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CLINICAL RESEARCH
Ablation for atrial fibrillation

Efficacy of catheter ablation for atrial fibrillation in patients with congenital heart disease

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Aims Advances in surgical techniques allow an increasing number of children with congenital heart disease (CHD) to reach adulthood. As patients grow older, atrial fibrillation (AF) is evolving into a major clinical concern and can be difficult to manage medically. Primary AF catheter ablation may, therefore, have a role in this setting but few reports have evaluated its efficacy in CHD patients.

Methods and results We retrospectively reviewed 58 consecutive patients [median age 51, interquartile range (IQR) 44–63 years, 57% male] with AF (45% paroxysmal) who underwent 122 ablation procedures in our tertiary centre in the last decade. The majority had CHD of moderate or severe complexity (57%, Bethesda Class 2 or 3) with a dilated left atrium (LA) (81%) and/or right atrium (86%). At 1-year from the first ablation, 32.8% of patients remained in sinus rhythm. Multiple procedures were required in 35 (60%) patients. Freedom from AF at 1-year after the 2nd and 3rd ablation was 40.9% and 36.5%, respectively. Multivariable predictors of AF recurrence were underlying anatomic complexity [hazard ratio (HR) in Bethesda 3 1.98, $P = 0.006$], type of AF (HR for persistent 1.87, $P = 0.004$), and indexed LA dimensions (HR for cm^2/m^2 1.06, $P = 0.03$).

Conclusion While ablation may be a valid option for the treatment of AF in CHD patients, multiple procedures are likely to be required. Early referral and careful patient selection are essential to optimize the results of AF ablation, achieving a low rate of recurrence. Further studies are needed to validate our prognostic model and guide clinical practice.

Keywords Atrial fibrillation • Congenital heart disease • Atrial tachycardia • Remote navigation

Introduction

Over recent decades, life expectancy of patients with congenital heart disease (CHD) has increased significantly, thanks to advances in medical care and surgical techniques.[1] However, long-term consequences, such as arrhythmias are common and are a significant cause of morbidity and mortality.[2] The unique myocardial substrate created by extensive suture lines and long-standing pressure and/or volume overload contribute to the onset and recurrence of arrhythmias.[3]

Atrial fibrillation (AF) is common among CHD patients; its prevalence ranges between 3.7% and 15%, significantly higher than that of the general population (0.95%).[4] Atrial fibrillation is often poorly tolerated by CHD patients, especially those with complex conditions, residual lesions, ventricular dysfunction, and pulmonary hypertension. Antiarrhythmic drugs are frequently ineffective and long-term treatment with drugs, such as amiodarone, is undesirable in this young population.[5] Atrial fibrillation ablation in the general population is a safe option, with the aim of improving rhythm control alongside antiarrhythmic medication or as stand-alone treatment and is currently recommended in the latest AF guidelines.[6] To date, little is known on the shorter- and longer-term efficacy of AF ablation in CHD. Moreover, it is unknown whether techniques and results from non-CHD experience may or may not be directly transferable to this complex and unique patients' cohort.

The purpose of our study was to examine the acute and long-term results of radiofrequency catheter ablation in CHD patients presenting with AF. Moreover, we aimed to identify predictors of recurrence after acutely successful AF ablation in CHD.

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What's new?

- This paper represents one of the largest study population with acute and long-term results of radiofrequency catheter ablation for AF in patients with CHD.
- AF ablation is feasible and acutely successful in CHD patients (even of moderate and severe complexity), but recurrence rates are higher and multiple procedures may be required.
- Early referral and careful patient selection are essential to optimize the results of AF ablation.
- Persistent AF, complex anatomy and left atrial size were independently associated with higher recurrence rates. A prognostic model is proposed which needs validation by larger registries and/or multicentre trials to guide clinical practice.

Methods

All patients with a diagnosis of CHD who had undergone AF ablation in our tertiary centre, between January 2008 and April 2018, were identified. The first and all subsequent AF ablation procedures were considered. In view of the potential causative relationship between AF ablation and subsequent atrial tachycardia (AT) in CHD patients, AT ablations performed after the index AF ablation were also included. In addition to procedural data, further diagnostic imaging data at the time of ablation were reviewed. Congenital heart disease patients were categorized according to anatomic severity using the classification developed by the American College of Cardiology Task Force 1 (32nd Bethesda Conference).[2,7] Pulmonary hypertension was defined as mean pulmonary artery pressure >25 mmHg whilst in patients with left to right shunt as pulmonary vascular resistance of at least 3 Wood Units (WU) or indexed pulmonary vascular resistance >5.2 WU m^2. Patients were followed for the endpoint of recurrence of AF or AT after ablation, documented on electrocardiogram (ECG), lasting >30 s. This analysis was approved by the Research and Development Department at the Royal Brompton & Harefield NHS Foundation Trust.

Atrial dimension assessment by echocardiography

Echocardiograms were reviewed by an operator blinded to patient characteristics and the parameters of interest were specified a priori. Measurements were obtained at least twice on different cardiac cycles to obtain an average if the rhythm was AF. Single-plane area was evaluated from the four-chamber view of the left and right atrium at end of ventricular systole while maximal biplane left atrial (LA) volume was measured in all patients using the Simpson method.[8,9] All values were indexed.

Pre-procedural 3D imaging

The majority of patients underwent advanced cardiac imaging prior to the ablation to acquire a 3D roadmap of their cardiac anatomy. This was achieved by non-contrast cardiac magnetic resonance imaging[10] or by cardiac computer tomography scan with contrast. All pre-acquired imaging data were processed to obtain individual 3D reconstructions of all cardiac chambers and vessels which were merged with the 3D maps of the respective 3D mapping systems (see *Figure 1*).

Invasive ablation procedure(s)

After obtaining written informed consent, procedures were performed under general anaesthesia in the presence of a cardiac anaesthetist, as it is standard in our centre. Prior to each procedure, intracardiac thrombus formation was excluded using transoesophageal echocardiography. Oral anticoagulation was continued: in patients on vitamin K antagonists, ablation was performed with therapeutic international normalized ratio values between 2 and 3 whilst patients on non-vitamin K anticoagulants omitted the morning dose on the day of the procedure. Heparin was administered during the procedure with doses adjusted to achieve an activation clotting time (ACT) of >300 ms. In patients with complex anatomy requiring a retrograde transaortic approach, femoral arterial access was gained to perform the ablation using the remote magnetic navigation system (Stereotaxis Inc.). Remote navigation was used in patients with difficult access to the target chamber, having for example large Amplatzer Occluder which didn't allow any residual rim for safe transseptal puncture, in patients with interrupted IVCs and (hemi)-azygos continuation who would have needed otherwise a transjugular or transhepatic transseptal access.

The electroanatomical mapping system (EAM, CARTOE, or CARTO-RMT, Biosense Webster, Brussels, Belgium) was used in the vast majority of procedures. Alternatively, the high-density sequential mapping system (HDM, Rhythmia, Boston Scientific, Marlborough) or the simultaneous non-invasive mapping systems (ecVUE, CardioInsight Technologies Inc., Cleveland or ACUTUS Medical, Carlsbad) were used.

Ablation techniques varied according to operator discretion, anatomical features, type of AF/AT, history and type of previous surgery, interventions, or ablations. In all cases, irrigated tip RF ablation was used with 25–35 W in manual procedures and 45–50 W in remote magnetic navigation, respectively. Techniques included radiofrequency ipsilateral pulmonary vein isolation (PVI),[11] focal activity ablations, and atrial substrate modification by applying ablation at complex fractionated atrial electrograms (CFAE),[12] cavotricuspid isthmus (CTI), and/or ganglionated plexus (GP) ablation. Linear lesions[13] were also performed and consisted of an intercaval line in the right atrium, and various line designs in the LA such as roof line, posterior box lesion, or mitral valve line from the annulus to the inferior PVs. During PVI, a circumferential mapping catheter (Lasso, Biosense Webster) was placed inside the ipsilateral PV, except in retrograde remote magnetic procedures. The endpoint of PVI was defined as the absence of any PV spike potential recorded on the Lasso catheter for at least 20 min. When remote navigation was used, the map catheter itself was used in a sequential fashion to check for absence of signals after isolation either using the 'beat trigger' function of the electrophysiology (EP) recording system or be creating a post-ablation map of the respective PVs. In AT procedures, tachycardias were carefully mapped and re-entry circuits or the origin of focal ATs was targeted for ablation. If the LA was entered, PVs were also checked and isolated, if a conduction gap was present. Acute successful ablation was defined as PVI and non-inducibility of any sustained AF or AT episodes with atrial stimulation.

Follow-up

Patients were reviewed immediately after the procedure and acute complications were excluded. Patients were discharged on continuous antiarrhythmic medication and oral anticoagulation. Patients were followed using the standard follow-up arrangements which consists of scheduled follow-up visits at 3, 6, and 12 months in the EP clinics, beside their regular CHD outpatient appointments. After EP follow-up finished, patients had regular periodic review in the CHD clinic only (typically annually). In the first 6 months, a 48-h Holter was regularly performed or whenever symptoms recurred. Device checks were scheduled every 6–12 months or more frequent if necessary. Patients were followed for the endpoint of recurrence of AF or AT after

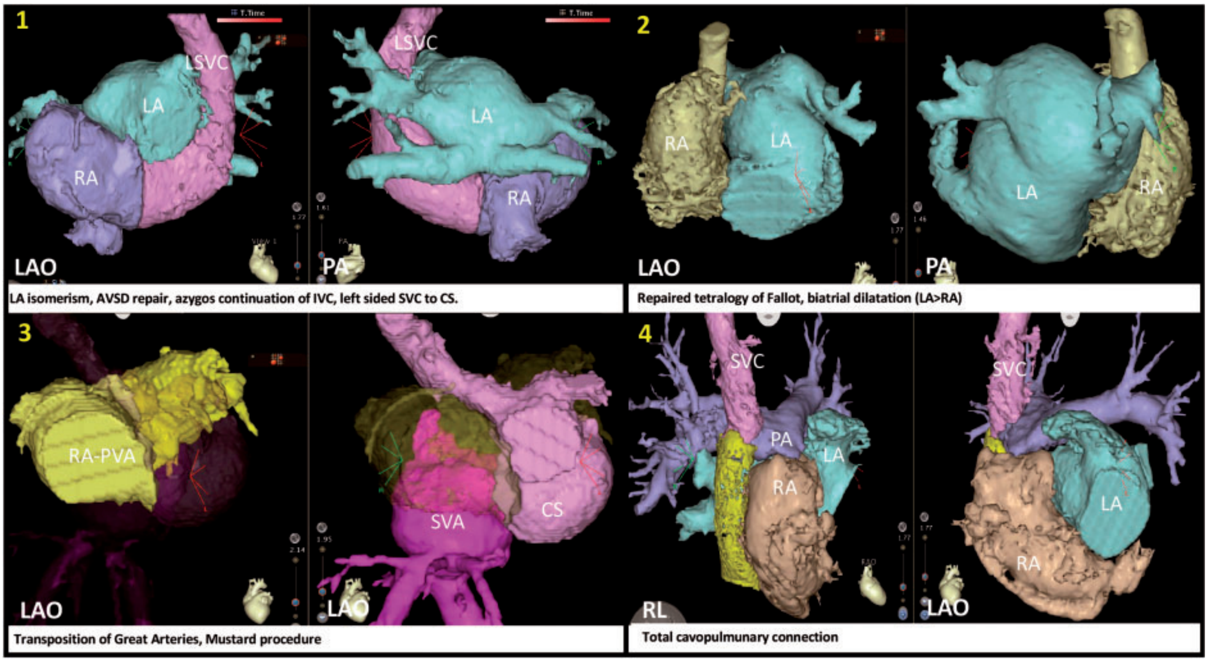

Figure 1 Examples of different atrial configurations in CHD. (1) Left atrial (LA) isomerism, atrial ventricular septal defect (AVSD) repair, azygos continuation of inferior vena cava (IVC), left sided superior vena cava (SVC) to coronary sinus (CS), absent right SVC, hepatic drainage in the right atrium (RA). (2) Repaired (infundibular resection followed by definitive repair) tetralogy of Fallot, criss-cross heart, biatrial dilatation (LA > RA). (3) Transposition of the great arteries with a persistent left SVC (LSVC). Mustard procedure (yellow = systemic system, pink = venous system). (4) Situs solitus, large VSD, total cavopulmunary connection (extracardiac tunnel, yellow).

ablation, documented on ECG, lasting >30 s. Twelve-lead ECG, Holter recordings and device-based electrograms were reviewed.

Statistical methods

Analyses were performed with the use of R Version 3.5.0 (http://cran.r-project.org/) and the package *survival*. Data were presented as numbers, percentages, or median [interquartile range (IQR)]. Kaplan–Meier curves were plotted to demonstrate the time to AF/AT recurrence after 1st, 2nd, and 3rd ablation. Univariable Cox proportional hazards regression analysis, with censoring at the time of death or last follow-up, was used to identify clinical and demographic variables associated with arrhythmia recurrence during follow-up. As many patients underwent multiple ablations during the study period the survival analysis was repeated using the *cluster* function, based on generalized estimating equation approach and being part of *survival* package in R Project, to account for clustering of procedures within patients. Variables significant on univariable analysis were included in the multivariable models (stepwise backward). The proportional hazards assumption was assessed using the *cox.zph* function, which is based on weighted Schoenfeld residuals, and no violation of the assumption was found. Heatmaps were generated to reflect the risk of recurrence over time using parameters in the multivariable model. All *P*-values were two-sided, and a *P*-value of <0.05 was pre-specified as indicative of statistical significance.

Results

Baseline characteristics

Fifty-eight consecutive patients with drug-refractory AF [paroxysmal in 26 (45%)], were included (*Table 1*). Median age at first ablation was 51 (44–63) years and 33 (57%) patients were male. The majority had cardiac defects of moderate or severe complexity (57%, Bethesda Class 2 or 3, *Table 2*). The most prevalent comorbidities were systemic hypertension (12%), congestive heart failure (5%), and diabetes mellitus (8%). Thirty-three (55%) patients had undergone at least one previous surgery whereas 19 (33%) had >1 (up to 4) operations. In 9% of cases, a Maze operation had been performed during the index or subsequent surgeries prior to the first ablation. Most patients ($n = 48$, 8%) had a preserved systemic ventricular function [ejection fraction (EF) > 55%] on transthoracic echocardiography. Atrial dilatation was present in the vast majority of patients; 47 (81%) presented with LA dilatation (LA volume index, LAAi, > 29 mL/m^2) whilst 50 (86%) presented with right atrial (RA) dilation (RA area > 18 cm^2). Three patients presented with pulmonary arterial hypertension. The antiarrhythmic medication is detailed in *Table 1*.

Procedures

A total of 122 AF or AT (post-AF ablation) procedures were performed during the study period, with individual patients undergoing up to a maximum of six procedures (*Figure 2*). The vast majority (97%) of patients underwent PVI ablation at AF first procedure, except for 2 (3%) with a previous surgical Maze operation in whom the right atrium was the target of the ablation, using CFAE ablation and linear lesions. In 25 (43%) patients, a CTI line was also created and, in 29 (50%) patients, CFAEs were ablated during the first procedure. Eight (14%) patients had an additional mitral or roof line.

Table 1 Patients' characteristics

Median age in years	51 (44–63)
Gender (M)	33 (57%)
Body mass index (kg/m^2)	25.9 (23.6–29.0)
Type of AF	
Paroxysmal	26 (45%)
Persistent	32 (55%)
Previous surgery	
1	14 (24%)
2	11 (20%)
3	6 (10%)
4	2 (3%)
Previous atrial tachycardia 16 (28%)	
Previous ablation (non-AF)	7 (57%)
PM/ICD	8 (14%)
Bethesda class	
1/Simple lesions	25 (43%)
2/Moderate lesions	20 (34%)
3/Complex lesions	13 (23%)
Antiarrhythmic drugs	
Beta-blocker	26 (45%)
Digoxin	2 (3%)
Amiodarone	12 (21%)
Flecainide	7 (12%)
Sotalol	11 (19%)
Ca^{++} antagonist	3 (5%)
$CHAD_2VASC_2 > 2$	16 (28%)
DM	5 (9%)
Hypertension	12 (21%)
Previous stroke	7 (12%)
Congestive heart failure	3 (5%)
LVEF (%)	
>50	52 (90%)
35–50	3 (5%)
<35	3 (5%)
LA area (cm^2)	26.0 (22.2–33.4)
LA area index (cm^2/m^2)	13.9 (11.6–17.1)
RA area (cm^2)	24.7 (20.0–29.0)
RA area index (cm^2/m^2)	12.6 (11.4–14.9)
LA volume (mL)	73.7 (54.7–111.0)
LA volume index (mL/m^2)	41.3 (28.6–58.2)
TAPSE (cm)	1.7 (1.3–2.0)
FAC (%)	35.0 (33.5–38.5)

AF, atrial fibrillation; DM, diabetes mellitus; F, female; FAC, fractional area change; ICD, internal cardiac defibrillator; LA, left atrium; LVEF, left ventricular ejection fraction; M, male; PM, pacemaker; RA, right atrium; TAPSE, tricuspid annular plane systolic excursion.

Thirty-five patients underwent 64 re-ablation procedures, 24 of which were primarily for AT. Subsequent procedures consisted of PVI re-isolation (30/64, 47%) and/or CTI line (15, 23%), CFAE (14, 22%), linear (25, 39%), or ganglionated plexus (GP, 11%) ablation. At least a single PV demonstrated electrical reconnection in 30/64 cases.

Table 2 Details of congenital heart diseases anatomic complexity

Anatomic complexity	*n* (%)
Bethesda 1/simple lesions	25 (43%)
ASD/PFO	22 (36.2%)
VSD	1 (1.7%)
Bicuspid aortic valve	1 (1.7%)
Cor triatriatum	1 (1.7%)
Bethesda 2/moderate lesions	20 (34.4%)
AVSD	3 (5.1%)
Aortic coarctation	7 (12%)
Ebstein's anomaly	3 (5.1%)
RVOTO	1 (1.7%)
Pulmonary valve disease	1 (1.7%)
Sinus venosus ASD	2 (3.4%)
Subaortic stenosis	1 (1.7%)
VSD and associated lesions	1 (1.7%)
ALCAPA	1 (1.7%)
Bethesda 3/complex lesions	13 (22.4%)
Double outlet right ventricle	1 (1.7%)
Pulmonary atresia and MAPCA	1 (1.7%)
TCPC/Fontan	2 (3.4%)
AVSD and pulmonary stenosis	1 (1.7%)
Tricuspid atresia (Waterstone shunt)	2 (3.4%)
LA isomerism, AVSD repaired	2 (3.4%)
Criss-cross heart(repaired TOF)	1 (1.7%)
Double inlet left ventricle	2 (3.4%)
Truncus arteriosus (Rastelli procedure)	1 (1.7%)

ALCAPA, anomalous origin of the left coronary artery from the pulmunary artery; ASD, atrial septal defect; AVSD, atrioventricular septal defect; IVC, inferior vena cava; LA, left atrium; MAPCA, major aortopulmunary collateral arteries; PFO, patent forame ovale; RVOTO, right ventricular outflow tract obstruction; TCPC, total cavopulmunary connection; TOF, tetralogy of Fallot; VSD, ventricular septal defect.

In 25 (20%) procedures, remote magnetic navigation was used to reach the target chambers, 11 (9%) of which in a retrograde fashion via the aorta. A sequential electroanatomical mapping system was used in most of procedures (112, 92%) while 6 (5%) procedures were performed using a high-density mapping system and 4 (3%) using a simultaneous mapping system.

Ninety percent of all ablations were performed on continuous antiarrhythmic medication, mostly Class III (38%) or beta-blockers (33%).

Outcomes

All procedures were acutely successful in restoring sinus rhythm (SR), except for one patient of a 27 years old with an anomalous left coronary artery from the pulmonary artery (ALCAPA) and mitral valve stenosis, persistent AF, and a massively dilated left atrium (indexed volume 170 mL/m^2) who remained in AF despite multiple ablations and external cardioversions. No major complications occurred in any patient, including tamponade, major bleeding, valvular

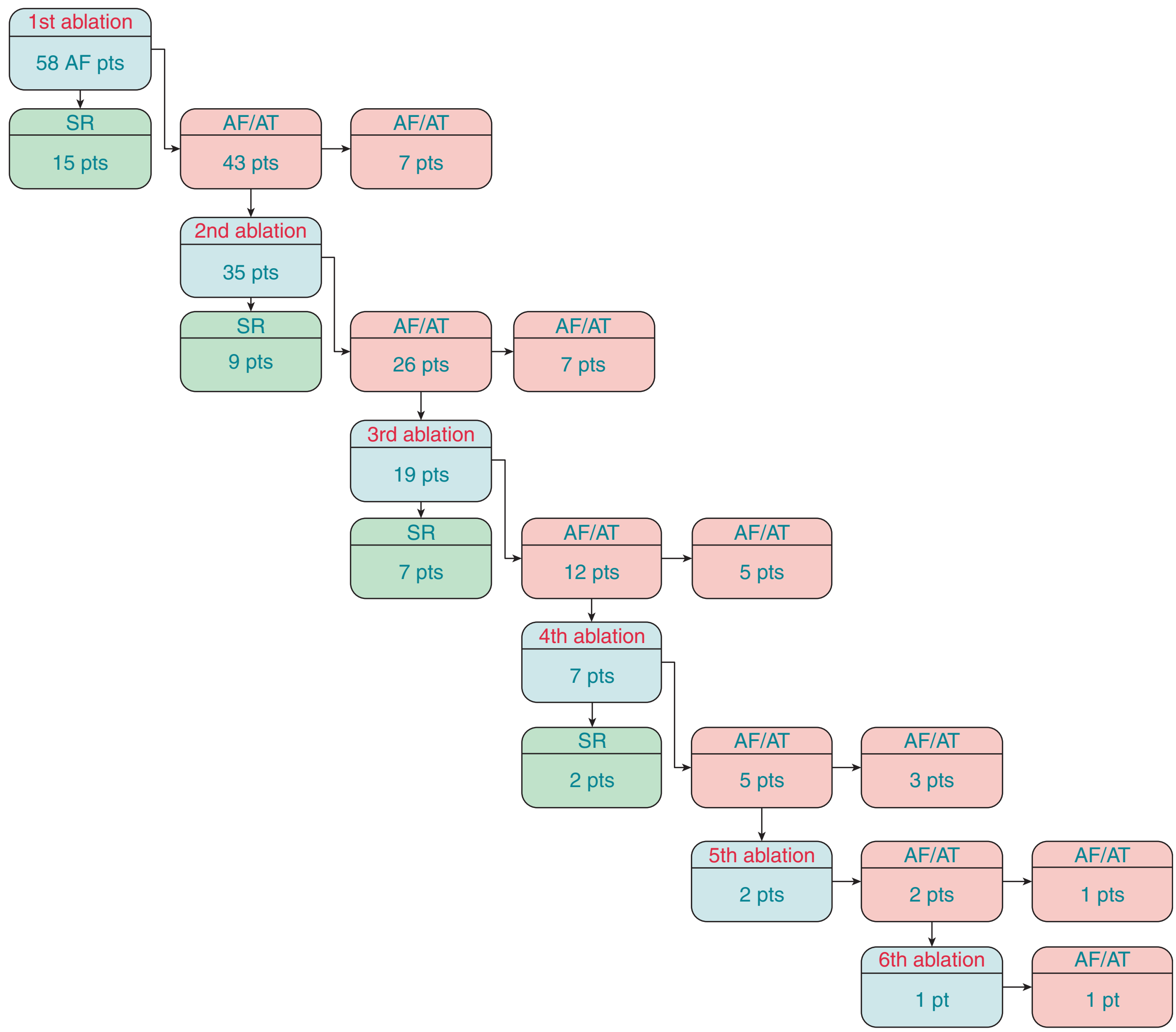

Figure 2 Chronologic flow chart of all AF/AT ablation procedures and rhythm outcomes. AF, atrial fibrillation; SR, sinus rhythm.

damage, or vascular access complications requiring surgery or blood transfusion.

At 1 year after the index ablation, 32.8% of patients had remained in SR. Thus, multiple procedures were required to control atrial arrhythmias in 35 (60%) patients. Freedom from AF/AT at 1 year after the 2nd and 3rd ablation was 40.9% and 36.5%, respectively (*Figure 3*).

Predictors of arrhythmia recurrence

During a median follow-up of 24 (11–69) months, one patient died due to infective endocarditis of a percutaneous pulmonary valve prosthesis. Univariable Cox proportional hazards regression analysis identified female gender [hazard ratio (HR) 1.56, 95% confidence interval (CI) 1.01–2.4; $P = 0.04$), anatomy complexity (severe, HR 1.92, 95% CI 1.19–3.11; $P = 0.007$), type of AF (persistent HR 1.8, 95% CI 1.11–2.90; $P = 0.016$), and LA dimension (area index – LAAi for cm^2/m^2, HR 1.07, 95% CI 1.02–1.12; $P = 0.005$) as factors associated with the risk of recurrence (*Table 3*, *Figure 4*). A positive trend was noticed for the deployment of a CTI line (HR 0.67, 95% CI 0.43–1.05; $P = 0.08$) and higher body mass index (HR 0.95 for kg/m^2, 95% CI 0.91–1.00; $P = 0.06$). In the multivariate analysis, severe anatomy complexity (HR 1.97, 95% CI 1.22–3.22; $P = 0.006$), persistent AF (HR 1.87, 95% CI 1.22–2.89; $P = 0.0049$), and LA area index (HR 1.06 for cm^2/m^2, 95% CI 1.01–1.12; $P = 0.03$) were independent predictors of recurrence (*Table 4*). Based on the multivariable analysis, predicted recurrence rates over the first 2 years after ablation vs. LA size, in patients with complex vs. simple/moderate CHD and paroxysmal vs. persistent AF were plotted in the form of heatmaps (*Figure 5*). Based on our model, patients with paroxysmal atrial fibrillation (PAF), simple-moderate lesions and normal LA atrial dimension show estimated arrhythmias free survival range at 1 year above 60% (*Figure 5A*). Arrhythmia free survival at 1 year is lower in patients with persistent AF or complex congenital patients (approximately 40% if the atrium is not dilated, *Figure 5B, C*).

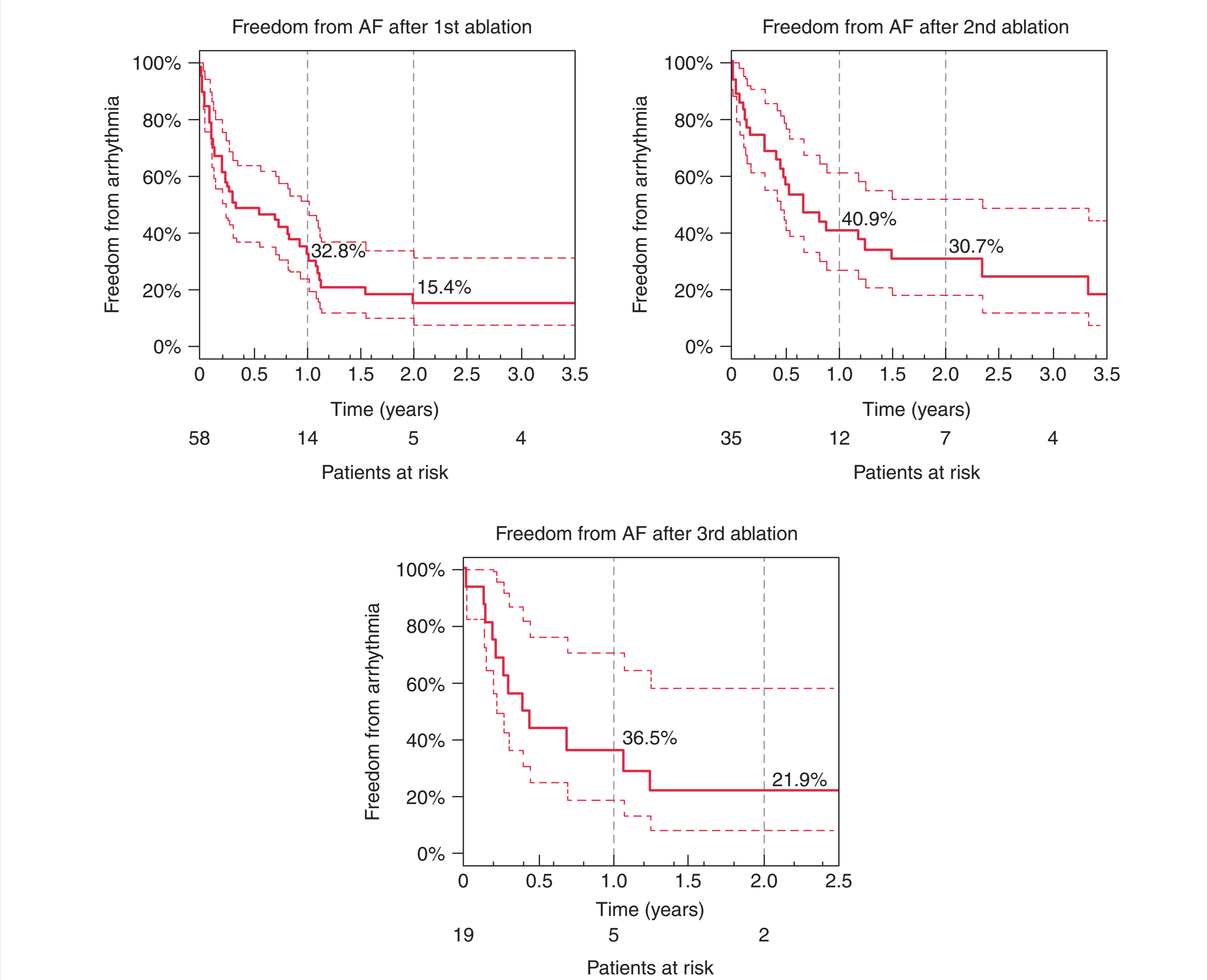

Figure 3 Kaplan–Meier for arrhythmia free survival after the 1st, 2nd, and 3rd procedures with examples (%) at 1 and 2 years. AF, atrial fibrillation.

We also examined the value of additional techniques, such as CFAE, linear, or GP ablations, on the freedom from recurrence after the 1st procedure. There was a trend supporting a potentially beneficial effect of CTI line deployment (HR 0.53, 95% CI 0.28–1.00; $P = 0.052$), while there was no benefit of other techniques, in addition to PVI alone (HR 0.99, 95% CI 0.54–1.82; $P = 0.97$).

Discussion

To our knowledge, this is the largest report in terms of procedures including 122 catheter ablations for AF/AT post-AF in CHD patients, mostly of moderate or severe complexity. The present study intended to investigate the feasibility and short-/long-term effectiveness of AF catheter ablation and to identify predictors of recurrence after a successful procedure. The most important findings of our series include that (i) AF ablation is feasible and acutely successful in CHD patients, but recurrence rates are higher and multiple procedures may be required to control AF/AT; (ii) persistent AF, complex anatomy, and left atrial size were independently associated with higher recurrence rates and should be taken into account when considering AF ablation in CHD patients; (iii) AF ablation appears safe even in patient with complex anatomy but may necessitate special techniques such as remote magnetic navigation and more extensive ablation strategies and/or novel mapping tools like high-density mapping or simultaneous AF mapping.

Congenital heart disease atrial fibrillation ablation compared to normal hearts

While AF ablation has become standard treatment for non-CHD patients, it is often avoided or delayed in patients with CHD due to the procedural challenges posed by their unique anatomy and the lack of evidence to guide the choice of ablation technique. The reluctance to ablate AF in CHD patients is reflected by the limited sample size in our study: in a tertiary CHD centre only 58 patients received AF ablation over a decade, representing <15% of total number of

Table 3 Univariable analysis using Cox proportional hazards model with *cluster* function

	Univariable analysis with cluster function		
	HR	CI	*P*-value
Female gender	1.56	1.01–2.4	0.04
Age per 10 years	0.93	0.76–1.13	0.46
BMI (kg/m²)	0.95	0.91–1.00	0.06
Previous cardiac surgery	1.21	0.78–1.86	0.4
Bethesda = 3	1.92	1.19–3.11	0.007
Previous ablation	1.16	0.77–1.73	0.49
Type AF (persistent)	1.8	1.11–2.90	0.017
EF <30%	0.99	0.76–1.30	0.96
LA area index (cm²/m²)	1.07	1.02–1.12	0.005
LA vol index (mL/m²)	1.02	1.00–1.03	0.025
RA area index (cm²/m²)	1.04	1.00–1.09	0.054
CTI blocked	0.67	0.43–1.05	0.08
RMN	1.04	0.65–1.67	0.62

AF, atrial fibrillation; BMI, body mass index; CI, confidence interval; CTI, cavotricuspid isthmus; EF, ejection fraction of the systemic ventricle; HR, hazard risk; LA, left atrium; RA, right atrium; RMN, remote magnetic navigation.

CHD procedures performed during the study period. Also, over half of the patients in this study were referred for ablation in an advanced stage, when AF had already become persistent. Despite procedural challenges, all procedures were feasible even though they often required advanced techniques such as remote magnetic navigation and careful planning with 3D imaging roadmaps. Importantly, AF ablation was shown to be safe when performed in a tertiary centre with expertise in CHD and pulmonary hypertension.

Freedom from arrhythmia at 1 year from the first ablation in non-CHD patients ranges from 40% to 70%,[13] with higher recurrence rates in persistent AF. Outcomes are even worse in patients with atrial dilatation and/or heart failure.[14–16]

Only few reports are available in CHD patients with a reported freedom from arrhythmia > 70% at 1 year in patients with simple cardiac defects (mostly atrial septal defect (ASD)/patent forame ovale] and of 40–63% in patients with more anatomic complexity.[17–21] We report a lower long-term efficacy in our cohort: only 33% of our patients remained in SR at 1 year after the first ablation. This may be explained by the inclusion of more complex subjects compared to previous reports, including many patients with moderate-severe anatomical complexity, persistent AF and significantly dilated atria. Philips *et al* reported 36 patients, mostly ASD and ventricular septal defect and only 28% with persistent AF. Sohns *et al.* and Liang *et al.* described recently their cohorts with mostly persistent AF (63 and 65%, respectively), but simple anatomical complexity (61% and 51%). The atrial size has been rarely reported and wasn't correlated to ablation outcome. Moreover, compared to other studies, no blanking period was applied resulting in an overall higher event rate in our series. Nevertheless, even in our complex cohort, AF can be controlled in many patients but both clinicians and patients should be aware that multiple procedures are likely to be required to achieve acceptable outcomes.

Atrial fibrillation ablation strategies in CHD patients

Ectopic activity triggering AF, in patients without CHD, mostly originates from the pulmonary veins (PVs).[22] The role of PV ectopy in patients with CHD is less well established; some studies suggest that activity from different areas, including the right atrium, may also play a significant role in the pathogenesis of AF.[23,24] Furthermore, atrial structural remodelling due to volume and pressure overload or atrial fibrosis and scarring may play a more important role than trigger activity in the pathogenesis of AF in CHD. The exact effect of the additional ablation techniques in modifying the substrate is still unclear and may vary in their result according to the underlying individual structural anatomy. Our data showed no difference in the risk of recurrence between PVI alone or PVI plus additional substrate modification during the first procedure, except for a trend suggestive of a potentially beneficial effect of CTI line deployment ($P = 0.052$). In non-CHD patients, prophylactic CTI has not been associated with an improved long-term success in AF ablation.[25] However, this may be different in CHD patients, who are at much higher risk of having dilated 'diseased' right atria that may contribute to the initiation and maintenance of AF.

Exclusive right atrial substrate for atrial fibrillation

In two of our patients only right ablation was performed. Both had very dilated RAs due to Ebstein's anomaly or tricuspid atresia respectively and during planned atrial tachycardia ablation procedure were paced into AF exclusively. As the atrial substrate in both patients consisted of massively dilated RAs with relatively smaller LAs (∼ratio 3:1), a transseptal approach to perform PV isolation seemed dispensable as the substrate for AF maintenance resided most likely inside the RA. Since techniques for this situation are not yet defined, we elected to modify the RA substrate by intercaval and CTI lines, as well as CFAE ablations. The Epstein patient had a recurrence only 2 years after ablation, whilst the second patient is still in SR.

Predictors of recurrence

Similarly to non-CHD patients, in our series left atrial dilatation and persistent AF were independently associated with higher recurrence rates in the multivariable analysis. Moreover, we showed that severe anatomic complexity was an independent predictor of arrhythmia recurrence. The latter could be related to the defect itself, the presence of surgical scars and artificial material or the long-standing haemodynamic lesions and cyanosis which all contribute to a more complex arrhythmogenic substrate, not easily addressed with standard ablation techniques. Ablation in patients with complex anatomy required uncommon techniques and comes with difficulty in both approaching the sites and delivering lesions. The retrograde approach for example limits the mapping to a quadripolar mapping catheter as opposed to simultaneous multipolar circumferential catheter.[26] Also, the delivery of transmural ablation lesions may be prevented by excessive wall thickness (up 7–10 mm) that has been reported in several congenital heart conditions (e.g. Fontan palliation).[27] The inclusion of more anatomical complex patients compared to other studies[17,18] may in part explain our higher recurrences rates.

The type of AF, the anatomical complexity and LA size may be used to predict the outcome of AF ablation and may influence

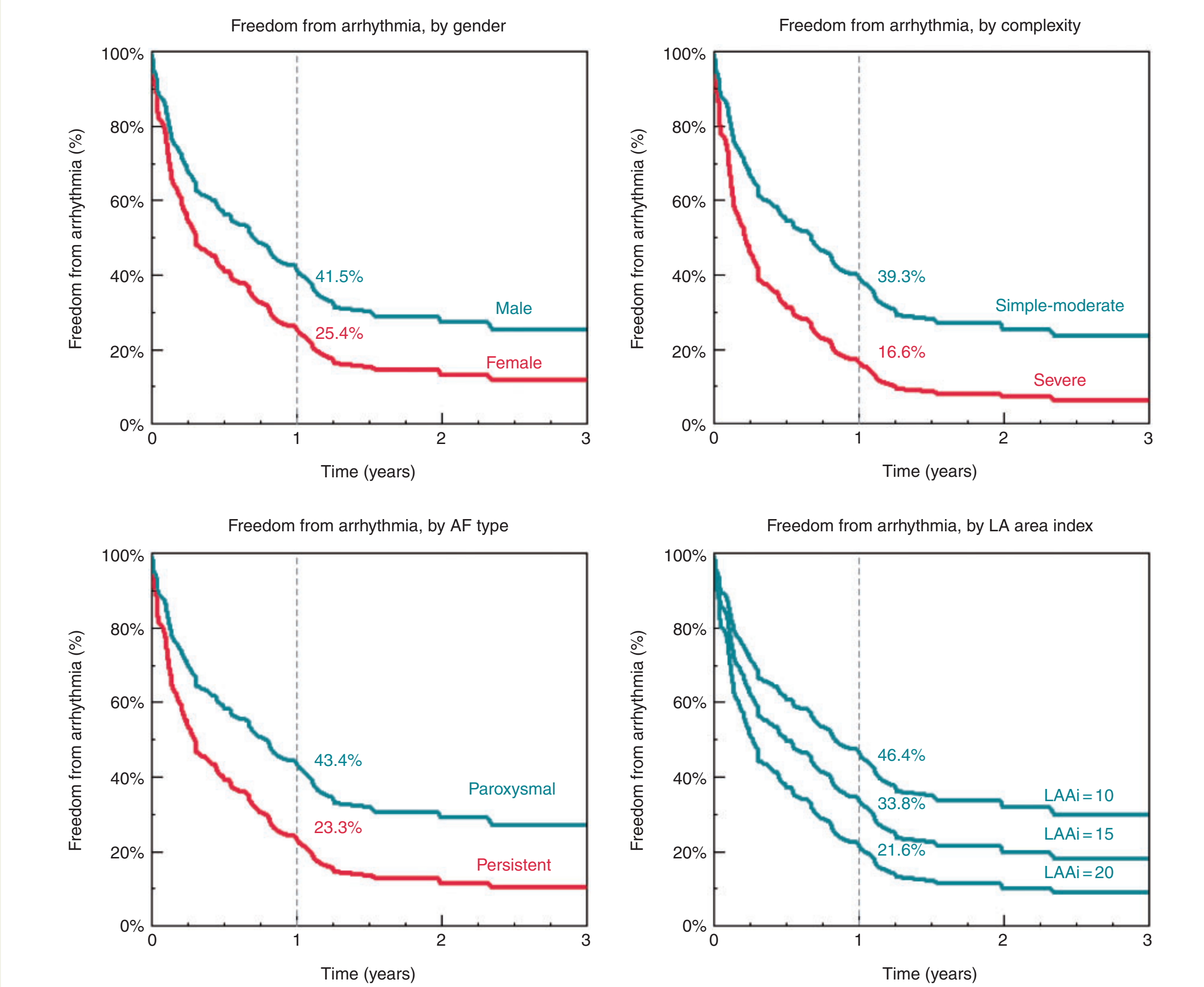

Figure 4 Adjusted survival curves for Cox model by parameters significant in the univariable model (gender, anatomy complexity, AF type, LA area index). AF, atrial fibrillation.

Table 4 Multivariable analysis using a stepwise Cox proportional hazards model

	Multivariable analysis		
	HR	**CI**	***P*-value**
Type (persistent)	1.87	1.22–2.89	0.004
Bethesda = 3	1.98	1.22–3.22	0.006
LA area index (cm^2/m^2)	1.06	1.01–1.12	0.03

CI, confidence interval; HR, hazard ratio; LA, left atrial.

the decision to offer this treatment. Patients with PAF, simple or moderate lesions and normal left atrial size, showing an estimated arrhythmia-free survival at 1 year above 60%, can be good candidates for ablation. This assessment is in agreement with the findings of other reports.[17,18] Persistent AF ablation carries a worse outcome but may still be acceptable in selected patients. On the contrary, patients with complex anatomy and significantly dilated left atria are less likely to benefit from the procedure. Unfortunately, these complex patients, especially those with residual lesions, ventricular dysfunction and pulmonary hypertension, are also the ones who tolerate AF the least. The loss of the atrial 'kick' in fact leads to a loss of stroke volume, due to decreased in left ventricular end diastolic volume, that can be detrimental in these patients who may already suffer of diastolic dysfunction, impaired contraction and altered haemodynamic. On a case-by-case basis, these patients need to be carefully assessed and the herewith presented data is meant to be an additional tool in their clinical management, which must be the result of a weighted CHD team decision. Although limited by relatively small numbers, it was the first attempt to propose a model for the clinicians to estimate the outcome of a potential

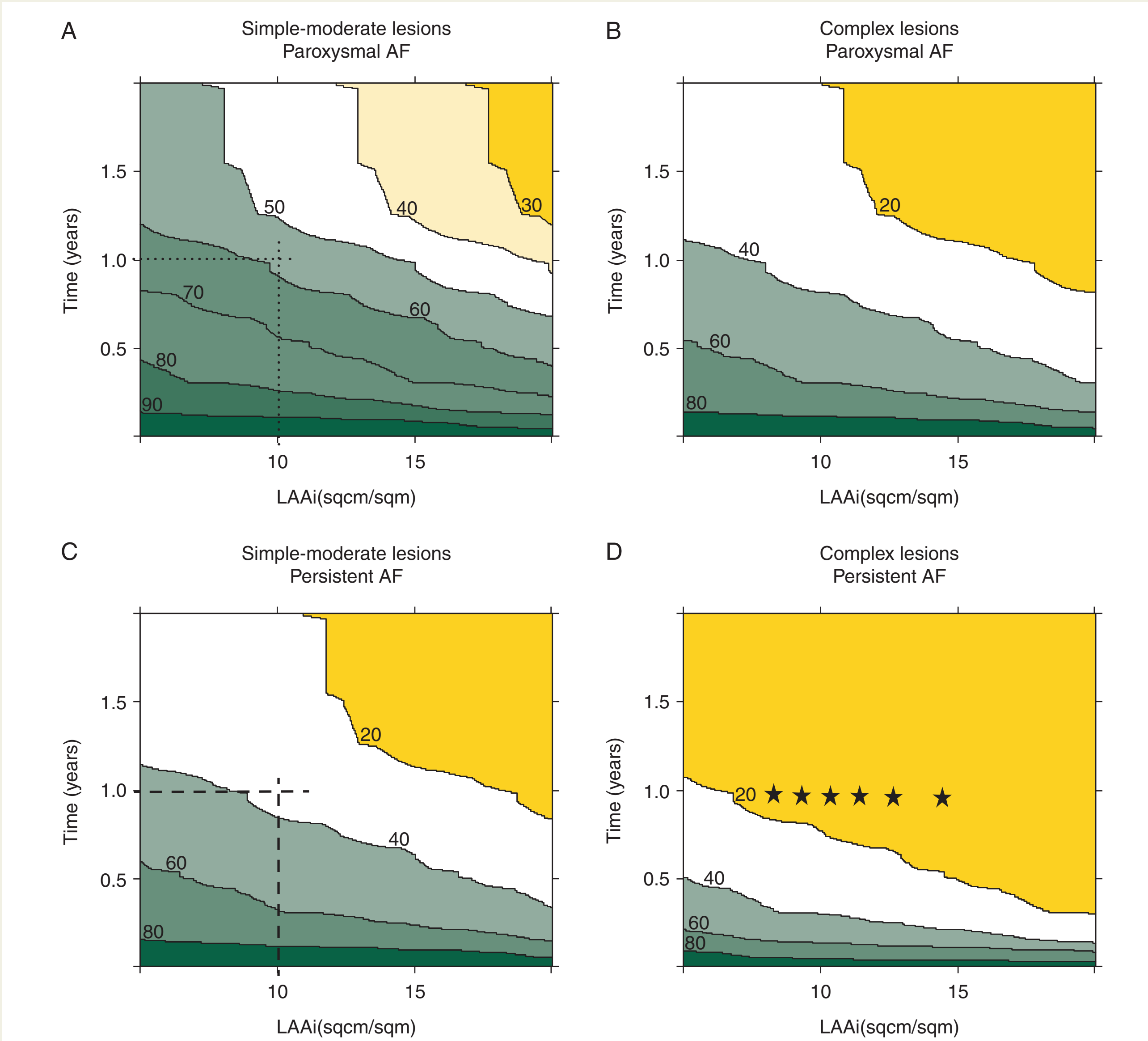

Figure 5 Heat maps reflecting predicted recurrence rates over the first 2 years after ablation against LA size, in patients with simple/moderate (*A* and *C*) vs. complex (*B* and *D*) CHD and paroxysmal (*A* and *B*) vs. persistent (*C* and *D*) AF. For example, a patient with PAF, simple-moderate lesions and an atrial area index=10 sqcm/sqm shows an estimated arrhythmias free survival range at 1 year of 55–60% (*A*, dotted line). In comparison, in a similar patient with persistent AF, arrhythmia free survival at 1 year is approximately 40% (*C*, dashed line). Patient with complex lesions and persistent AF has predicted higher recurrence rates (*D*). The stars represent different patients with different atrial dimensions: whatever the atrial size is, the success is lower than 20% at 1 year). AF, atrial fibrillation; CHD, congenital heart disease.

ablation and to select patients who have the lowest recurrence probability.

In patients with high probability of recurrences and who do not tolerate pharmacologic rate control, all alternatives should be taken into account. These may include atrioventricular nodal ablation plus pacemaker implantation (despite a reported higher mortality of paced patients with complex univentricular heart as compared to native SR and the high thromboembolic risk of the ongoing AF[2]) and/or surgical AF ablation (taking into account the related operative risk in patients with previous surgical interventions). Lastly, transplantation may be the final option and recent reports show a good long tern survival after an initially higher 30 days mortality.[28,29]

Clinical precursor of atrial fibrillation

Coexistence of AF and AT is common in ACHD patients; almost 20% of our patients had been referred for management of an atrial tachycardia before the index AF ablation. It has been postulated that the shortening of the atrial effective refractory period and electrical remodelling caused by chronic atrial tachycardia may facilitate the development of sustained AF[30]; vice versa AT are not uncommon after AF ablation. Catheter ablation for atrial tachycardia in CHD patients has been reported having much better outcomes when compared to AF, ranging from 70% to 80% acutely and approximately 60% longer-term success.[2,31,32] It may be postulated that an aggressive and early approach to AT could help prevent its degeneration to AF, which appears far more challenging to manage. Similarly, in patients presenting with new onset PAF, early ablation should be considered.

Future perspectives

While we recognize the limitations of our study based on small numbers of heterogeneous CHD patients, it is an attempt to understand outcomes of AF catheter ablation in CHD. Larger registries and/or a prospective multicentre trial should validate our results and the proposed risk model. An individualized approach is needed and current technology, such as novel imaging software for 3D scan reconstruction allowing to visualize scar/fibrosis burden, would facilitate proper planning and the procedure itself. In addition, high density sequential mapping information may provide crucial information such as functional conduction pathways, not necessarily bounded by scars from previous interventions and/or ablation. Lastly, simultaneous mapping during ongoing AF may help to understand preferential conduction and allow an 'informed' compartmentalization approach that would interrupt the main rotor/re-entry/driver activity.

Limitations

Our study is limited by the relatively small sample size and the retrospective design. It includes a heterogeneous group of CHD patients with different anatomical, clinical, and procedural characteristics. The choice of including only documented recurrences, despite a better specificity, bears the potential for failing to recognize short lasting AF episodes. Moreover, we focused only on the first AF/AT recurrence and we didn't assess the effect of ablation on symptoms or AF burden. Finally, a blanking period after the index ablation was not applied.

Conclusion

Catheter ablation is a valid option for the treatment of AF in CHD patients, even though multiple procedures may be required. Early referral and careful patient selection are essential to optimize the results of AF ablation in CHD patients, achieving a low rate of recurrence.

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Conflict of interest: S.E. is a consultant for Stereotaxis and Bisosense Webster. All other authors declared no conflict of interest.

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High resolution map of aortic root tachycardia

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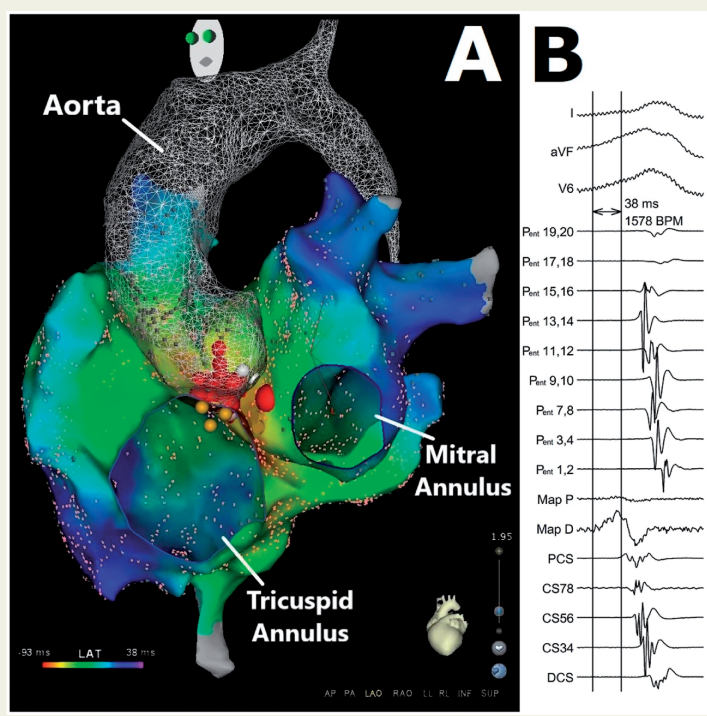
A 63-year-old woman without structural heart disease was referred with frequent, sustained episodes of atrial tachycardia. The episodes had terminated spontaneously before vagal manoeuvres or acute pharmacological intervention could be tried. Tachycardia with a cycle length 390–420 ms was induced. High-density electroanatomic mapping using the Carto mapping system and a pentaray mapping catheter revealed earliest right atrial activation close to the His bundle. The earliest left atrial activation was in an adjacent position at similar timing, but mapping in the aortic root revealed earlier activation than obtained endocardially in either atrium (*Panel A*). In the non-coronary sinus of Valsalva, low-amplitude atrial electrograms preceded any other electrogram by 20 ms (*Panel B*). Radiofrequency delivery at this site terminated the tachycardia, resulting in non-inducibility and clinical resolution.



Ablation of atrial tachycardia usually involves electrical mapping in just one chamber. In patients with focal AT arising close to or within the inter-atrial septum, high-density electroanatomical mapping of both atria and the aorta can be clinically useful. We have found the electroanatomic map produced in this case to be helpful in understanding the interrelationships between the relevant structures (Supplementary material online, *Video S1*).

Supplementary material is available at *Europace* online.

The full-length version of this report can be viewed at: https://www.escardio.org/Education/E-Learning/Clinical-cases/Electrophysiology.