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Catheter Ablation of Ventricular Arrhythmias in Patients With Congenital Heart Diseases: A Nationwide Prospective Study

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Keywords:

catheter ablation; congenital heart disease; ventricular arrhythmia; ventricular tachycardia.

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Abstract

Background:

Sudden death and ventricular arrhythmias (VAs) remain a significant concern among patients with congenital heart disease (CHD). Although catheter ablation techniques have improved dramatically over the last decade, current evidence in this specific population is primarily derived from small retrospective studies.

Objectives:

The aim of this study was to describe the burden and characteristics of VAs targeted by catheter ablation in CHDs, as well as associated outcomes and emerging preventive ablative strategies.

Methods:

This prospective nationwide study included all patients with CHD referred for catheter ablation of a VA from 2020 to 2024 in France. The primary outcome was the rate of per-procedural acute success. Secondary outcomes included complications as well as freedom from arrhythmia recurrence.

Results:

Among a total of 1,192 consecutive catheter ablation procedures, 210 (17.6%) VA catheter ablations were performed in 190 patients (mean age 43.8 ± 15.5 years; 63.8% male): ventricular tachycardia (VT) was targeted in 164 (78.1%) procedures and premature ventricular complex in 53 (25.2%) (both VT and premature ventricular complex were targeted in 7). Fourteen (6.7%) patients had a simple CHD, 161 (76.7%) a moderate CHD, and 35 (16.7%) a complex CHD. In patients with tetralogy of Fallot ($n = 126$), catheter ablation was performed without clinically documented VA in 46 (36.5%), mainly before transcatheter or surgical intervention. Overall, the clinical arrhythmia was successfully ablated in 182 (86.7%) patients. An acute complication was reported in 6 (2.9%) procedures, with no related death. The overall 1- and 2-year rates of freedom from recurrence were 81.5% (95% CI: 75.3%-88.4%) and 78.2% (95% CI: 71.2%-85.8%), respectively. The presence of anatomical isthmuses related to prior cardiac surgeries was associated with lower recurrence rates (HR: 0.30; 95% CI: 0.14-0.64; $P < 0.001$).

Conclusions:

VAs represent approximately 20% of catheter ablation procedures performed in patients with CHD. This large cohort provides key insights into the effectiveness of catheter ablation and the main mechanisms of VAs in patients with CHD. The significant differences in outcomes reported depending on underlying substrate are important to consider to inform the benefit/risk assessment.

ABBREVIATIONS AND ACRONYMS

3D = three-dimensional

CHD = congenital heart disease

EPS = electrophysiological study

PVC = premature ventricular complex

ICD = implantable cardioverter-defibrillator

RF = radiofrequency

TOF = tetralogy of Fallot

VA = ventricular arrhythmia

VT = ventricular tachycardia

Advances in pediatric cardiology, particularly in surgical techniques, have led to a continuous increase in the number of patients living with congenital heart disease (CHD).¹ Although life expectancy in this population has improved significantly, it is often offset by late complications, most notably the development of arrhythmias. Abnormal cardiac anatomy, postsurgical scarring, and other systemic factors such as chronic hemodynamic or hypoxic stress predispose these patients to ventricular arrhythmias (VAs), which may occur even decades after surgical repair. Sudden cardiac death remains a leading cause of mortality in this population.- -

In patients with CHD, most VAs present as monomorphic ventricular tachycardias (VTs) involving specific anatomical isthmuses related to previous cardiac surgeries.^{2,3} Because most circuits encountered are relatively reproducible, catheter ablation targeting the main anatomical boundaries has become an appealing therapeutic strategy. In selected cases, catheter ablation may even be considered as an alternative to implantable cardioverter-defibrillator (ICD) therapy, given the substantial burden of long-term ICD-related complications in young patients.^{4,5} However, data on the outcomes of VA catheter ablation in patients with CHD remain limited. Most evidence comes from small retrospective, single-center studies, often spanning long inclusion periods. In addition, the identification of specific electrophysiological features associated with VT in certain CHD subtypes⁶⁻⁸ has paved the way for novel therapeutic strategies, including proactive preventive catheter ablation. This approach is mainly being explored in patients without documented or inducible VA but who exhibit slowly conducting anatomical isthmuses.⁹

Using a large, nationwide prospective registry, the aim of the current study was to characterize the main VAs targeted across different CHD types, assess associated outcomes, and evaluate current practices, including emerging preventive ablation strategies.

METHODS

STUDY POPULATION AND SETTINGS.

This prospective registry was a nationwide French observational study, initiated in January 2020 by the French Institute of Health and Medical Research, and registered under NCT04202796.¹⁰ It includes all patients with CHD referred for catheter ablation. All French centers accredited for catheter ablation were invited to participate, and all types of CHD and patients of all ages were eligible for inclusion. Written informed consent was obtained in all participants. For the purposes of this analysis, we included all patients who underwent catheter ablation for VA between January 1, 2020, and October 31, 2024.-

This registry was declared to and authorized by the French Data Protection Authority (Commission Nationale Informatique et Liberté). The study was approved by the appropriate institutional review boards. Data were centrally collected and managed by using REDCap electronic data capture tools, hosted by the Cardiovascular Epidemiology and Sudden Death Unit (Inserm 970, Paris Cardiovascular Research Center, European Georges Pompidou Hospital).¹¹⁻

COLLECTED DATA.

Baseline patient characteristics were collected before catheter ablation. These included demographic information, medical history, and detailed data of the underlying CHD, including the dates and types of prior cardiac surgeries. CHD complexity was classified as simple, moderate, or complex according to the most recent guidelines from the European Society of Cardiology classification. As previously described, patients were stratified into 2 groups for comparison. Group A included patients with anatomical isthmuses related to prior cardiac surgeries, typically associated with a high likelihood of re-entrant monomorphic VT using predictable isthmuses. Patients with no history of prior ventricular surgery in whom arrhythmias circuits were anticipated to be associated with a more diffuse substrate at a less predictable location were considered in Group B. Patients were classified a priori, according to underlying defect and prior surgical repairs; no cross-sectional imaging, preprocedural substrate analysis, or three-dimensional (3D)-electroanatomical mappings reviewing were considered to make these classifications. Additional data collected included the history of supraventricular and VAs, prior catheter ablation procedures, antiarrhythmic drug use, cardiac imaging parameters, and clinical symptoms. - - - - -

Comprehensive details of the catheter ablation procedures were also recorded. The procedural approach, including anesthesia type, vascular access, catheter types, and energy source, was left to the discretion of each participating center. The targeted arrhythmia was categorized as premature ventricular contraction (PVC), VT, or both. Ablation indications were classified into the following categories: 1) documented VA (patient with clinically confirmed PVC or VT); 2) nondocumented VA with catheter ablation during systematic electrophysiological study (EPS) before transcatheter or surgical intervention (patient without documented VA but with inducible VA or identifiable substrate targeted during EPS); and 3) nondocumented VA with catheter ablation during EPS performed for risk stratification in other contexts (patients undergoing EPS outside the preprocedural setting). - -

Postprocedure, follow-up modalities and decisions regarding antiarrhythmic and anticoagulation therapy were left to the managing physician's discretion. The recommended follow-up protocol included outpatient visits with electrocardiogram, 24-hour Holter recordings, and/or pacemaker/defibrillator check at 3, 6, and 12 months, followed by annual evaluation. Additional appointments were scheduled promptly in response to any symptoms suggestive of arrhythmia. -

OUTCOMES. The primary outcome was the rate of acute procedural success, defined as termination of

The clinical arrhythmia (where applicable) with noninducibility postablation and confirmation of bidirectional conduction block across the targeted critical isthmus (in case of VT or preventive ablation of a slowly conducting anatomical isthmus). Systematic final programmed electrical stimulation and isoprenaline infusion were mandated by the study protocol, although the specific pacing protocol was left to the discretion of the operator. Secondary outcomes included the incidences of complications related to catheter ablation and the rate of arrhythmia recurrence during follow-up. Recurrence was defined as either any episode of sustained VT >30 seconds or reappearance of PVCs with the same morphology (following PVC ablation) with a significant burden (according to operator or local team evaluation). PVCs were considered recurrence only in patients with PVCs as the initial arrhythmia targeted, but VT was considered as recurrence in all patients (with VT or PVC as the initial

arrhythmia targeted). Arrhythmia morphology on electrocardiogram, tachycardia cycle length, and 3D mapping during repeat procedures (when applicable) were analyzed to differentiate between the recurrence of the arrhythmia initially targeted and the development of a new arrhythmia.- - - - -

STATISTICAL ANALYSIS.

This report was prepared in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology checklist for observational studies. 13 Categorical data are presented as counts and percentages. Continuous data are expressed as mean \pm SD or median (Q1-Q3) for normally and non-normally distributed data, respectively. Comparisons between groups were conducted by using the chi-square or Fisher exact test for categorical variables and either the Student's *t*-test or the Mann-Whitney-Wilcoxon test for continuous variables, as appropriate based on distribution.-

For the analysis of arrhythmia recurrence during follow-up, the time-to-event endpoint was defined as the time from catheter ablation to first documented recurrence. Censoring occurred at the time of loss to follow-up, heart transplantation, or death. Survival curves were generated by using the Kaplan-Meier method. Proportional hazards assumptions were checked for all variables (Shoenfeld residuals) with use of appropriate functional forms. Subgroup analyses were performed based on arrhythmia type and according to the main categories of CHDs. Sensitivity analyses were also conducted in patients with a first VA catheter ablation procedure (excluding patients with a history of prior VA catheter ablation) and excluding patients with proactive preventive catheter ablation (without clinical VA).-

A two-tailed P value <0.05 was considered statistically significant. All analyses were conducted by using R version 4.4.2 (R Project for Statistical Computing).-

RESULTS

POPULATION AND TARGETED ARRHYTHMIAS.

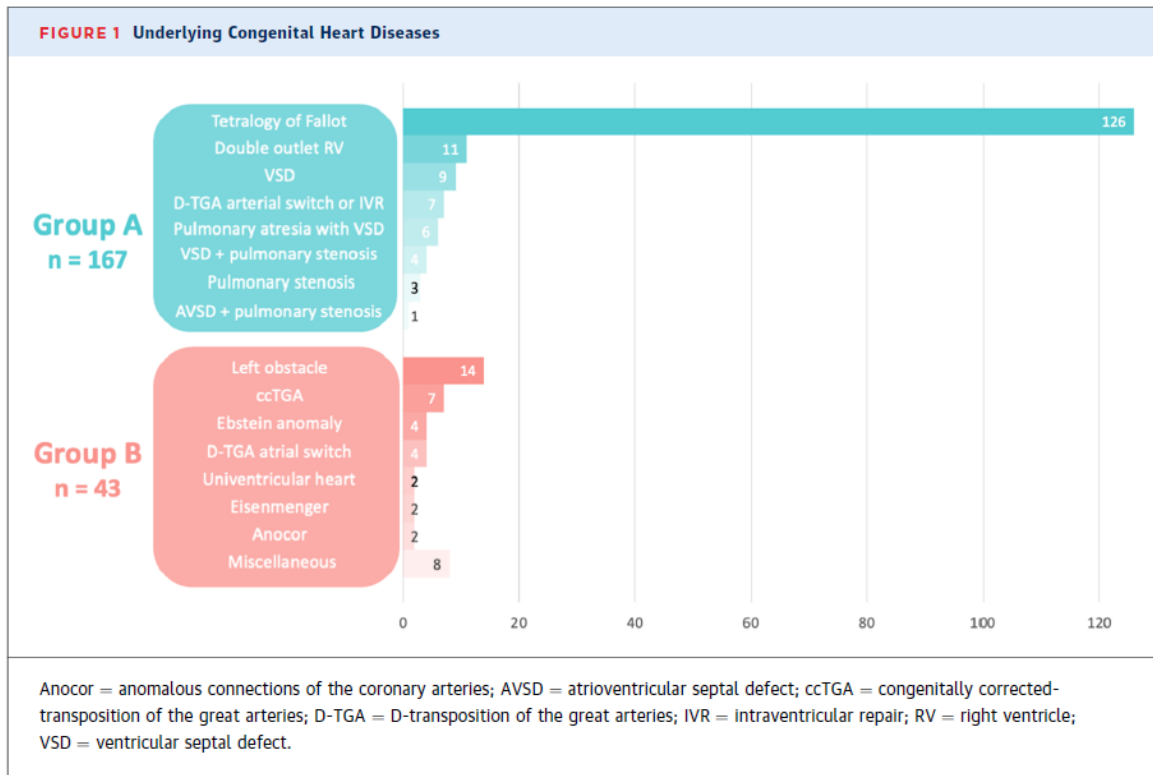
TABLE 1 General Characteristics of Patients at Baseline				
	All Patients (N = 210)	Group A (n = 167)	Group B (n = 43)	P Value
Age at ablation, y	43.8 ± 15.5	44.0 ± 15.3	42.8 ± 16.6	0.648
Male	134 (63.8)	109 (65.3)	25 (58.1)	0.490
No. of cardiac surgeries	2.0 ± 1.2	2.1 ± 1.1	1.6 ± 1.4	0.021
History of IART/FAT	62 (29.5)	53 (31.7)	9 (20.9)	0.231
History of atrial fibrillation	29 (13.8)	23 (13.8)	6 (14.0)	1.000
Cardiovascular risk factors				
Smoking	21 (10.0)	17 (10.2)	4 (9.3)	1.000
Overweight (BMI >25 kg/m ²)	33 (15.7)	21 (12.6)	12 (27.9)	0.026
Coronary heredity	1 (0.5)	1 (0.6)	0 (0.0)	1.000
Coronary artery disease	5 (2.4)	2 (1.2)	3 (7.0)	0.059
Diabetes mellitus	7 (3.3)	7 (4.2)	0 (0.0)	0.349
Dyslipidemia	16 (7.6)	14 (8.4)	2 (4.7)	0.534
Stroke	9 (4.3)	4 (2.4)	5 (11.6)	0.019
Hypertension	25 (11.9)	17 (10.2)	8 (18.6)	0.209
Antiarrhythmics				0.061
Amlodarone	40 (19.0)	27 (16.2)	13 (30.2)	0.061
Beta-blockers	117 (55.7)	82 (49.1)	35 (81.4)	<0.001
Sotalol	15 (7.1)	14 (8.4)	1 (2.3)	0.316
Class I antiarrhythmic	8 (3.8)	4 (2.4)	4 (9.3)	0.057
Heart failure drugs				
Aldosterone antagonists	25 (11.9)	18 (10.8)	7 (16.3)	0.466
Renin-angiotensin acting agents	25 (11.9)	15 (9.0)	10 (23.3)	0.021
Diuretics	36 (17.1)	28 (16.8)	8 (18.6)	0.953
Sacubitril-valsartan	16 (7.6)	7 (4.2)	9 (20.9)	0.001
Anticoagulants				
Vitamin K antagonist	25 (11.9)	15 (9.0)	10 (23.3)	0.021
Direct oral anticoagulant	46 (21.9)	41 (24.6)	5 (11.6)	0.105
NYHA functional classification				0.977
I	64 (43.5)	49 (42.6)	15 (46.9)	
II	59 (40.1)	46 (40.0)	13 (40.6)	
III	22 (15.0)	18 (15.7)	4 (12.5)	
IV	2 (1.4)	2 (1.7)	0 (0.0)	
Systemic ventricular ejection fraction	53 ± 12	54 ± 10	47 ± 15	0.008
Systemic ventricular ejection fraction ≤35%	18 (9.5)	7 (4.7)	11 (26.8)	<0.001
Subpulmonary ventricular ejection fraction				0.013
Preserved	93 (58.9)	63 (52.5)	30 (78.9)	
Moderate dysfunction	50 (31.6)	43 (35.8)	7 (18.4)	
Severe dysfunction	15 (9.5)	14 (11.7)	1 (2.63)	

Values are mean ± SD or n (%).
 BMI – body mass index; FAT – focal atrial tachycardia; IART – Intra-atrial re-entrant tachycardia.

Among a total of 1,192 consecutive catheter ablation procedures in patients with CHD, 210 VA (17.6%) catheter ablations performed in 190 patients (age 43.8 ± 15.5 years, 5.2% children, and 63.8% male) were prospectively included across 20 centers. Overall, 174 (91.6%) patients had only 1 procedure during the study period. VT was targeted in 164 (78.1%) procedures, and PVC was targeted in 53 (25.2%) procedures (both VT and PVC were targeted in 7 procedures). General characteristics of patients are presented in **Table 1**, and underlying CHDs are detailed in **Figure 1**. Overall, 14 (6.7%) had a simple CHD, 161 (76.7%) a moderate CHD, and 35 (16.7%) a complex CHD. A total of 167 (79.5%) patients were classified in Group A and 43 (20.5%) were in Group B.

Catheter ablation was performed after occurrence of spontaneous clinical VA in all CHDs except in some patients with tetralogy of Fallot (TOF). Preventive catheter ablations were performed in 46 (36.5%) of the patients with TOF: systematic EPS before transcatheter or surgical intervention without documented VA in 40 (87.0%) and EPS for risk stratification in

another context in 6 (13.0%). Among patients with TOF, VA was inducible in 67 (83.8%) of 80 patients with clinical VA, 26 (65.0%) of 40 patients with systematic EPS before intervention, and in 5 (83.3%) of 6 patients with EPS for risk stratification in another context.



CATHETER ABLATION PROCEDURES.

Before the procedure, 134 (63.8%) patients had a cardiac computed tomography scan and 39 (18.6%) underwent cardiac magnetic resonance imaging. The catheter ablation was performed with the patient under general anesthesia in 88 (43.3%) procedures, local anesthesia in 91 (44.8%), and conscious sedation in 24 (11.8%). A superior approach (jugular or subclavian) was used in 8 (3.8%) procedures, a transhepatic access in 1 (0.5%), and a transapical ventricular access in 1 (0.5%). --

A 3D-electroanatomical mapping system was used in all procedures, and the energy used was irrigated radiofrequency (RF) in 188 (89.5%) procedures and non-irrigated RF in 19 (9.1%). Among 188 procedures with irrigated RF, at least one VT was targeted in 148 (78.7%), at least one PVC was targeted in 47 (25.0%), and 8 (4.3%) were performed in a pediatric patient. Among 19 procedures with non-irrigated RF, at least one VT was targeted in 13 (68.4%), at least one PVC was targeted in 6 (31.6%), and 3 (15.8%) were performed in a pediatric patient.

A contact-force catheter was used in 185 (91.6%) procedures. A transseptal/transbaffle/transtube puncture was performed in 20 (9.5%) procedures, a retrograde aortic approach in 55 (26.2%), and a robotic magnetic navigation system was used in 5 (2.4%). The mean duration of the procedure was 160 ± 67 minutes, median fluoroscopy duration was 4.0 minutes (0.2-13.0 minutes), and median fluoroscopy dose was $128.0 \mu\text{Gy}/\text{m}^2$ (1.8-585.0 $\mu\text{Gy}/\text{m}^2$).

ACUTE PROCEDURAL OUTCOMES.

Overall, the clinical arrhythmia was successfully ablated in 182 (86.7%) patients (**Figure 2**). The mean number of VAs targeted was 1.3 ± 0.6 by procedure, with only 1 VA targeted in 163 (77.6%), 2 VAs targeted in 38 (18.1%), 3 in 8 (3.8%), and 4 in 1 (0.5%). Among those 182 patients with the clinical arrhythmia successfully ablated, 8 (3.8%) patients had another nonclinical arrhythmia inducible non-targeted and 3 (1.4%) had another nonclinical arrhythmia inducible with catheter ablation failure. The acute success rate was 82.6% in patients with PVC targeted and 87.3% in patients with VT targeted ($P = 0.423$). Consistent results were observed in patients with a first VA catheter ablation procedure (excluding patients with previous VA catheter ablation, $n = 170$) with an overall acute success rate of 86.5% (147 of 170 [82.5%] in patients with PVC targeted and 87.3% in patients with VT targeted). -

According to CHD complexity, the acute success rate was 85.7% in patients with simple CHD, 88.8% in patients with a moderate CHD, and 77.1% in patients with a complex CHD ($P = 0.137$). Corresponding acute success rates were 87.4% in Group A vs 83.7% in Group B ($P = 0.525$). The mechanism and location of VAs targeted and the acute success rates according to main underlying CHD are summarized in Supplemental Table 1. The acute success rate was 87.8% in procedures using irrigated RF vs 78.9% in procedures using non-irrigated RF ($P = 0.284$).

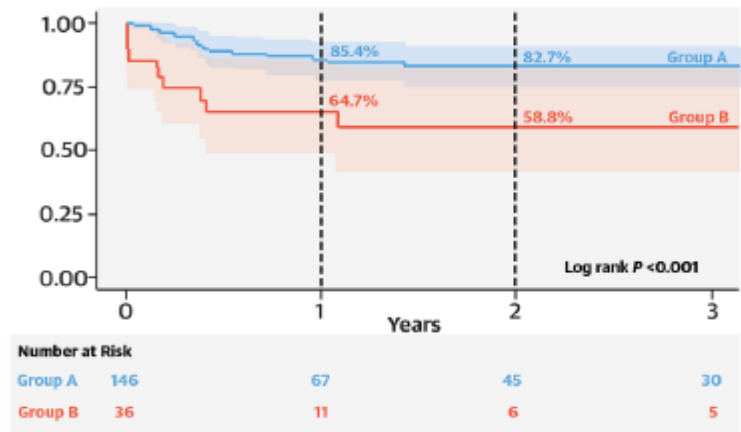
An acute complication was reported in 6 (2.9%) procedures, including 2 femoral pseudoaneurysms, 1 complete atrioventricular block, 1 hemothorax, 1 pulmonary atelectasis, and 1 transient sinus node dysfunction. No death related to catheter ablation procedure was reported. The patient with atrioventricular block had a congenital aortic disease and a VT circuit close to atrioventricular conduction pathways. The very high risk of atrioventricular block was anticipated but accepted because of very frequent VT episodes despite the antiarrhythmic therapy. -

FOLLOW-UP AND RECURRENCES.

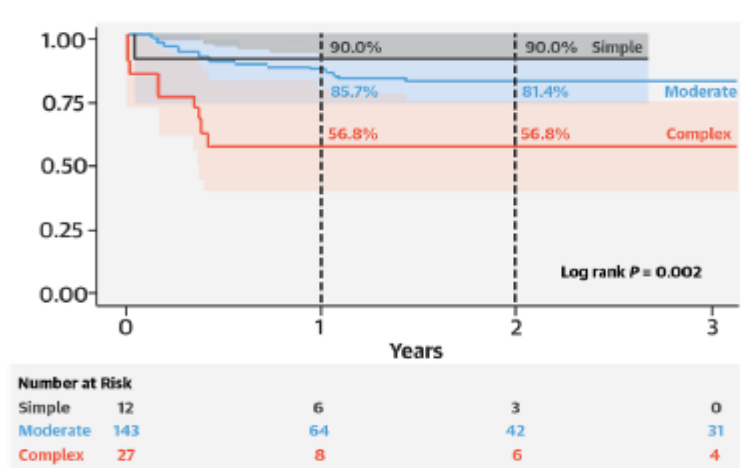
Overall, among 182 patients with acute success and over a median follow-up duration after catheter ablation of 1.2 years (0.4-2.8 years), a recurrence was reported in 34 (18.7%) patients. The recurrent arrhythmia was the arrhythmia initially targeted in 19 (55.9%) patients, another arrhythmia in 5 (14.7%), and the difference between the arrhythmia initially targeted or another arrhythmia remained uncertain in 10 (29.4%). The overall 1 and 2-year rates of freedom from recurrence were 81.5% (95% CI: 75.3%-88.4%) and 78.2% (95% CI: 71.2%-85.8%), respectively. Among 147 patients with a first VA catheter ablation procedure, a recurrence was reported in 24 (16.3%) patients. The overall 1 and 2-year rates of freedom from recurrence in this subgroup were 84.7% (95% CI: 78.1%- 91.8%) and 81.9% (95% CI: 74.6%-89.9%).

The 1 and 2-year rates of freedom from recurrence in Group A vs Group B were 85.4% (95% CI: 78.9%- 92.4%) vs 64.7% (95% CI: 48.5%-86.1%) and 82.7% (95% CI: 75.5%-90.5%) vs 58.8% (95% CI: 41.7%- 82.8%), respectively ($P < 0.001$) (**Central Illustration A**). The risk of recurrence was significantly lower in Group A patients (HR: 0.30; 95% CI: 0.14-0.64; $P < 0.001$). After exclusion of patients with proactive preventive catheter ablation (without clinical VA documented), the risk of recurrence was still significantly lower in Group A (HR: 0.38; 95% CI: 0.18-0.81; $P = 0.009$). The median follow-up duration was 1.3 years (0.4-2.9 years) in Group A vs 0.9 year (0.3-2.3 years) in Group B ($P = 0.470$).

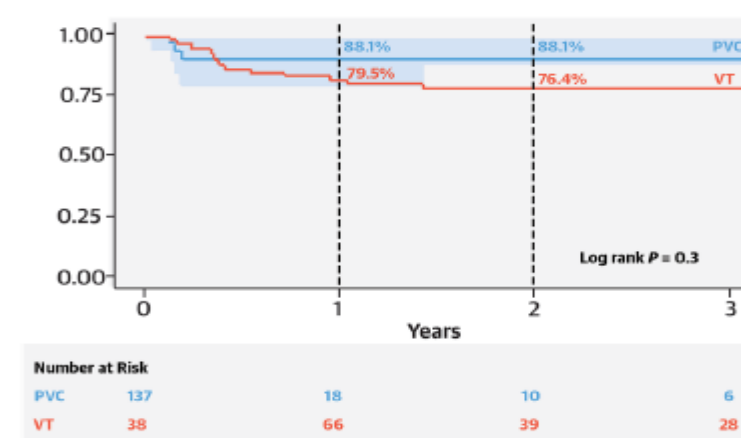
A Group A vs Group B



B CHD Complexity



C VT vs PVC Targeted



Kaplan-Meier survival curves of freedom from recurrence according to group (A), CHD complexity (B), and ventricular arrhythmia targeted (VT vs PVC, [C]). *Patients with both VT and PVC targeted were not considered in C. CHD = congenital heart disease; PVC = premature ventricular complex; VT = ventricular tachycardia.

The 1and 2-year rates of freedom from recurrence in patients with simple vs moderate vs complex CHD were 90.0% (95% CI: 73.2%-100.0%) vs 85.7% (95% CI: 79.1%-92.8%) vs 56.8% (95% CI: 39.6%- 81.5%) and 90.0% (95% CI: 73.2%-100.0%) vs 81.4% (95% CI: 73.8%-89.9%) vs 56.8% (95% CI: 39.6%- 81.5%), respectively ($P = 0.002$) (**Central Illustration B**).

The 1and 2-year rates of freedom from recurrence in patients with VT targeted vs PVC targeted were 79.5% (95% CI: 71.9%-87.9%) vs 88.1% (95% CI: 77.8%-99.8%) and 76.4% (95% CI: 68.0%-85.7%) vs 88.1% (95% CI: 77.8%-99.8%), respectively ($P = 0.30$) (**Central Illustration C**). The median follow-up duration was 1.1 years (0.4-2.9 years) in patients with VT vs 1.4 years (0.4-2.3 years) in patients with PVC ($P = 0.829$).

The 1and 2-year rates of freedom from recurrence in procedures using irrigated RF vs non-irrigated RF were 83.9% (95% CI: 77.7%-90.6%) vs 54.2% (95% CI: 30.2%-97.2%) and 80.3% (95% CI: 73.3%-88.0%) vs 40.6% (95% CI: 18.0%-91.6%), respectively ($P = 0.01$). Results observed in different subgroups of patients with first VA catheter ablation procedure were consistent and are provided in Supplemental Table 2. In patients with TOF, among 110 patients with acute success, a recurrence was reported in 16 (14.5%) patients. The overall 1and 2-year rates of freedom from recurrence were 85.6% (95% CI: 77.9%- 94.0%) and 81.7% (95% CI: 72.9%-91.5%), respectively. The 1and 2-year rates of freedom from recurrence in patients with clinical VA targeted vs patients with systematic EPS before intervention or for risk stratification were 83.1% (95% CI: 73.5%- 93.9%) vs 90.9% (95% CI: 79.6%-100.0%) and 76.9% (95% CI: 65.3%-90.5%) vs 90.9% (95% CI: 79.6%- 100.0%) ($P = 0.20$). The median follow-up duration was 1.2 years (0.4-2.2 years) in TOF patients with clinical VA targeted vs 0.9 (0.3-2.4) in TOF patients with systematic EPS ($P = 0.604$). Overall, 4 TOF patients with systematic EPS who underwent VT ablation developed VT during follow-up. All of them had inducible VT during EPS. Also, 7 TOF patients with systematic EPS without clinical VT had catheter ablation failure. Among these, 1 developed VT during follow-up and subsequently underwent a successful repeat catheter ablation (critical isthmus between the pulmonary annulus and the ventricular septal defect patch with RF applications in the aorta); the other 6 patients were referred for surgical cryoablation during pulmonary valve replacement.

Among 28 patients with acute failure, a recurrence was reported in 16 (57.1%) patients. The recurrent arrhythmia was the arrhythmia initially targeted in 10 (62.5%) patients, another arrhythmia in 2 (12.5%), and the difference between the arrhythmia initially targeted or another arrhythmia remained uncertain in 4 (25.0%). The overall 1and 2-year rates of freedom from recurrence were 40.4% (95% CI: 23.6%- 69.2%) and 23.1% (95% CI: 10.0%-53.3%), respectively. The risk of recurrence was significantly higher in patients with acute failure (HR: 4.22; 95% CI: 2.287.81; $P < 0.001$).

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 61.5% vs 69.2% of patients ($P < 0.001$), beta-blockers in 54.4% vs 57.1% ($P < 0.001$), and amiodarone in 10.4% vs 18.7% ($P < 0.001$). Overall, 4 (1.9%) patients died during follow-up, and 2 (1.0%) underwent heart transplantation. Causes of death were heart failure in 3 and perioperative in 1. No sudden cardiac deaths were reported.

DISCUSSION

To the best of our knowledge, this study represents the largest prospective investigation thus far on catheter ablation of VAs in patients with CHD. The main findings that emerged from this nationwide cohort are: 1) catheter ablation of VAs in patients with CHD is associated with highly favorable acute outcomes; 2) the safety and overall rate of complications reported are low considering the complexity of underlying anatomies; and 3) the mid-term outcomes and recurrence rates during follow-up substantially differ according to the underlying myocardial substrates (complexity of the underlying CHD and/or previous surgical treatments). Our data also offer important insights into the main mechanisms/circuits driving VA in this complex and heterogeneous population. - - - -

In this large unselected population, acute outcomes were excellent, with clinical arrhythmia successfully ablated in >85% of patients. No significant difference was observed when PVC or VT were targeted. Although previous smaller studies reported similar favorable outcomes (acute success rates ranging from 75%-100%), 14-17 the substantial number of patients and exhaustive national collection analyzed in the current cohort provides a comprehensive unbiased description of main mechanisms and circuits of VA in the most distinctive CHDs. Progressive gain in experience managing these complex patients, combined with advancements in 3D-mapping and ablation technologies, are key underlying determinants. 18,19 All procedures were performed by using 3D-electroanatomical mapping systems, with irrigated contact-force catheters used in >90% of cases. The rate of complications associated with catheter ablation was also particularly low (2.9%), especially considering the complexity and heterogeneity of underlying anatomies, and no procedure-related death was reported. For comparison, a large meta-analysis on catheter ablation of VT in patients with structural heart disease recently reported a pooled incidence of 8.2%. 20 Here again, the better understanding of main CHDs associated with accumulated experience over time likely plays an important role. Moreover, only accredited centers specialized in CHD are permitted to perform catheter ablation in patients with CHD in France, which may have contributed to these outcomes. - - - -

During follow-up, heterogeneous results were, however, observed according to underlying substrate. While acute success rates were broadly excellent across all CHDs, recurrence rates significantly differed over time. Freedom from VA recurrence was lowest in patients with most severe CHDs, but beyond CHD complexity, recurrence rates were significantly lower in Group A patients compared with Group B patients (**Central Illustration**). This important finding highlights the excellent and durable efficacy of catheter ablation in most patients with CHD when VA are related to well-defined, discrete postsurgical anatomical isthmuses (Group A, primarily TOF and other conotruncal defects). These patients frequently exhibit well-characterized macro-re-entrant VT circuits, often involving the conus or infundibulum, with the conal septum being a key arrhythmogenic zone. Patients with isolated ventricular septal defect and D-transposition of the great arteries after arterial switch or intraventricular repair also exhibit re-entrant circuits involving isthmuses between surgical patches and conduits. In contrast, when VAs arise from a more diffuse and less predictable substrate (Group B), mid-term outcomes are less favorable. The characteristics of patients in these 2 groups also differed, with those in Group B showing markers of more advanced heart failure and additional comorbidities (eg, lower mean systemic ejection fraction, higher burden of antiarrhythmics and heart failure therapies). This classification, based a priori on previous cardiac surgeries, is relatively simplistic, but although individual specific characteristics are important to consider (eg, preprocedural substrate analysis using cross-sectional imaging and/or image integration through dedicated software), this approach allows comparisons of

outcomes between main patient groups to help inform the benefit-risk balance of these procedures when discussing the different therapeutic options. Furthermore, although catheter ablation may now sometimes be considered as an alternative to ICD implantation when ablation endpoints are perfect, this approach should probably be restricted to carefully selected patients from Group A. - - - -

The findings from this registry also provide insights into the context and indication for VA ablation and the potential emerging role of preventive ablative approaches. In patients with TOF, approximately one-third of all catheter ablations were performed in the absence of documented clinical arrhythmia, with the vast majority before transcatheter or surgical intervention. The rationale behind this approach is that patients with TOF who require pulmonary valve replacement have a constellation of factors that renders them at higher risk for VAs^{9,21} and that the pulmonary prosthesis may cover parts of the infundibular septum and interfere with later attempts to transect the isthmus by ablation. In addition, transmural surgical ablation lines can be performed if a critical isthmus is identified during preoperative mapping by applying both endocardial and epicardial lesions. Different studies have reported a significant proportion of inducible VA or substrate to target in this setting, primarily based on the identification of slowly conducting anatomical isthmuses.^{22,23} However, the impact of such preventive approaches on long-term arrhythmic outcomes remains to be better determined, and it also appears essential to validate current criteria used (conduction velocity <0.5 m/s) in larger cohorts of patients.⁹ Notably, 4 patients without a history of clinical VTs developed VTs during follow-up after catheter ablation. Although all had inducible VT (with no cases of catheter ablation performed solely for a slowly conducting anatomical isthmus without inducible VA), the potential risk of arrhythmogenesis resulting from incomplete or nondurable lesions is also important to consider. In all other CHDs, a clinical VA was documented before catheter ablation, including in patients with Ebstein anomaly, in which systematic EPS is also sometimes performed before tricuspid valve surgery.²⁴ The predominance of accessory pathways or atrial arrhythmias targeted during preoperative EPS in these patients likely explains the absence of VAs in this context in our study.

STUDY LIMITATIONS.

This study was observational, with inherent biases. The different approaches for catheter ablation were left to the discretion of the operator and managing center. 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). However, by incorporating patients from a wide range of centers and health care settings, it closely mirrors typical clinical practice. Moreover, patients with CHD are usually managed in specialized centers with regular followup. 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 electrocardiogram morphology (also because of ablation lesions performed). Hence, approximately 30% of recurrent arrhythmias could not be classified as either the same or a different arrhythmia. Third, data were analyzed from a nationwide registry including all catheter ablations performed in patients with CHD, not restricted to VA. For that reason, data on ICD were not collected at inclusion or during follow-up, and we cannot comment on the proportion of patients who underwent ICD implantation. However, all VA recurrences were considered, not only those associated with appropriate ICD therapies. Nevertheless, a potential risk remains of underestimating some

asymptomatic recurrences, especially in patients who did not receive an ICD (and thus without continuous monitoring). Finally, the median duration of follow-up was relatively modest (1.2 years). The ongoing prospective follow-up of this cohort will bring valuable information to better assess the longterm rate of recurrence of the different types of arrhythmias.-----

CONCLUSIONS

VAs represent approximately 20% of catheter ablation procedures performed in patients with CHD. This study provides key insights into the effectiveness of catheter ablation and the main mechanisms of VAs in patients with CHD. It underscores the predominance of anatomical isthmus-related arrhythmias, particularly in patients with TOF or TOF-like conditions, reinforcing the need for targeted electrophysiological interventions and the potential emerging role of preventive ablative approaches. Contrasting with relatively homogeneous and high acute success rates, the risk of recurrence during follow-up differs significantly, with higher recurrence rates among patients with diffuse fibrosis-related substrates making VA circuits less predictable and leading to less favorable results. This nationwide multicenter study provides valuable data that can help refine clinical practice, guide future research, and ultimately improve patient care and outcomes.---

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.

FUNDING SUPPORT AND AUTHOR DISCLOSURES

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PERSPECTIVES

COMPETENCY IN MEDICAL KNOWLEDGE:

Catheter ablation of VAs accounts for 18% of all procedures in patients with congenital adult heart diseases, with an acute success rate of 86.7%. The 1- and 2-year rates of freedom from recurrence were 81.5% and 78.2%, respectively, and the presence of anatomical isthmuses related to prior cardiac surgeries is associated with a lower risk of recurrence.

TRANSLATIONAL OUTLOOK: The significant differences in outcomes reported after VA catheter ablation depending on underlying substrate are important to consider to inform the benefit/risk assessment.

Conflict of interest statement

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