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Role of transoesophageal echocardiography in evaluating the effect of catheter ablation of atrial fibrillation on anatomy and function of the pulmonary veins

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Aims Radiofrequency ablation (ABL) of pulmonary veins (PVs) is an effective treatment of atrial fibrillation (AF). The aim of this study was to evaluate the possible morphological and functional consequences of this procedure on PV during a 12-month follow-up.

Methods and results Ninety-six patients underwent transoesophageal echocardiography (TEE) before ABL, and 48 h, 3, and 12 months later. The peak velocity, mean velocity, mean/peak flow velocity, and diameter of each vein were measured at every follow-up examination. All patients also underwent multidimensional computer tomography (MCT) 3 months after ABL. At the first control, a 5% reduction in PV diameters and an increase in the peak velocity, mean velocity, and mean/peak velocity (34.3, 42.2, and 6.9, respectively: $P < 0.000$) of their Doppler flow were observed. Later follow-up examinations revealed no further significant increase in PV narrowing or flow velocities. MCT showed PV stenoses (>50%) in four PVs, while TEE showed a >100% increase over basal values in flow velocities and a plateau configuration of the pulsed-wave Doppler spectrum.

Conclusion ABL of AF reduces the diameter and increases the flow velocities of PV. However, critical stenosis is rare and can be diagnosed by TEE through a marked change in the velocities and in the configuration of the Doppler flow.

Introduction

Atrial fibrillation (AF) is the most common sustained cardiac arrhythmia, with a prevalence in the general population of ~1%[1] and an incidence of 0.2% per year.[2] The occurrence of this arrhythmia is associated with an increased risk of systemic thromboembolism, heart failure, death, and impairment of quality of life.[2] The antiarrhythmic drugs used to prevent this arrhythmia are often ineffective or even harmful. New therapeutic strategies have therefore been recently investigated. Among these, catheter ablation (ABL) with pulmonary vein (PV) isolation has proved an effective treatment for symptomatic recurrent AF.[3–5] The application of radiofrequency (RF), however, can damage the tissues of the PV[6] and may result in subsequent stenosis of the vessel.[7,8] Indeed, PV stenosis is a possible major complication of this therapeutic approach and occurs more frequently when ABL is performed close to the ostia of the veins.[9] Multidimensional computer tomography (MCT) has been widely regarded as the gold standard for detection of this type of post-procedure complication.[10] Transoesophageal echocardiography (TEE) has also proved to be an accurate means of detecting post-ABL PV stenosis;[11] however, few reports are available in the literature on its utility in documenting and monitoring the degree of PV injury over a long period of observation.[12,13] The aim of the present study was to evaluate, by means of repeated TEE examination, the morphological and functional consequences of catheter ABL on PV anatomy and function over a 1-year follow-up.

Methods

Study population

We retrospectively evaluated 96 consecutive patients (mean age 59 ± 9.7 years): 59 males and 37 females, who underwent ABL of

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AF in our institution from April 2001 to June 2003. The arrhythmia was paroxysmal in 41 (43%), persistent in 38 (40%), and permanent in 17 (17%). Underlying cardiac abnormalities were reported in 61 patients (63%): hypertensive heart disease was present in 26 patients (27%), mitral prolapse in 17 (18%), dilated cardiomiopathy in 11 (11%), hypertrophic cardiomiopathy in 6 (6%), and ischaemic heart disease in 1 (1%).

Ablation procedure

After 4 weeks of anticoagulant treatment, which was tailored to maintain an international ratio from 2 to 3, all patients came to the electrophysiology laboratory in the fasting state, and ABL was performed according to the methods previously described by Haissaguerre *et al.*,[14] Pappone *et al.*,[15] and Marrouche *et al.*,[4] which had long been used at our institution. The three different approaches are briefly summarized below.

ANGIO-guided approach (14 patients—Group 1)

Mapping of the left atrium and PVs was carried out after approaching the left atrium via transseptal puncture. Isolation of the PVs was performed with the aid of angiography to define the PV. A decapolar circular catheter (Lasso®, Biosense-Webster, Diamond Bar, CA, USA) was placed at the PV-left atrium ostium, as determined by angiography, where ABL was performed by means of an 8 mm tip catheter (Biosense-Webster). Radiofrequency was delivered in a temperature-controlled mode with a power of 30 W.

CARTO approach (20 patients—Group 2)

Three-dimensional LA maps and PV profiles were reconstructed through a transseptal route using a non-fluoroscopic electromagnetic mapping system (CARTO, Biosense-Webster). After characterizing PV ostia, RF energy was delivered by the distal electrode of the navigation catheter to create circular lines of conduction block around each vein ostium at 0.5–1 cm from the tube-like portion. Radiofrequency was delivered in a temperature-controlled mode with a power of 30 W.

Intracardiac echocardiography-guided PVAI approach (62 patients—Group 3)

Mapping of the left atrium and PVs was carried out after approaching the left atrium via transseptal puncture. Isolation of the PV was performed with the aid of intracardiac echocardiography (ICE) to define the PV ostium and to titrate the power of RF. A decapolar circular catheter (Lasso®, Biosense-Webster) was placed at the PV-left atrium antrum, as determined by ICE, where ABL was performed by means of an 8 mm tip catheter (Biosense-Webster); power titration was guided by the appearance of micro-bubbles. Radiofrequency delivery was controlled by progressively increasing the power (W), until scattered micro-bubbles were observed on ICE.

Echocardiographic examination

Each patient was examined by means of TEE before and 48 h (first control), 3 months (second control), and 12 months (third control) after ABL. The examination was performed by means of an omniplane probe connected to a Sonos 4500 Philips ultrasound imaging system. A cross-section was utilized to visualize the structures of interest: by automatically shifting the plane of section from 0° to 20° and by tilting the probe left or right, we investigated the inferior left and right PVs; using a plane of section from 0° to 40°, we investigated the left atrial appendage (LAa), both the superior left and right PVs and any accessory veins (*Figure 1*). After exploring left-seated structures, the probe was rotated clockwise in order to visualize right-seated structures.

During each TEE examination, the LA and LAa were examined to exclude the presence of thrombi. The diameter of each PV at the junction with the left atrium was measured on the narrowest 2D section of the vein, and the velocities of its forward flow pulmonary vein flow velocity (PVF) were measured by placing the sample volume of the pulsed-wave Doppler at the ostium of the vein at an angle $\leq 25°$ for superior and $\leq 45°$ for inferior veins: the peak velocity (peak vel), the mean velocity (mean vel), and their ratio (mean vel/peak vel) were recorded.

Echocardiograms were recorded on videotapes and subsequently analysed by two independent readers. An average value for each parameter was finally adopted if the discrepancy between the two

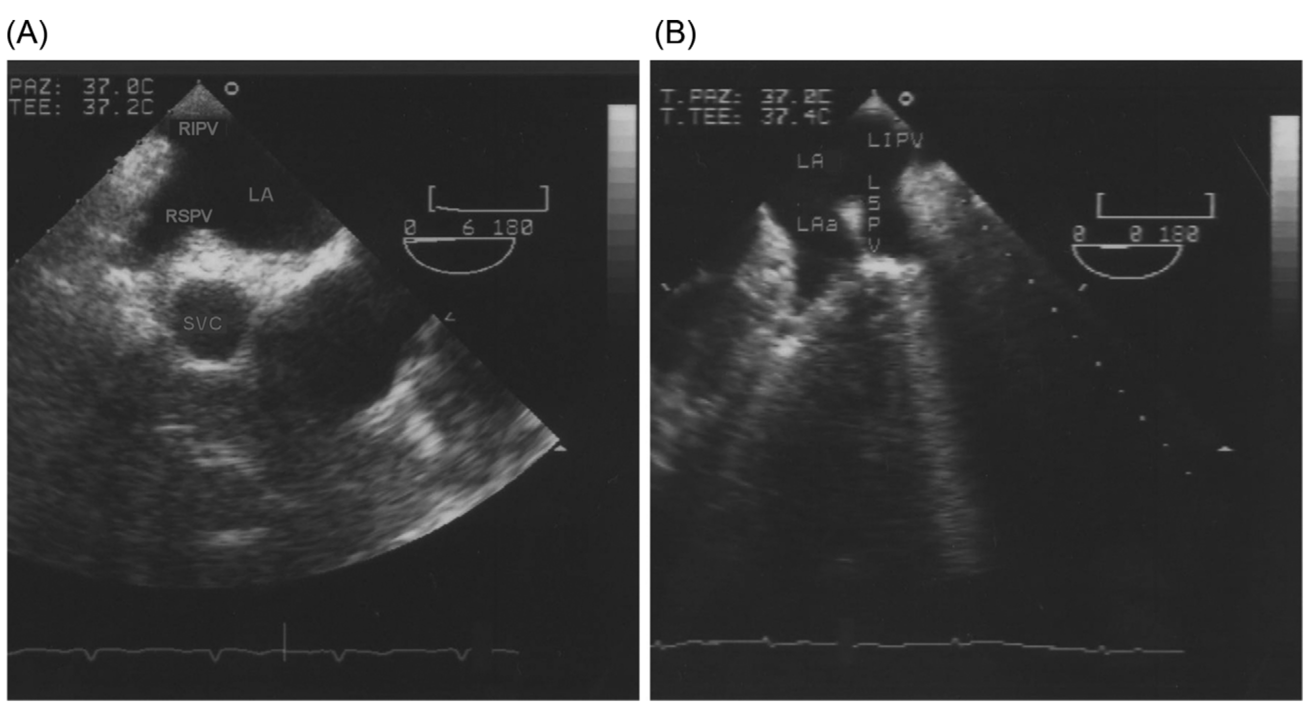

Figure 1 Transoesophageal echocardiography image of pulmonary veins (title). (*A*) Frontal section of right inferior and right superior pulmonary veins. SVC, superior vena cava. (*B*) Frontal section of left inferior and left superior pulmonary veins. LAa, left atrial appendage.

Table 1 Transoesophageal echocardiography findings before and after pulmonary vein ablation

Parameters (average values of the 4 PVs)	Basal	First (1) control (48 h)	*P*	Second (2) control (3 months)	*P*	Third (3) control (12 months)	*P*
Dimension (mm)	14.28 ± 1.51	13.52 ± 1.47	0.0001 (0.0003)	13.42 ± 1.38	0.0001 (0.0003)	13.10 ± 1.30	0.000001 (0.000003)
Peak vel (cm/s)	56 ± 16.5	73.7 ± 19.8	0.00001 (0.00003)	75.0 ± 24.4	0.0001 (0.0003)	75.2 ± 28.9	0.00001 (0.00003)
Mean vel (cm/s)	25.6 ± 8.4	36.5 ± 12.1	0.00001 (0.00003)	37.8 ± 14.9	0.00001 (0.00003)	37.8 ± 16.5	0.00001 (0.00003)
Mean/peak vel	0.45 ± 0.07	0.49 ± 0.07	0.000001 (0.000003)	0.50 ± 0.08	0.000001 (0.000003)	0.50 ± 0.09	0.000001 (0.000003)

P, statistical difference in comparison with basal values with paired *T*-test (the Bonferroni correction).

Table 2 Transoesophageal echocardiography findings during follow-up

Parameters (average values of the 4 PVs)	Variation (%), 2 vs. 1	Variation (%), 3 vs. 2
Dimension (mm)	−0.7%, $P = \text{NS}$	−2.2%, $P = 0.04$*
Peak vel (cm/s)	+1.7%, $P = \text{NS}$	+0.3%, $P = \text{NS}$
Mean vel (cm/s)	+3.6%, $P = \text{NS}$	−0.08%, $P = \text{NS}$
Mean/peak vel	+2.1%, $P = 0.05$*	+0.9%, $P = \text{NS}$

*Not significant with the Bonferroni test.

calculated values did not exceed 15%; if it proved greater, the final value was established by consensus. The average intra- and inter-observer variability values for dimension measurements were 15 and 19%, respectively; for Doppler velocity measurements, they were 10 and 16%.

Clinical follow-up

All patients were clinically evaluated 1, 3, and 6 months after catheter ABL, and every 6 months thereafter. At every follow-up examination, ECG and Holter recording were performed, and any symptoms of PV stenosis, such as cough, haemoptysis, dyspnoea and reduced exercise capacity, were carefully sought.

Computed tomography scan control

Computed tomography (CT) scan was performed in each patient 3 months after the procedure and was repeated after 6 and 12 months in patients with suspected or certain PV stenosis. The degree of stenosis was regarded as severe if the narrowing of the vessel was >70%, moderate if it was between 50 and 70%, and mild if it was <50%.

Statistical analysis

Continuous variables were expressed as mean ± SD and were compared by paired Student's *t*-test and ANOVA test. Categorical variables were compared by χ^2 analysis or Fisher's exact test. The results with $P < 0.05$ were considered statistically significant.

Results

Transoesophageal echocardiography: general data

TEE was performed without complications in all patients by two operators. A total of 384 PVs were investigated at each step; all PVs, except for three (0.8%) inferior right veins and one (0.2%) inferior left vein, were visualized at the four examinations. Procedure time was 25 ± 7 min during the first 6 months of the study and decreased to 13 ± 4 min at the end, with little difference between the two operators. Intra- and inter-observer variability also diminished during the same time interval: from 15 to 12% and from 19 to 15%, respectively, for dimension measurements; and from 10 to 7% and from 16 to 11%, respectively, for Doppler velocity measurements.

Ablation: general data

Procedural endpoints were obtained in all patients. No periprocedural complications occurred. Radifrequency time was 48 ± 11, 52 ± 10, and 54 ± 9 min, respectively, in the three groups ($P = \text{NS}$).

Quantitative features of the pulmonary veins

The average PV diameter on basal examination was 14.28 ± 1.51 mm, as shown in *Table 1*; superior PVs proved larger than inferior ones: 14.45 ± 1.9 vs. 12.85 ± 1.2 mm. At the first post-ABL examination, the average diameter of the PV in the study population had decreased by 5% ($P < 0.000$ compared with the basal values), while the peak vel had increased by 31.5% ($P < 0.000$), the mean vel by 42.2% ($P < 0.000$), and the mean vel/peak vel by 6.9% ($P < 0.000$). The subsequent examinations revealed no further significant narrowing of the PV and no further increase in the parameters measuring PVF. At the final evaluation, the average PV diameter was clearly reduced and the flow parameters were increased, in comparison with basal values, as shown in *Tables 1* and *2*. The rate of variation was greater for left veins, especially for the inferior one, while right veins exhibited a flatter trend, as shown in *Figure 2*.

No significant differences were seen in PV diameter or PV flow pattern between patients with AF recurrence and those in whom sinus rhythm (SR) was maintained (AF group—26 patients: 13 ± 2 mm, 68 ± 19 cm/s; SR group—70 patients: 13 ± 1 mm, 76 ± 25 cm/s, $P =$ NS).

Evaluation of stenotic pulmonary veins

Three months after ABL, MCT revealed 50–70% narrowing of one PV in three patients and >70% narrowing in one patient who had undergone CARTO-guided catheter ABL. In these four patients with PV narrowing ≥50% on MCT, TEE clearly demonstrated a reduction in the diameter of the vein, as shown in *Figure 3C*; peak vel was 107.7 ± 57.5 cm/s ($P = 0.009$), mean vel 58.3 ± 33.6 cm/s ($P = 0.05$), and mean vel/peak vel 0.54 ± 0.05 ($P = 0.05$). In each PV with stenosis ≥50%, a more than 100% increase compared with pre-ABL values was detected (peak vel >139 cm/s, mean vel >92 cm/s, and mean vel/peak vel >0.66). The ratio between the peak vel recorded in the stenosed PV and the average peak vel recorded in the remaining non-stenosed PVs in the same patient was >1.8, as shown in *Table 3*.

Furthermore, the stenotic PV exhibited a clear change in the spectrum of the pulsed-wave Doppler, owing to the prevalent increase in the mean velocity; *Figure 3A* and *B* show the Doppler flow spectrum of a patient with a PV stenosis >70%: the normal systolic and diastolic waves are not distinguishable and the whole flow exhibits a 'plateau' configuration. This subject was symptomatic for dyspnoea and haemoptysis. The stenosed PV was successfully treated by angioplasty and stent insertion. Only one of the other three patients with moderate stenosis experienced mild shortness of breath.

The mean flow velocities recorded in the patients with normal or mild stenosis, moderate stenosis, and severe stenosis at the end of the follow-up were 74 ± 21, 163 ± 61, and 260 cm/s, respectively.

At the first examination, the mean diameters (13.38 ± 1.17 mm) and the flow velocities (74.9 ± 18.6 cm/s; 36.4 ± 13 cm/s; and 0.48 ± 0.03) of the PVs recorded in the patients who later developed significant stenosis were not significantly different from those recorded in the PVs of the patients without stenosis.

In the group of 92 patients with no or mild PV stenosis, the peak vel was 74 ± 21 cm/s, mean vel 36.9 ± 13 cm/s, and mean vel/peak vel 0.49 ± 0.06; no statistical correlation was found between dimensions and flow velocities calculated by means of the TEE and MCT results.

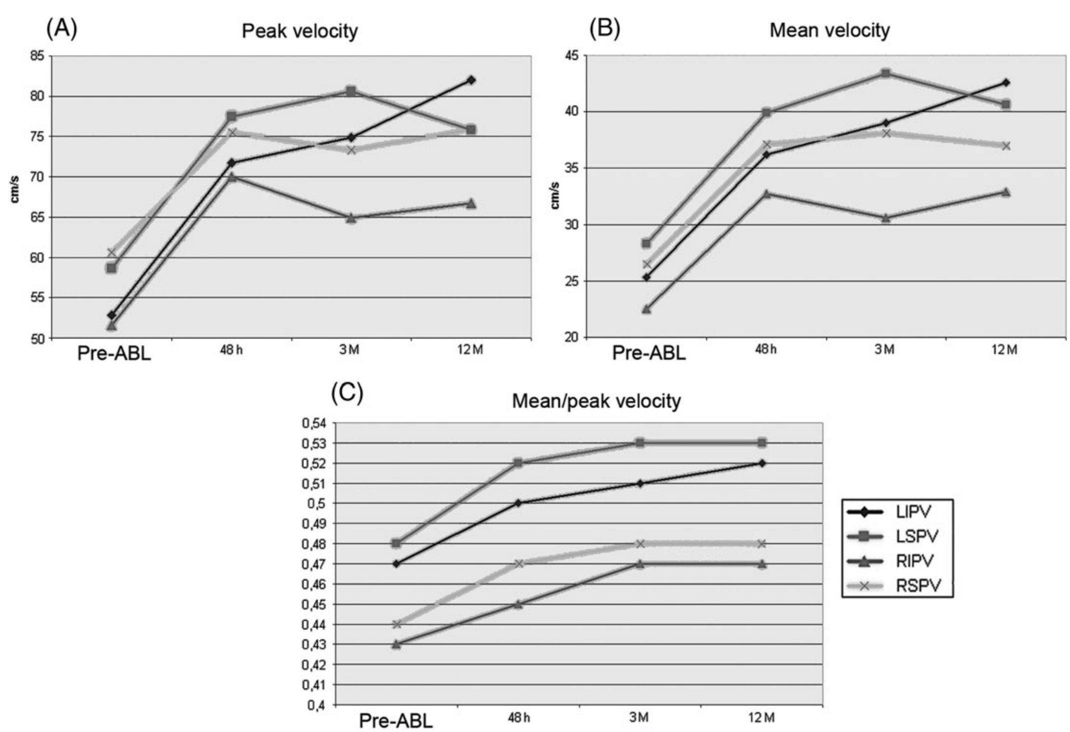

Figure 2 Trend in pulmonary vein velocities during 1-year follow-up (title): peak velocity (*A*), mean velocity (*B*), and mean vel/peak vel ratio (*C*). The four control times considered are reported on the abscissas. On the ordinates, the values of the three parameters are reported for each vein.

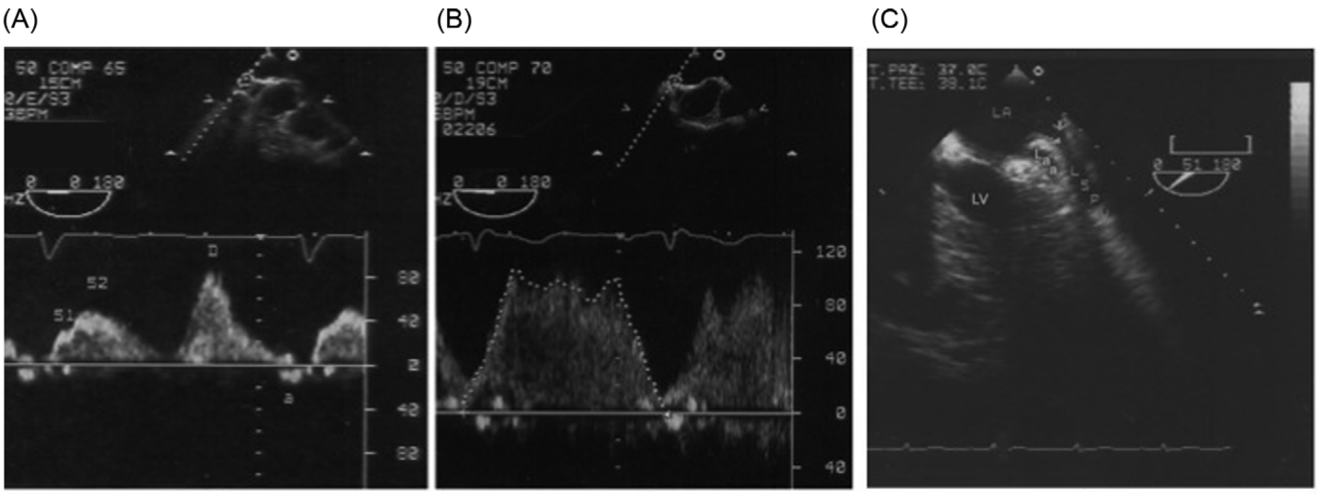

Figure 3 Spectrum of the forward pulsed-wave Doppler flow of a pulmonary vein (title). (*A*) A normal polyphasic flow (S1 + S2, systolic flow; D, early diastolic flow; a, reverse flow). (*B*) Flow in a critically stenotic vein: monophasic with a plateau configuration (*C*): transoesophageal echocardiography image of a stenotic left superior pulmonary vein (title). Frontal section: the arrows indicate the stenosis (7 mm) of the vein. LAa, left atrial appendage; LA, left atrium; LV, left ventricle.

Table 3 Flow velocity parameters in the four PVs with ≥50% stenosis

Peak vel (cm/s)	>139	↑>100% in comparison with the basal values
Mean vel (cm/s)	>92	
Mean vel/peak vel	>0.66	
Peak vel in stenosed/average peak vel in non-stenosed PV of the same patient	>1.8	

Discussion

This is the first study in which TEE was repeatedly performed in a large number of patients for 1 year in order to document the consequences of catheter ABL on PV dimensions and flow velocities.

Severe PV stenosis after PV-antrum isolation by RF has been reported in previous studies that have utilized imaging techniques.[16,17] In the present study, moderate PV stenosis was detected in three patients, while only one patient (1% of the study population), who had been treated by the CARTO approach, developed a severe stenosis. No patient treated under ICE guidance developed ≥50% PV narrowing. These results agree with those of the previous studies in which ICE was adopted.[4,8] Intracardiac echocardiography not only enables the ablator catheter to be positioned correctly, it also allows opportune titration of RF, as it visualizes the bubbles that develop as a result of tissue heating by RF delivery. In this group of patients, RF was interrupted whenever a dense shower of bubbles was detected; this policy might explain the absence of severe PV stenosis documented in our patients treated with this strategy. Nevertheless, the small number of subjects treated by means of the ANGIO-guided or CARTO approach does not allow us to draw definite conclusions about the different rates of safety of the methods used.

However, ABL of AF reduced PV diameter and, consequently, increased flow velocity in almost every vein treated. This variation in parameters took place soon after ABL and may be the consequence of wall swelling in response to RF delivery.[18] Later, we documented no further significant changes in flow velocities during follow-up. This trend probably reflects permanent anatomical damage to the wall of the treated vein; indeed, fibrotic thickening of the wall as a result of the inflammation caused by RF delivery has been described.[6,19] The redundant fibrotic thickening of the PV wall that causes critical stenosis of the vein surely takes place some time after RF delivery; thus, PV which will develop significant narrowing are not identifiable soon after the procedure. Indeed, in the present study, the stenosed PV was documented at the second follow-up examination, 3 months after ABL.

Left PV, especially left inferior one, exhibited greater narrowing than right PV. In our view, this does not reflect an intrinsic property of the vein wall, but rather depends on technical factors; as the left PV are situated 'behind' the LAa, the approach of the ablator catheter to their ostia may be less precise than in right veins, with the result that RF delivery may involve the inner part of the vein, thereby causing more extensive anatomical damage. From our data, we can speculate that all PVs suffer a small amount of anatomical injury, but that only in the rare event of inappropriate RF application does real stenosis of the vessel ensue.

The diagnosis of PV stenosis was supported by both MCT and TEE, the latter providing both anatomical and functional information. The feature of PV narrowing may not always yield information on the physiological significance of the stenosis. Indeed, symptoms may be absent despite the visualization of a reduced PV calibre; furthermore, by calculating PVF velocities, we can better quantify the haemodynamic consequences of applying RF to the PV ostium.[20]

The small number of moderate and severe PV stenoses makes it more difficult to establish a real cut-off value of the degree of stenosis. In any case, the mean flow velocities recorded in the three different groups (normal or mild stenosis, moderate stenosis, and severe stenosis) at the end of the follow-up were 74 ± 21, 163 ± 61, and 260 cm/s, respectively. On the basis of these data, we can interpret a PV flow velocity <90 cm/s as indicating the absence of stenosis; a range between 90 and 140 cm/s (especially, when an increased ratio between stenotic and normal veins is present) as indicating mild stenosis; a range between 140 and 220 cm/s as indicating moderate stenosis, and a value >220 cm/s as indicating severe stenosis. Only large increases in flow velocities are diagnostic of marked PV stenosis. In the present study, PV stenosis $\geq$50% on spiral CT was identified by a velocity increase of $>$100% over basal values; moreover, there was a clear discrepancy between the peak velocity of the stenosed vein and the average peak velocity of the remaining, not significantly stenosed, veins in the same patient. In addition, the spectrum of the pulsed-wave Doppler of the PVF in these patients displayed a significant variation in morphology, showing a 'plateau' configuration instead of the usual peaked morphology. In our series, we were unable to establish a certain predictive value of TEE; nevertheless, some considerations can be made. First, the only patient who developed severe PV stenosis had a higher basal flow velocity in the stenotic vein than all the other patients (75 cm/s vs. mean basal value of 56 ± 16 cm/s). Secondly, all four patients who developed moderate or severe PV stenosis had a basal diameter of the stenotic vein of 12 mm or less. While these data obviously do not allow us to draw any conclusions, it could be reasonable to regard patients with these characteristics as having a potentially higher risk of developing post-ABL PV stenosis. Conversely, as seen in our series, a basal PV diameter greater than 15 mm could be regarded as predictive of the absence of PV stenosis during follow-up, if ABL is not performed inside the vein.

Limitations

This was a retrospective study of consecutive patients who underwent different types of procedures to treat AF over time. Nevertheless, a mild reduction in the PV diameter and a mild increase in the PVF velocity detected in all patients seem to be related only to the delivery of RF energy and not to the approach used. The small number of patients with moderate–severe PV narrowing did not allow us to ascertain a correlation between the echocardiographic patterns of different degrees of vein stenosis and the MCT findings.

Conclusions

Catheter ABL of AF reduces the calibre and increases the flow velocity of almost every PV treated; both consequences are detectable soon after ABL and remain largely stable over a 1-year follow-up. Pulmonary vein stenosis with a clinical impact is a fairly rare complication of the ABL of AF. TEE provides fundamental information on this pathology: only a $>$100% variation over the basal values and a change in the morphology of the spectrum of the pulsed-wave Doppler of the PVF are diagnostic of significant PV narrowing. Moderate–severe PV stenosis ($>$50%) is not identifiable within a short time after ABL; our experience suggests that a period of 3 months is probably required in order to detect this complication by means of TEE.

Conflict of interest: none declared.

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