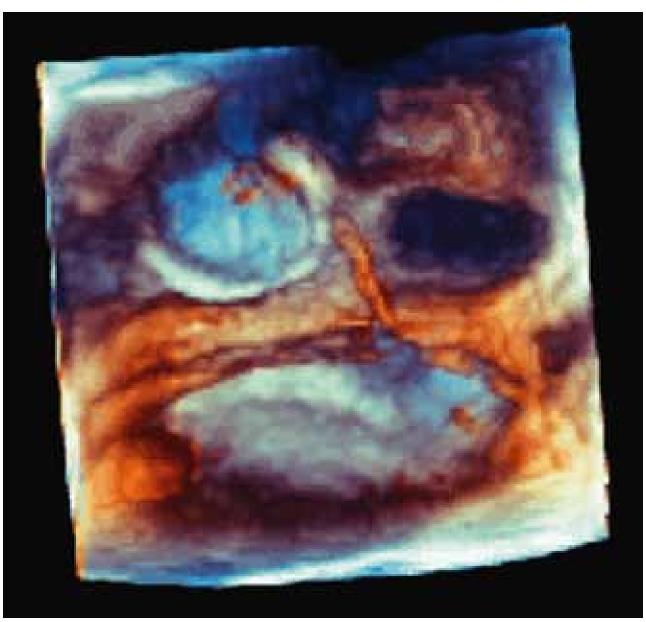

Fig. 6 – Three-dimensional echocardiogram of the left pulmonary veins with circular mapping catheter in the inferior pulmonary vein (left side). Dark structure on the right side corresponds to the left superior pulmonary vein. Ellipsoid structure in the lower part represents left atrial appendage.

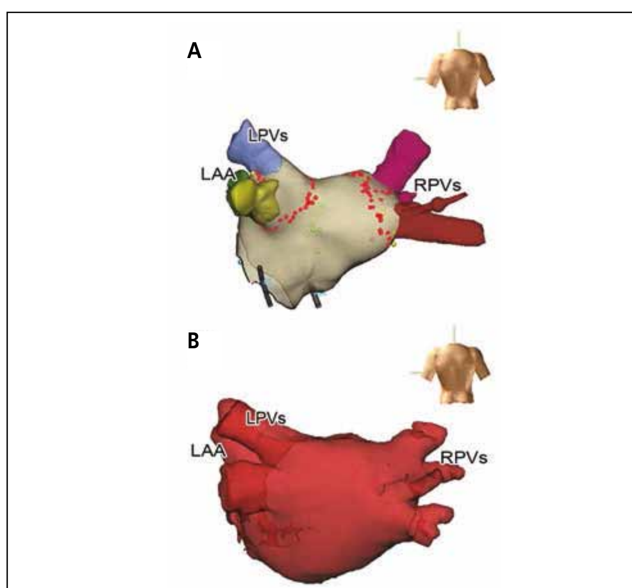

Fig. 7 – An example of electroanatomical map of the left atrium and PVs in posteroanterior view with annotation of ablation points (red dots) (A). CT angiogram of the left atrium and PVs from the same patient for comparison (B). LAA – left atrial appendage; LPVs – left pulmonary veins; RPVs – right pulmonary veins.

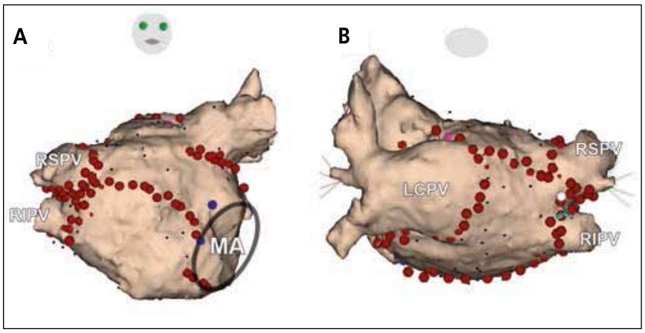

Fig. 8 – Following fusion of 3D CT angiogram with electroanatomical map, CT image can be used for navigation during the procedure and for annotation of ablation points (red dots). In this case, ablation was performed for chronic AF and figure shows multiple ablation lines. (A) Anteroposterior view, (B) tilted posteroanterior view. LCPV – left common pulmonary vein; MA – mitral annulus; RSPV and RIPV – right superior and inferior pulmonary vein, respectively.

grams to navigate ablation catheter within the left atrium and PVs (Fig. 8). Some studies have reported a significant decrease in fluoroscopic time and improvement in efficacy [55–59]. Others showed no significant advantage in terms of efficacy as compared with ablation of AF supported by electroanatomical mapping system only [60,61].

Fluoroscopy overlay

Work is in the progress to integrate CT 3D angiograms in the fluoroscopic framework using visual matching and landmark-based registration approaches. This allows catheter manipulation within integrated 3D shell without the need for electroanatomical mapping system [62]. Such practice was gauged as extremely helpful by the operator and resulted in a significant reduction of fluoroscopy time (61 ± 18 minutes vs. 77 ± 26 minutes; $p = 0.009$) and a trend toward shorter procedure duration (230 ± 67 minutes vs. 257 ± 58 minutes; $p = 0.06$) versus conventional procedures. On the other hand, both fluoroscopy and procedural times in this study are excessive compared to the use of electroanatomical mapping system. Fluoroscopy overlay is now commercially available (e.g. EP Navigator, Philips Healthcare, Best, the Netherlands). Preliminary experience suggests very good accuracy to support catheter ablation of AF [63,64]. It also allows overlay of the 3D shell obtained using rotational angiography and fused with fluoroscopic system [65]. Radiation exposure with this system was significantly reduced compared with preprocedural CT scan (2.1 ± 0.3 mSv vs 13.8 ± 2.4 mSv, $p < 0.001$). However, the risk/benefit of this strategy has to be evaluated in comparison with advanced electroanatomical mapping system or ICE.

Medical positioning system

In an attempt to minimize fluoroscopic exposure during various cardiovascular interventions, Medical Positioning System (MPS) has been developed as an analogy to the Global Positioning System (GPS) [65,66]. Instead of satellites that enable assessment of actual position of the navigator on the globe, MPS localises miniature sensor in 3D magnetic field that is emitted from C-arm flat detector. A miniaturised sensor can be mounted on any catheter or thin wire. To track appropriately position of the sensor and correct for any movement of the patient, another

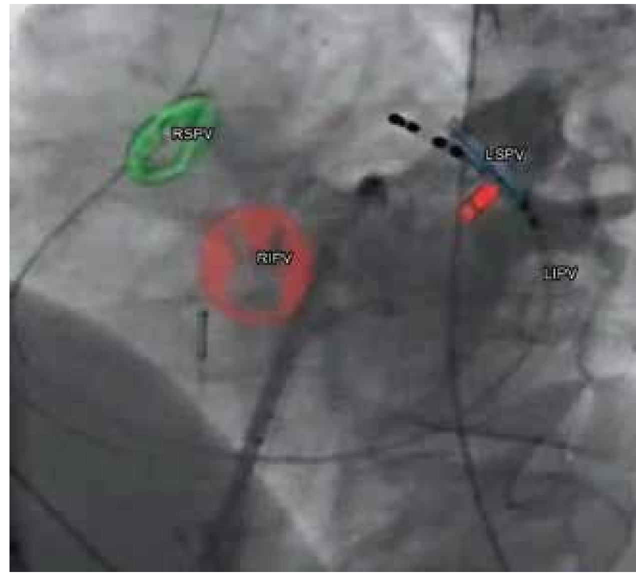

Fig. 9 – Example of the screen of the MediGuide technology depicting fluoroscopy loop with angiogram of the left pulmonary veins (LSPV and LIPV – left superior and inferior, respectively) and markers of ostia of the right pulmonary veins (RSPV and RIPV – right superior and inferior, respectively). Red icon in the ostium of the LSPV shows tip of the ablation catheter within fluoroscopy loop.

electromagnetic field reference sensor is attached to the patient's chest. Essentially, there are two ways how the system can be used. One is real-time non-fluoroscopic tracking of the sensor (or catheter tip) in pre-recorded fluoroscopy loop. To adjust for cardiac cycle-dependent changes in catheter position within the cine loop, its speed is matched with the real-time ECG signal. It also takes into account respiratory movements of the patient. As a result, the MediGuide System accurately displays the intracardiac catheter position and compensates for respiration and patient movement (Fig. 9). Early observations have shown a significant reduction in fluoroscopy time. The other, more sophisticated clinical use, is a marriage with the electroanatomical mapping system (Velocity NavX, St. Jude Medical, Inc., Minneapolis, MN, USA). It enables software algorithms to provide better volume scaling and achieve more accurate anatomy of the virtual maps together with a better spatial stability.

Postprocedural monitoring

Postprocedural imaging is mainly used to detect delayed complications of the procedure. Routine echocardiography after the ablation procedure may reveal development of pericardial effusion or delayed tamponade, however, there are no conclusive studies on efficacy of such an approach. Obviously, echocardiography is indicated in any suspected cardiac tamponade.

CT or MR imaging of the PVs prior to, and several months after catheter ablation, are the most precise methods for detecting PV stenosis (Fig. 10) [14,67,68]. Studies show that both of these imaging modalities are equal in evaluation of PV size and detecting PV stenosis. Alternatively, a ventilation perfusion scan may be useful to screen for severe PV stenosis when a CT or MR scan cannot be obtained. Accor-

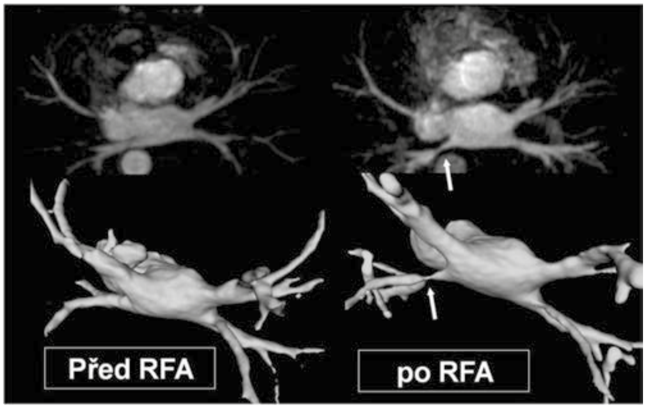

Fig. 10 – MR angiograms of the left atrium and pulmonary veins before (left panel – "před RFA") and after (right panel – "po RFA"). Arrows show significant stenosis of the left inferior pulmonary vein after ablation.

ding to the percentage reduction of the luminal diameter, the severity of PV stenosis is generally defined as mild (< 50%), moderate (50–70%), or severe (> 70%). Symptoms are more likely with severe stenoses, but even severe PV stenosis or complete PV occlusion may be asymptomatic. Therefore, exact incidence of PV stenosis is not known. However, prevailing practice of ablation around PV ostia has been associated with a minimum risk of PV stenosis.

Both CT and MR imaging are also the best diagnostic modalities in the case of suspected atrioesophageal fistula [69,70]. The suspicion should arise from clinical picture of fever, chills, and recurrent neurological events (septic emboli), or septic shock 2–4 weeks after the procedure. In such cases, endoscopy should be avoided or undertaken with extreme caution, since insufflation of the oesophagus with air may result in a large air embolus producing stroke or death. The early recognition of an atrial-esophageal fistula may be missed due to the low awareness of this rare complication [71].

Conclusions

Ablation of AF is a complex procedure with an increased risk of complications. Individual anatomy of the left atrium and PVs contributes to a challenge of AF ablation. In addition, AF is associated with a variable risk of intracardiac thrombosis. For all these reasons, imaging techniques play an increasingly important role. Preprocedural imaging becomes important not only to rule out thrombus but also for assessment of anatomy of the PVs and left atrium, left atrial size and the extent of a substrate. Various forms of imaging help significantly during the procedure both with identification of anatomy and with catheter navigation. Many studies have shown increased efficacy, safety and decreased fluoroscopy times. After the procedure, imaging techniques such as echocardiography, CT or MR imaging are useful to diagnose potential complications.

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