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Catheter ablation in congenital heart diseases: a French nationwide study

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Keywords:

Catheter ablation; Congenital heart disease; Supraventricular arrhythmia; Ventricular arrhythmia.

Abstract

Background and aims:

Current evidence on catheter ablation for patients with congenital heart disease (CHD) is derived from small, retrospective studies. This study aims to provide insights from a nationwide contemporary registry.

Methods:

This prospective study included all CHD patients referred for catheter ablation from 2020 to July 2024 across 28 French centres. The primary outcome was the rate of per-procedural acute success. Secondary outcomes included complications as well as freedom from arrhythmia recurrence.

Results:

A total of 1135 consecutive catheter ablation procedures were performed in 998 patients (mean age 46.1 ± 16 years, 55.5% male). The main primary clinical arrhythmias targeted were atrial flutter/tachycardia in 677 (59.6%), atrial fibrillation in 195 (17.2%), ventricular arrhythmia in 188 (16.6%), and atrioventricular reentrant tachycardia in 38 (3.3%), with significant variations in patterns observed based on the underlying substrate. Clinical arrhythmia was successfully ablated in 1071 patients (94.4%). The mean number of arrhythmias targeted per procedure was 1.5 ± 0.7 , with overall acute success rates exceeding 90% for all arrhythmias except for ventricular arrhythmias (86.7%). Acute complication occurred in 43 procedures (3.8%), including 1 (0.1%) death. The overall 1- and 2-year recurrence-free rates were 77.3% (95% confidence interval 74.2%-80.4%) and 68.4% (95% confidence interval 64.7%-72.3%), respectively. Significant variations in recurrence rates were noted based on the type of arrhythmia and the underlying CHD.

Conclusions:

Catheter ablation in patients with CHD demonstrates highly favourable acute outcomes and a low complication rate. Recurrence rates during follow-up vary depending on the targeted arrhythmia and the underlying CHD. These findings should be considered in the benefit-risk assessment.

Key Finding

In this prospective, contemporary, nationwide registry of catheter ablation in CHD patients, acute outcomes were excellent with 94% of success and a low incidence of complications. The overall 1-year and 2-year recurrence-free rates were 77.3% and 68.4%, but significant variations in recurrence rates were noted based on type of arrhythmia and underlying CHD.

Take Home Message

These findings should be carefully weighed in the benefit-risk assessment of CHD patients undergoing catheter ablation.



Prospective nationwide registry



2020–2024



1135 catheter ablation procedures



998 CHD patients

Main arrhythmias targeted

1.5±0.7 arrhythmias per procedure

IART/FAT 60%
AF 17%
PVC/VT 17%
AVRT 3%
AVNRT 2%

Significant variations of patterns according to CHD

Tetralogy of Fallot

Isolated ASD

D-TGA

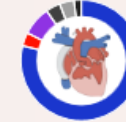
AVSD



Ebstein anomaly

Cc-TGA

Univentricular hearts



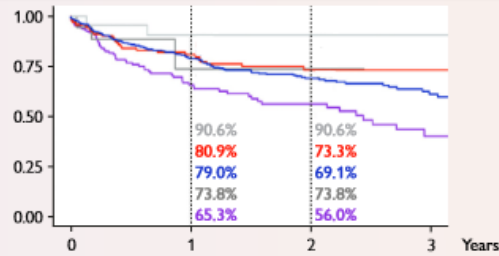
Excellent acute outcomes

Overall acute success rate 94%

IART/FAT 95%
AF 97%
PVC/VT 87%
AVRT 95%
AVNRT 91%

3.8% complications (0.1% death, n = 1)

Heterogeneous recurrence rates based on arrhythmia and CHD



Introduction

Advances in paediatric cardiology, especially surgical techniques, have resulted in an important increasing prevalence of patients with congenital heart disease (CHD).¹ The major improvement in life expectancy in this population is, however, tempered to some extent by late complications, especially the occurrence of arrhythmias.^{2,3} Abnormal anatomy, postsurgical scarring, and other systemic factors contribute to establishing a unique substrate for cardiac arrhythmia development. Projections indicate that 50% of 20-year-old CHD patients will experience at least one atrial arrhythmia during their lifespan,⁴ and sudden cardiac death remains an important mode of death in these patients.⁵ With progressive gain in experience in this specific population and advancements of ablation techniques,^{6,7} outcomes have significantly improved over time and catheter ablation is now recommended as a first line therapy in patients with recurrent arrhythmias.^{8,9} However, data on the outcomes of catheter ablation in CHD patients are primarily derived from retrospective studies, including small to moderate numbers of patients, sometimes with wide inclusion periods, and mostly from single-centre cohorts.^{7,10–18} In this context, this study aims to provide insights from a very large population, using a nationwide prospective registry reflecting contemporary practices and outcomes.

Methods

Study population and setting

This prospective registry is a nationwide French observational study including all patients with CHD referred for catheter ablation, initiated in January 2020 by the French Institute of Health and Medical Research [Catheter Ablation in Congenital Heart disease (CATCH): French National Prospective Registry, NCT04202796]. In France, healthcare system in CHD is based on a network of four national reference centres and 19 other competence centres. All reference and competence centres have teams of cardiologists specialized in CHD, but reference centres are designated according to their patient volume and technical resources (e.g. cardiac surgery and cardiac catheterization). Centres are re-labelled every 5 years based on their activities. All French centres accredited for catheter ablation were invited to participate. All CHD and all types of arrhythmias were considered, and patients of all ages were included. Written informed consent was obtained in all patients. In this study, patients who underwent catheter ablation from 1 January 2020, to 31 July 2024, were analysed.

This registry was declared to and authorized by the French data protection committee (Commission Nationale Informatique et Liberté), and the study was approved by the appropriate institutional review boards. Data were centralized, collected, and managed using REDCap electronic data capture tools hosted at the Cardiovascular Epidemiology and Sudden Death Unit (Inserm 970, Paris Cardiovascular Research Center, European Georges Pompidou Hospital, Paris, France).¹⁹

Collected data

Patient characteristics were collected at baseline before catheter ablation. Data included demographic characteristics, medical history, and details of the underlying CHD including date and types of previous cardiac surgeries. Congenital heart diseases were classified as simple, moderate, or complex according to the most recent European Society of Cardiology classification.⁹ History of supraventricular and ventricular arrhythmias, catheter ablation procedures, previous pharmacological therapy, cardiac imaging parameters, and symptoms were also recorded.

Comprehensive data on catheter ablation procedures were collected. The catheter ablation approach (anaesthesia, vascular access, catheters, and energy used) was left to the discretion of the managing centre. In patients in sinus rhythm at the beginning of the procedure, clinical arrhythmia was induced by programmed atrial or ventricle stimulation, with isoproterenol infusion if needed. In these patients, clinical arrhythmia was identified by operators as the most likely arrhythmia based on comparison with electrocardiogram (ECG) morphology and/or tachycardia cycle length. The type of targeted arrhythmia was classified as follows: intra-atrial reentrant tachycardia or focal atrial tachycardia (IART/FAT); atrial fibrillation (AF); atrioventricular reentrant tachycardia (AVRT); atrioventricular nodal re-entrant tachycardia (AVNRT); junctional ectopic tachycardia (JET); atrioventricular node ablation (AVN); premature ventricular contraction (PVC); and ventricular tachycardia (VT). For patients with AF, the ablation approach (pulmonary vein isolation and/or additional lesions) was also left to the discretion of the operator. In non-inducible patients, the ablation target was determined based on substrate mapping and most likely mechanism or critical isthmus according to underlying anatomy (such as empirical cavo-tricuspid isthmus ablation or ablation line between atriotomy incision and inferior vena cava for patients with IART or isthmus between ventricular septal defect patch and pulmonary annulus for Fallot patients with VT).

After the procedure, the choice to pursue antiarrhythmic and anticoagulation therapies was at the physician's discretion. The following follow-up protocol was encouraged: outpatient visits with ECG and 24-h Holter recordings and/or pacemaker/defibrillator check at 3, 6, and 12 months and then on an annual basis. Medical appointments were also promptly scheduled in case of any symptoms suggestive of arrhythmia.

Outcomes

The primary endpoint was the rate of acute per-procedural success, defined as termination of the clinical arrhythmia with non-inducibility of this clinical arrhythmia and subsequent validation of bidirectional block across the critical isthmus using activation maps (for reentrant arrhythmias). Systematic final programmed stimulation and isoprenaline infusion were required in the protocol, but the pacing protocol was left to the discretion of the operator. The acute success was assessed by the operator, and no central adjudication was performed. A partial success was defined as successful catheter ablation of the clinical arrhythmia but with at least one other non-clinical arrhythmia not targeted or not successfully ablated. Secondary main outcomes included complications associated with catheter ablation procedure and the 1- and 2-year freedom from arrhythmia recurrence. Recurrence was defined as any episode of documented arrhythmia of the same type (atrial vs junctional vs ventricular

arrhythmia) lasting more than 30 s (except for PVC, where recording of PVCs with the same morphology was considered as a relapse). Arrhythmia morphology on ECG, tachycardia cycle length, and 3D mapping during repeat procedures (when applicable) were analysed to differentiate between the recurrence of the arrhythmia initially targeted and the development of a new arrhythmia.

Statistical analysis

This report was prepared in compliance with the STROBE checklist for observational studies.²⁰ Categorical data were reported as numbers and percentages. Continuous data were reported as mean \pm standard deviation or median and interquartile range (IQR) for normally and non-normally distributed data, respectively. For arrhythmia recurrences during follow-up, the time to event endpoint was the time from catheter ablation to first documented arrhythmia of the same type (atrial vs junctional vs ventricular arrhythmia). Censoring occurred in the event of loss to follow-up, heart transplantation, or death. Survival curves were plotted by the Kaplan–Meier method. Subgroup analyses were performed according to the different types of arrhythmias, in most distinctive type of CHDs, and in the different types of centres (reference vs competence centres). Sensitivity analyses were also performed in patients with a first catheter ablation procedure (excluding patients with history of prior catheter ablation of the same type of arrhythmia). A two-tailed P-value of $<.05$ was considered statistically significant. All data were analysed using the R software, version 4.4.2 (R Project for Statistical Computing, Vienna, Austria).

Results

Population and targeted arrhythmias

A total of 1135 consecutive catheter ablation procedures performed in 998 patients were prospectively included across 28 centres: 890 (89.2%) patients had only 1 procedure during the study period, 88 (8.8%) had 2, 12 (1.2%) had 3, 7 (0.7%) had 4, and 1 (0.1%) had 5 procedures. The number of catheter ablations performed in each centre is provided in Supplementary data online, Table S1. The mean age at the time of catheter ablation was 46.1 ± 16.1 years, 67 (5.9%) patients were children < 18 years, and 629 (55.5%) were male. General characteristics of patients are presented in Table 1, and underlying CHDs are detailed in Figure 1. Overall, 198 (17.4%) patients had a simple CHD, 656 (57.8%) a moderate CHD, and 281 (24.8%) a complex CHD.

Table 1 General characteristics of patients

	N = 1135
Age at ablation (years), mean \pm SD	46.1 \pm 16.1
Age at ablation (years), min/Q1/median/Q2/max	0.2–36.1–47.2–58.2–87.7
Male, n (%)	629 (55.5)
Number of cardiac surgeries, mean \pm SD	1.7 \pm 1.2
Previous catheter ablations*, n (%)	
IART/FAT	206/677 (30.4)
AF	38/195 (19.5)
PVC/VT	37/188 (19.7)
AVRT	9/38 (23.7)
AVNRT	0/22 (0.0)
Cardiovascular risk factors, n (%)	
Smoking	115 (10.1)
Overweight (BMI > 25)	268 (23.6)
Coronary heredity	11 (0.0)
Coronary artery disease	22 (1.9)
Diabetes mellitus	53 (4.7)
Dyslipidemia	98 (8.6)
Stroke	49 (4.3)
Hypertension	175 (15.4)
Antiarrhythmics, n (%)	
At least 1 antiarrhythmic	878 (77.3)
Amiodarone	230 (20.3)
Beta-blockers	673 (59.3)
Sotalol	97 (8.6)
Class I antiarrhythmic	73 (6.4)
Calcium channel blockers	28 (2.5)
Digoxin	16 (1.4)
Anticoagulants, n (%)	
Vitamin K antagonist	184 (16.2)
Direct oral anticoagulant	575 (50.7)
Heart failure medications, n (%)	
ACE inhibitors or ARB	184 (16.2%)
Mineralocorticoid receptor antagonist	141 (12.4%)
Diuretics	266 (23.4%)
Sacubitril/valsartan	52 (4.6%)
SGLT2-i	16 (1.4%)
Systemic ventricle ejection fraction, mean \pm SD	52.6 (11.7)

*Previous catheter ablation means that the patient had already undergone a catheter ablation of an arrhythmia of the same type (IART/FAT, AF, PVC/VT, etc).

ACE, angiotensin-converting enzyme; AF, atrial fibrillation; ARB, angiotensin receptor blockers; AVNRT, atrioventricular nodal reentrant tachycardia; AVRT, atrioventricular reentrant tachycardia; BMI, body mass index; FAT, focal atrial tachycardia; IART, intra-atrial reentrant tachycardia; PVC, premature ventricular contraction; SGLT2-i, sodium glucose cotransporter 2 inhibitor; VT, ventricular tachycardia.

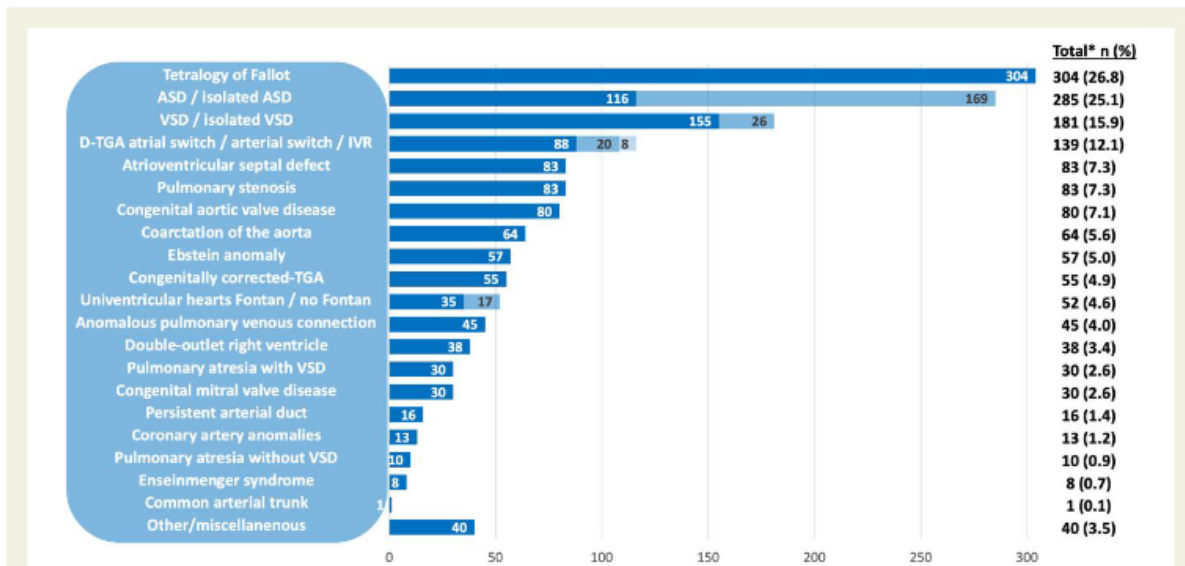


Figure 1 Underlying congenital heart diseases. Blue and light blue colours represent subgroups of patients in some congenital heart diseases. *Patients with multiple congenital heart diseases were counted in the different groups of congenital heart diseases. ASD, atrial septal defect; IVR, intraventricular repair; TGA, transposition of the great arteries; VSD, ventricular septal defect

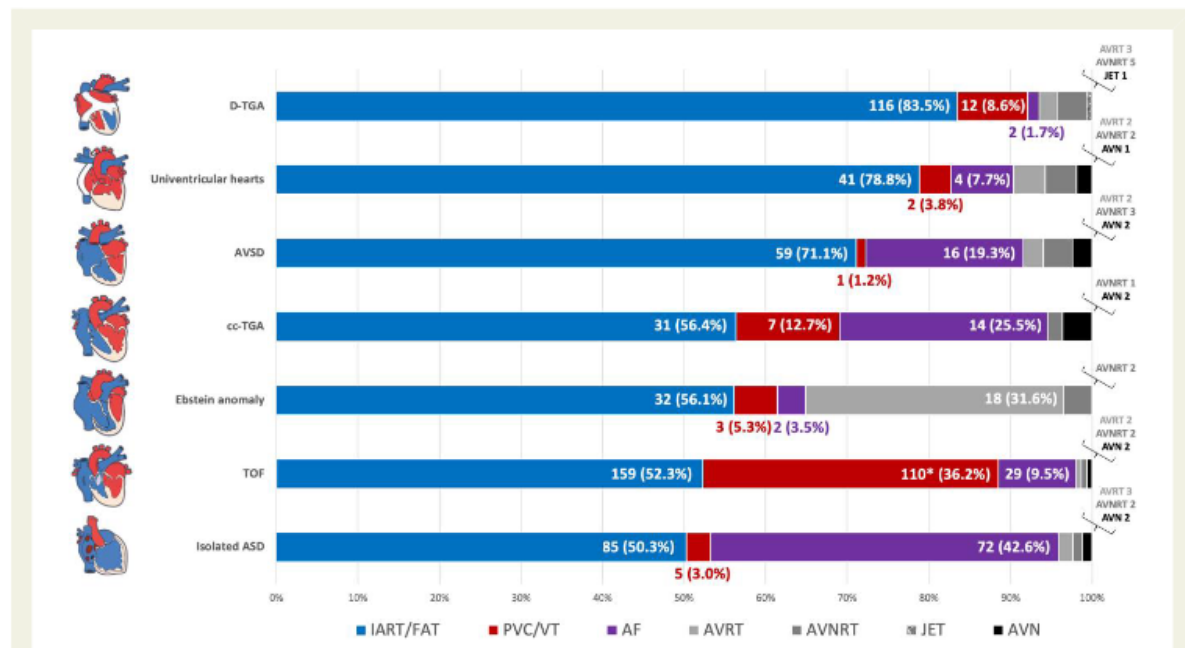


Figure 2 Primary arrhythmia targeted in most distinctive congenital heart diseases. *Among tetralogy of Fallot patients with ventricular tachycardia targeted (n = 95, premature ventricular contraction not considered), 58 patients had a spontaneous clinical ventricular tachycardia, whereas ventricular tachycardia catheter ablation was performed without clinically documented ventricular tachycardia during electrophysiological study for risk stratification or before pulmonary valve replacement in 37. AF, atrial fibrillation; ASD, atrial septal defect; AVN; atrioventricular node; AVNRT, atrioventricular nodal reentrant tachycardia; AVRT, atrioventricular reentrant tachycardia; AVSD, atrioventricular septal defect; cc, congenitally corrected; FAT, focal atrial tachycardia; IART, intra-atrial reentrant tachycardia; JET, junctional ectopic tachycardia; PVC, premature ventricular contraction; TGA, transposition of the great arteries; VT, ventricular tachycardia

The primary arrhythmia targeted was IART/FAT in 677 (59.6%), AF in 195 (17.2%), PVC/VT in 188 (16.6%), AVRT in 38 (3.3%), AVNRT in 22 (1.9%), AVN in 14 (1.2%), and JET in 1 (0.1%). The primary arrhythmias targeted according to the most distinctive types of CHD are presented in Figure 2. Intra-atrial reentrant tachycardia/FAT was the main

arrhythmia targeted in all CHDs accounting for 50.3% [isolated atrial septal defect (ASD)] to 83.5% [D-transposition of the great arteries (D-TGA)] of procedures. Intra-atrial reentrant tachycardia was the primary arrhythmia targeted in 604 (89.2%) patients and FAT in 73 (10.8%). The primary IART targeted was a cavotricuspid-dependent flutter in 340 (56.3%) patients, a reentrant circuit involving the atriotomy in 111 (18.4%), and another mechanism in 153 (25.3%). Intra-atrial reentrant tachycardia was inducible in 570 (94.4%) patients while an empirical ablation of the most likely critical isthmus was performed in 34 (5.6%) non-inducible patients. Atrial fibrillation catheter ablation was particularly prevalent in patients with isolated ASD (42.6%), congenitally corrected-D-TGA (cc-TGA) (25.5%), and atrio-ventricular septal defect (AVSD) (19.3%). Among patients with PVC/ VT ablation, the primary arrhythmia targeted was a VT in 145 (77.1%) and a PVC in 43 (22.9%). In patients with VT ablation, a VT was inducible in 108 (74.5%) patients while a substrate-only guided ablation was performed in 37 (25.5%) non-inducible patients. Tetralogy of Fallot (TOF) was the CHD in which PVC/VT ablation was the most frequent (36.2%) whereas Ebstein anomaly was the CHD in which AVRT ablation was the most frequent (31.6%). Among TOF patients with VT targeted (n = 95, PVC not considered), 58 (61.1%) patients had a spontaneous clinical VT, whereas VT catheter ablation was performed without clinically documented VT during electrophysiological study for risk stratification or before pulmonary valve replacement in 37 (38.9%).

Catheter ablation procedures

Before the procedure, 167 (14.7%) patients had a transoesophageal echocardiography, 695 (61.2%) had a cardiac computed tomography scan, and 73 (6.4%) had a cardiac magnetic resonance imaging. Catheter ablation was performed under general anaesthesia in 611 (55.0%) patients, local anaesthesia in 376 (33.9%), and conscious sedation in 123 (11.1%). A superior approach (jugular or subclavian) was used in 41 (3.6%) patients, a transhepatic access in 10 (0.9%), and a trans-apical ventricular access in 1 (0.1%). A 3D electroanatomical mapping system was used in 1061 (94.7%) patients whereas a non-electroanatomical mapping approach was used in 59 (5.3%). The energy used was radiofrequency in 1068 (94.9%) patients, cryoablation in 36 (3.2%), and pulsed field ablation in 21 (1.9%). A contact-force catheter was used in 899 (85.9% of all procedures and 90.9% of procedures using radiofrequency). A transseptal/transbaffle/trans-tube puncture was performed in 395 (34.8%) patients (all performed by electrophysiologists), a retrograde aortic approach in 70 (6.2%), and a robotic magnetic navigation system was used in 10 (0.9%). The mean duration of the procedure was 138 ± 64 min, median (IQR) fluoroscopy duration 5.4 (1.3–15.0) min, and median (IQR) fluoroscopy dose 170.0 (10.6–698.0) $\mu\text{Gy}/\text{m}^2$. Main catheter ablation procedures characteristics according to the type of arrhythmia targeted are presented in Table 2.

Table 2 Procedure characteristics according to the main primary arrhythmias targeted

	IART/FAT n = 677	AF n = 195	PVC/VT n = 188	AVRT n = 38	AVNRT n = 22
Anaesthesia, n (%)					
General anaesthesia	348 (52.6)	147 (75.8)	79 (43.4)	26 (68.4)	11 (52.4)
Local anaesthesia	233 (35.2)	30 (15.5)	83 (45.6)	9 (23.7)	8 (38.1)
Conscious sedation ^a	80 (12.1)	17 (8.8)	20 (11.0)	3 (7.9)	2 (9.5)
Imaging before procedure, n (%)					
TOE	105 (15.5)	52 (26.7)	6 (3.2)	4 (10.5)	0 (0.0)
CT scan	409 (60.4)	142 (72.8)	115 (61.2)	11 (28.9)	15 (68.2)
MRI	29 (4.3)	5 (2.6)	37 (19.7)	1 (2.6)	1 (4.6)
Electroanatomical mapping, n (%)					
Non-electroanatomical mapping	15 (2.2)	33 (17.2)	0 (0.0)	3 (7.9)	1 (4.5)
3D mapping system	656 (97.8)	159 (82.8)	184 (100.0)	35 (92.1)	21 (95.5)
Energy, n (%)					
RF	663 (97.9)	151 (77.4)	184 (97.9)	35 (92.1)	21 (95.5)
Cryoablation	3 (0.4)	28 (14.4)	1 (0.5)	1 (2.6)	3 (13.6)
PFA	4 (0.6)	17 (8.7)	0 (0.0)	0 (0.0)	0 (0.0)
Other technical characteristics					
Transseptal puncture, n (%)	209 (30.9)	155 (79.5)	18 (9.6)	7 (18.4)	6 (27.3)
Retrograde aortic approach, n (%)	12 (1.8)	1 (0.5)	51 (27.1)	2 (5.3)	0 (0.0)
Robotic magnetic navigation, n (%)	5 (0.7)	0 (0.0)	5 (2.7)	0 (0.0)	0 (0.0)
Procedure duration, min (SD)	130 (60.1)	146 (60.2)	165 (70.0)	127 (57.5)	150 (71.0)
Fluoroscopy duration, min, median (IQR)	4.5 (1.0–12.0)	15.0 (5.3–24.3)	4.6 (0.5–13.9)	3.4 (0.0–13.0)	6.5 (0.4–10.9)
Fluoroscopy dose, $\mu\text{Gy}/\text{m}^2$, median (IQR)	149 (7–602)	401 (101–1324)	146 (4–877)	23 (0–186)	142 (13–585)

^aConscious sedation was defined as a drug-induced depression of consciousness during which a patient retains control over his protective reflexes with spontaneous ventilation and can respond to command.

AF, atrial fibrillation; AVNRT, atrioventricular nodal reentrant tachycardia; AVRT, atrioventricular reentrant tachycardia; CT, computed tomography; FAT, focal atrial tachycardia; IART, intra-atrial reentrant tachycardia; IQR, interquartile range; MRI, magnetic resonance imaging; PFA, pulsed field ablation; PVC, premature ventricular contraction; RF, radiofrequency; TOE, transesophageal echocardiography; VT, ventricular tachycardia.

Table 3 Acute success rates according to underlying congenital heart disease and to primary arrhythmia targeted

CHD	All	IART/FAT	AF ^a	PVC/VT	AVRT	AVNRT
All patients, n (%)	1071 (94.4)	648 (95.7)	190 (97.4)	163 (86.7)	36 (94.7)	20 (90.9)
TOF, n (%)	281 (93.0)	153 (96.2)	28 (96.6)	97 (88.2)	2 (100.0)	1 (50.0)
Isolated ASD, n (%)	161 (96.4)	82 (96.5)	71 (98.6)	4 (80.0)	2 (66.7)	2 (100.0)
D-TGA, n (%)	126 (91.3)	108 (93.1)	1 (50.0)	10 (83.3)	3 (100.0)	4 (80.0)
AVSD, n (%)	74 (91.4)	55 (93.2)	15 (93.8)	1 (100.0)	2 (100.0)	1 (33.3)
Ebstein anomaly, n (%)	56 (98.2)	31 (96.9)	2 (100.0)	3 (100.0)	18 (100.0)	2 (100.0)
cc-TGA, n (%)	49 (92.5)	29 (93.5)	14 (100.0)	5 (71.4)		1 (100.0)
Univentricular heart, n (%)	46 (90.2)	39 (95.1)	3 (75.0)	1 (50.0)	2 (100.0)	1 (50.0)

^aAF ablation was considered a failure in five patients: one patient with early tamponade and aborted procedure, one patient with failure of left inferior pulmonary vein isolation using cryoballoon ablation, one patient with failure of right pulmonary veins isolation using radiofrequency because of an ASD occluder device, and two patients with persistent atrial fibrillation at the end of the procedure.

AF, atrial fibrillation; ASD, atrial septal defect; AVN: atrioventricular node; AVNRT, atrioventricular nodal reentrant tachycardia; AVRT, atrioventricular reentrant tachycardia; AVSD, atrioventricular septal defect; cc, congenitally corrected; FAT, focal atrial tachycardia; IART, intra-atrial reentrant tachycardia; JET, junctional ectopic tachycardia; PVC, premature ventricular contraction; TGA, transposition of the great arteries; VT, ventricular tachycardia.

Table 4 Complications associated with catheter ablation

Complications, n (%)	43 (3.8)
Vascular complications	9 (0.8)
Femoral pseudoaneurysm	6 (0.5)
Arteriovenous fistula	3 (0.3)
Pericardial effusion	6 (0.5)
Tamponade with drainage	5 (0.4)
Pericardial effusion without drainage required	1 (0.1)
Permanent pacemaker implantation ^a	6 (0.5)
Permanent AV block	4 (0.4)
Permanent sinus node dysfunction	2 (0.2)
Transient heart failure	4 (0.4)
Stroke	2 (0.2)
Transient sinus node dysfunction	2 (0.2)
Phrenic nerve injury	2 (0.2)
Moderate haemoperitoneum (transhepatic access) without drainage	2 (0.2)
Haemothorax	2 (0.2)
Embolization of a broken guidewire recaptured with a lasso	2 (0.2)
Embolization of a part of the venous introducer recaptured with a lasso	2 (0.2)
Death (accidental aortic puncture with tamponade)	1 (0.1)
Transient desaturation related to post-transseptal puncture with right to left shunt	1 (0.1)
Pneumonia	1 (0.1)
Pulmonary atelectasis	1 (0.1)

AV, atrioventricular.

^aPacemaker implantation in six patients after catheter ablation:

- Two patients with ASD and AV block after cavotricuspid-dependent atrial flutter catheter ablation (with septal ablation lines).
- One patient with VSD and AV block after cavotricuspid-dependent atrial flutter catheter ablation (recovery after pacemaker implantation).
- One patient with congenital aortic disease and AV block after VT ablation close to AV conduction pathways (AV block was anticipated).
- One patient with D-TGA and atrial switch with sinus node dysfunction after septal intraatrial reentrant tachycardia catheter ablation.
- One patient with univentricular heart with sinus node dysfunction after extensive catheter ablation of multiple atrial arrhythmias (electrical isolation of sinus node).

Acute per-procedural outcomes

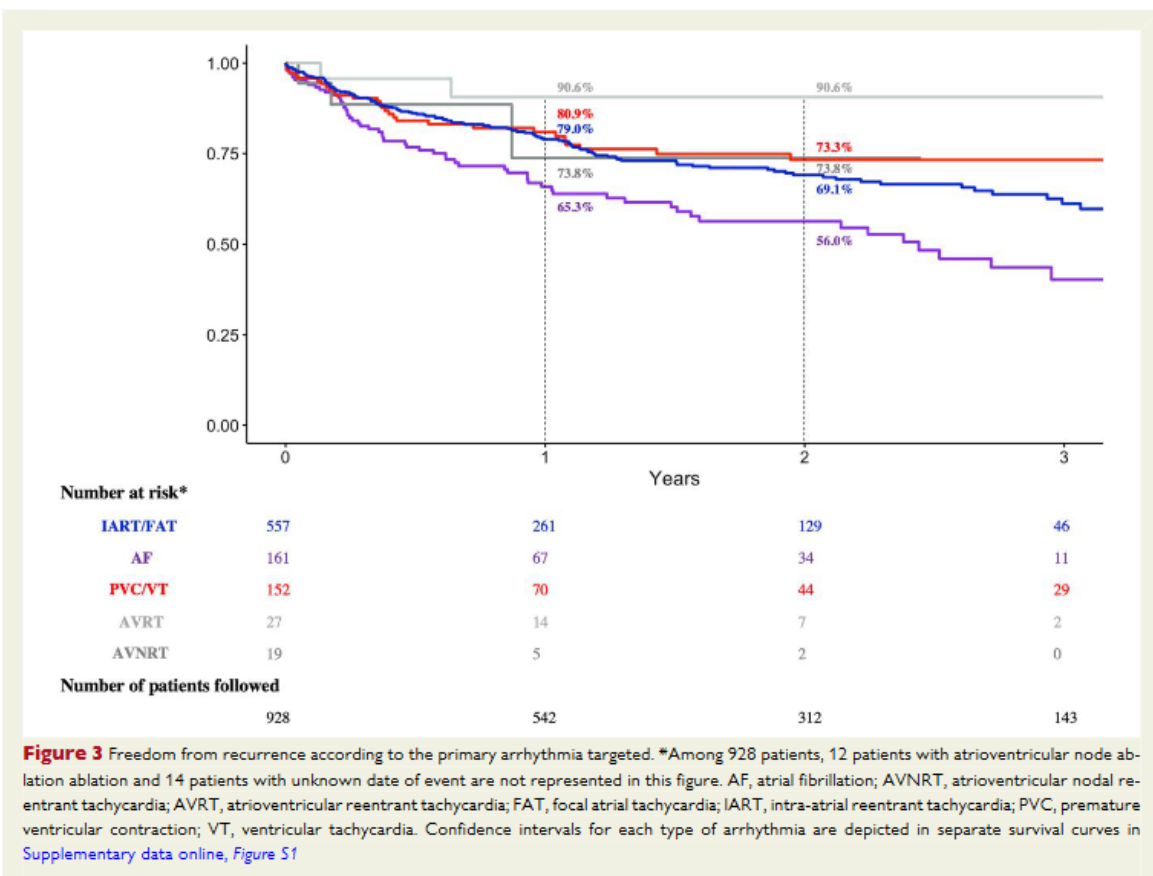
Overall, the clinical arrhythmia was successfully ablated in 1071 (94.4%) procedures. The mean number of arrhythmias targeted by procedure was 1.5 ± 0.7 , with only one arrhythmia targeted in 723 (63.7%), two arrhythmias targeted in 307 (27.0%), three in 80 (7.0%), four in 20 (1.8%), and five in 5 (0.4%). Among whose 1071 procedures with the clinical arrhythmia successfully ablated, 68 (6.3% of patients with acute success and 5.1% of all patients) had a partial success: another non-clinical arrhythmia was inducible in 53 (4.9%) but not targeted and ablation was unsuccessfully attempted for 15 (1.4%) another non-clinical inducible arrhythmias. The acute success rates according to underlying CHD and to the primary arrhythmia targeted are summarized in Table 3. Consistent results were observed in patients with a first catheter ablation procedure (excluding patients with previous catheter ablation, $n = 797$; Supplementary data online, Table S2). The overall acute success rate was $>90\%$ for all types of arrhythmias targeted except for PVC/VT (86.7%). The acute success rate was 96.4% for IART vs 90.4% for FAT ($P = .018$) and 87.6% for VT vs 83.7% for PVC ($P = .512$). The acute success rate was 96.5% in patients with simple CHD, 94.4% in patients with a moderate CHD, and 91.8% in patients with a complex CHD ($P = .095$). In TOF patients with VT catheter ablation, the acute success rate was 87.9% in patients with spontaneous VT vs 86.5%

in patients with VT targeted during electrophysiological study or before pulmonary valve replacement without clinically documented VT (P = .836).

Table 5 Main complications associated with catheter ablation in main congenital heart diseases

Type of complication n (%)	Tetralogy of Fallot (n = 304)	Isolated ASD (n = 169)	D-TGA (n = 139)	Atrioventricular septal defect (n = 83)	cc-TGA (n = 55)	Univentricular hearts (n = 52)
Vascular complications	1 (0.3)	2 (1.2)	3 (2.2)		2 (3.6)	1 (1.9)
Femoral pseudoaneurysm	1 (0.3)	1 (0.6)	2 (1.4)		2 (3.6)	
Arteriovenous fistula		1 (0.6)	1 (0.7)			1 (1.9)
Pericardial effusion		4 (2.4)				
Tamponade with drainage		3 (1.8)				
Pericardial effusion without drainage required		1 (0.6)				
Permanent pacemaker implantation		2 (1.2)	1 (0.7)			1 (1.9)
Permanent AV block		2 (1.2)				
Permanent sinus node dysfunction			1 (0.7)			1 (1.9)
Transient heart failure	1 (0.3)	1 (0.6)				
Stroke			1 (0.7)			
Death				1 (1.2)		

ASD, atrial septal defect; AV, atrioventricular; cc-TGA, congenitally corrected transposition of the great arteries; D-TGA, D-transposition of the great arteries.



An acute complication was reported in 43 (3.8%) procedures. The most frequent complications were vascular complications (n = 9 including 6 pseudo aneurysms and 3 arteriovenous fistula), pericardial effusion (n = 6 including 5 requiring drainage), bradycardia requiring permanent pacemaker implantation (n = 6 including 4 for AV block and 2 for sinus node dysfunction), transient heart failure (n = 4), and stroke (n = 2). One (0.1%) death related to a catheter ablation was reported in a patient with accidental aortic puncture during transseptal access with tamponade and multiple organ failure after urgent cardiac surgery. The detail of all complications is provided in Table 4, and the main complications according to underlying CHD are detailed in Table 5.

Table 6 One-year rate of freedom from recurrence according to underlying congenital heart disease and to primary arrhythmia targeted

CHD, % (95% CI)	All	IART/FAT	AF	PVC/VT	AVRT	AVNRT
All patients	77.4 (74.4–80.6)	79.0 (75.2–83.0)	65.3 (57.5–74.2)	80.9 (74.1–88.4)	90.6 (79.0–100.0)	73.8 (49.7–100.0)
TOF	79.7 (74.2–85.7)	81.5 (74.4–89.3)	49.0 (31.7–75.8)	86.2 (74.4–89.3) ^a	100.0 (100.0–100.0)	
Isolated ASD	71.7 (62.4–82.4)	79.9 (68.2–93.6)	59.7 (45.4–78.5)	100.0 (100.0–100.0)		
D-TGA	77.4 (68.8–87.1)	78.4 (69.4–88.6)		62.5 (32.0–100.0)		75.0 (42.6–100.0)
AVSD	76.0 (64.3–89.7)	72.6 (58.6–90.0)	90.9 (75.4–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)	
Ebstein anomaly	94.3 (86.7–100.0)	93.8 (82.6–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)	90.9 (75.4–100.0)	
cc-TGA	67.2 (53.9–83.8)	75.4 (58.6–97.0)	61.9 (40.4–94.7)	60.0 (29.3–100.0)		
Univentricular heart	82.1 (69.9–96.4)	80.9 (67.0–97.7)	100.0 (100.0–100.0)	50.0 (12.5–100.0)		

^aIn TOF patients with VT catheter ablation, the 1-year freedom from recurrence was 82.3% (95% CI 70.2%–96.4%) in patients with spontaneous VT vs 90.0% (95% CI 77.8%–100.0%) in patients with VT targeted during electrophysiological study or before pulmonary valve replacement without clinically documented VT (P = .08).

AF, atrial fibrillation; ASD, atrial septal defect; AVN, atrioventricular node; AVNRT, atrioventricular nodal reentrant tachycardia; AVRT, atrioventricular reentrant tachycardia; AVSD, atrioventricular septal defect; cc, congenitally corrected; CHD, congenital heart disease; CI, confidence interval; FAT, focal atrial tachycardia; IART, intra-atrial reentrant tachycardia; JET, junctional ectopic tachycardia; PVC, premature ventricular contraction; TGA, transposition of the great arteries; VT, ventricular tachycardia.

Follow-up and recurrences

Overall, a follow-up was available in 988 (87.0%) patients, with a median (IQR) follow-up duration after catheter ablation of 1.4 (0.6–2.4) years. Among these patients, when considering only procedures with acute success (n = 928), a recurrence was reported in 245 (26.4%) patients. The recurrent arrhythmia was the arrhythmia initially targeted in 124 (50.6%) patients, another arrhythmia in 72 (29.4%, same type of arrhythmia but with another circuit/location), and the difference between the arrhythmia initially targeted or another arrhythmia remained uncertain in 49 (20.0%). The overall 1- and 2-year rates of freedom from recurrence were 77.3% [95% confidence interval (CI) 74.2%–80.4%] and 68.4% (95% CI 64.7%–72.3%), respectively. Rates at 1- and 2-year ranged from 65.3% (95% CI 57.5%–74.2%) and 56.0% (95% CI 47.4%–66.2%) for AF to 90.6% (95% CI 79.0%–100.0%) and 90.6% (95% CI 79.0%–100.0%) for AVRT. Kaplan–Meier survival curves for freedom from recurrence according to the primary arrhythmia targeted are presented in Figure 3. Rates of freedom from recurrence according to the most distinctive types of CHD are detailed in Table 6. Corresponding rates for patient with a first catheter ablation procedure were similar (see Supplementary data online, Table S3).

At the end of the follow-up, the proportion of patients receiving antiarrhythmics was lower than before the catheter ablation procedure, with at least one antiarrhythmic in 58.1% vs 77.3% of patients ($P < .001$), beta-blockers in 46.6% vs 59.3% ($P < .001$), amiodarone in 9.0% vs 20.3% ($P < .001$), sotalol in 7.0% vs 8.6% ($P < .001$), and Class I antiarrhythmic in 3.9% vs 6.4% ($P < .001$). Overall, 23 (2.3%) patients died during follow-up, and 8 (0.8%) underwent heart transplant. Causes of death were heart failure in 11, non-cardiovascular in 5, perioperative in 2, and sudden death in 1 (cause unknown in 4).

Healthcare system organization and impact of centre on outcomes

Overall, 1088 (95.9%) procedures were performed in reference ($n = 411$, 36.2%) or competence ($n = 677$, 59.6%) centres. Only 47 (4.1%) procedures were performed in a centre without a specific team specialized in CHD. The proportion of simple, moderate, and complex CHD was 23.4%, 61.7%, and 14.9% in non-specialized centres, 23.2%, 55.4%, and 21.4% in competence centres, and 7.3%, 61.3%, and 31.4% in reference centres, respectively. Corresponding acute success rates were 91.5%, 93.8%, and 94.9% ($P = .485$), whereas complication rates were 4.3%, 4.0%, and 3.6% ($P = .855$). No significant difference was observed according to volume centre.

Discussion

To the best of our knowledge, this study represents the largest prospective investigation on catheter ablation of cardiac arrhythmias in patients with CHD so far. The main findings that emerge from this nationwide cohort are as follows: (i) the spectrum of arrhythmias targeted significantly differs according to the type of CHD, (ii) catheter ablation in CHD patients is associated with highly favourable acute outcomes, (iii) the overall rate of complications reported is low considering the complexity of underlying anatomies, and (iv) the recurrence rates during follow-up vary depending on the targeted arrhythmia and the CHD (Structured Graphical Abstract). Considering the continuous increase in the number of patients in this expanding population, these results are important to consider to inform the benefit/risk assessment.

With more than 1000 catheter ablation procedures enrolled across 28 centres, our first results provide a comprehensive overall picture of the type of arrhythmias targeted and the type of CHD most frequently referred for catheter ablation in the whole CHD population. While patients with TOF, ASD, D-TGA, AVSD, Ebstein anomaly, cc-TGA, or univentricular hearts

were among the most represented patient groups, the pattern of arrhythmias targeted substantially differed according to the underlying substrate. Although IART/FAT remained the main arrhythmia targeted in all CHDs, the proportion of PVC/VT ablation was for example notably higher in patients with TOF (and to a less extent in patients with TGA), AF ablation was significantly more frequent in patients with isolated ASD, cc-TGA, and AVSD, and AVRT ablation accounted for almost a third of all procedures in patients with Ebstein anomaly. These findings mirror specific underlying substrates, whether primarily congenital (accessory pathways in Ebstein anomaly), postoperative (ventricular anatomical isthmuses in repaired TOF), or related to chronic haemodynamic remodelling (intra-cardiac shunt or valve regurgitation/stenosis in patients with ASD, AVSD, or cc-TGA).

The overall acute success rate, among 1135 ablation procedures, was excellent (94.4%) and was comparable when all procedures or only first ablation procedures were considered. The acute success rate was >90% for all types of arrhythmias targeted, except for PVC or VT ablation, for which this rate remained very good (86.7%). Progressive gain in experience in specialized centres and significant improvement of mapping and ablative techniques are key underlying determinants.^{6,7} Almost all procedures were performed using 3D electroanatomical mapping systems and contact-force catheters, and more than 95% of procedures were performed in national reference or competence centres in CHD. While the acute success rate was comparable between non-specialized and specialized centres, the proportion of patients with complex CHD referred for catheter ablation in reference or competence centres was greater. These findings highlight a coherent and rational approach to patient referrals within the national healthcare network.

The burden of complications associated with catheter ablation was low, particularly considering the complexity of underlying anatomies in most complex defects. Despite atypical vascular accesses, such as superior vena cava or transhepatic accesses, as well as transseptal/trans-baffle/trans-tube punctures, a complication was reported in only 3.8% of procedures. However, few patients experienced severe complications, such as pacemaker implantations (0.5%), cardiac tamponades (0.4%), strokes (0.2%), and death (0.1%, one patient). These rare but severe complications are important to keep in mind when discussing the benefit/risk balance of such invasive procedures, would it be during multidisciplinary collegial discussions or for shared decision-making with patients. This low rate of complications is likely explained by the accumulated experience of operators treating these complex patients over the years, the improvement of catheters and mapping technologies, and better analysis and understanding of underlying anatomies as reflected by the high proportion of patients with cross-sectional imaging techniques performed before procedures.

Despite encouraging results, recurrences during follow-up remained relatively common. Recurrence rates notably differed according to the type of arrhythmia targeted and the

underlying substrate. The higher recurrence rate was observed for patient with AF (34.7% at 1 year and 44.0% at 2 years). Considered as the next epidemic in the aging population of adults with CHD,²¹ underlying mechanisms are poorly understood, and specific data on catheter ablation in this specific population remain scarce.^{22–25} Despite its increasing prevalence, the proportion of AF ablation (17.2%) was approximately the same as that of PVC/VT ablation (16.6%). This is likely explained by less referral for catheter ablation given this limited experience, whereas specific substrate to target for VT is now well described in some CHDs.

Further analyses may help better identify the best candidates for AF catheter ablation, while significant effort is still needed to determine the most appropriate phenotype-specific ablation targets. A significant recurrence rate was also reported after AVNRT ablation, likely explained by challenging procedures in most complex anatomies with sometimes displaced or uncertain AV conduction pathways location and careful or conservative ablative approaches to avoid any risk of potential AV injury. Although long-term outcomes were more favourable in patients with IART or FAT, several catheter ablations were sometimes required to achieve a stable sinus rhythm in some patients. This is also evidenced by the fact that around 30% of these patients had already undergone catheter ablation prior to study inclusion. The same initial arrhythmia targeted was involved in significant proportion of cases, but other new arrhythmias were also observed. This highlights that recurrence may result from both non-durable prior ablation lesions but also progressive atrial or ventricular remodelling with development of different potential circuits over time.²⁶ Furthermore, although the recurrence rate remains significant, some data have suggested that the overall burden of arrhythmia-related symptoms was improved after catheter ablation.²⁷ Our results also demonstrated that it allowed for a reduction in antiarrhythmic treatment during follow-up, potentially lowering drug-related side effects, improving daily tolerability and adherence.

We acknowledge several limitations. This study was observational, with inherent biases. The different approaches for catheter ablation were left to the discretion of the operator and managing centre. No central adjudication (blinded analysis of activation maps for conduction block assessment and no uniform final pacing protocol) was performed regarding the primary outcome (acute success). Also, while comparative analyses were carried out according to the type or volume of the different centres, no data were collected on the operator (e.g. experience, training in CHD). However, by incorporating patients from a wide range of centres and healthcare settings, it closely mirrors typical clinical practice. Moreover, patients with CHD are usually managed in specialized centres with regular follow-up. For that reason, the number of missing data was very low, and it also limits the likelihood of non-diagnosed arrhythmia recurrence. Second, the differentiation between the recurrence of the arrhythmia initially targeted and the development of a new arrhythmia may have been inaccurate, as an arrhythmia involving the same critical isthmus can present with a different ECG morphology (also because of ablation lesions performed). For the same reason, ~20% of recurrent arrhythmias could not be classified as either the same or a different arrhythmia. Third, the median duration of follow-up remained relatively modest (1.4 years). The ongoing prospective follow-up of this cohort will bring valuable information to better assess the long-term rate of recurrence of the different types of arrhythmias.

Conclusions

This large nationwide study paints a contemporary overall picture of catheter ablation in patients with CHD. Our results demonstrate that catheter ablation in CHD patients is associated with highly favourable acute outcomes and a low rate of complications. However, heterogeneous and complex underlying substrates are associated with more recurrences during follow-up, with rates differing according to the type of targeted arrhythmia and the type of CHD. These findings are essential to consider to inform the benefit–risk assessment of such procedures in this expanding population

Declarations

Disclosure of Interest

Nothing to declare.

Data Availability

The data, analytic methods, and study materials will be made available to other researchers for purposes of reproducing the results or replicating the procedure upon reasonable request by contacting the corresponding author.

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Ethical Approval

This registry was declared to and authorized by the French data protection committee (Commission Nationale Informatique et Liberté), and the study was approved by the appropriate institutional review boards.

Pre-registered Clinical Trial Number

NCT04202796.

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