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CLINICAL RESEARCH

Catheter ablation in adults with congenital heart disease: A 15-year perspective from a tertiary centre

Ablation par cathéter dans les cardiopathies congénitales adultes: une perspective à 15 ans d'un centre expert

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KEYWORDS
Adult congenital heart disease;
Catheter ablation;
Outcomes;
Trends

Summary
Background. — With the growing adult congenital heart disease (ACHD) population, the number of catheter ablation procedures is expected to dramatically increase. Data reporting experience and evolution of catheter ablation in patients with ACHD, over a significant period of time, remain scarce.

Abbreviations: 3D, three-dimensional; ACHD, adult congenital heart disease; AF, atrial fibrillation; AVN, atrioventricular node; AVNRT, atrioventricular nodal reentrant tachycardia; AVRT, atrioventricular reentrant tachycardia; CHD, congenital heart disease; CI, confidence interval; CTI, cavotricuspid isthmus; FAT, focal atrial tachycardia; IART, intra-atrial reentrant tachycardia; JET, junctional ectopic tachycardia; OR, odds ratio; PVC, premature ventricular contraction; VT, ventricular tachycardia.

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Aim. — We aimed to describe temporal trends in volume and outcomes of catheter ablation in patients with ACHD.
Methods. — This was a retrospective observational study including all consecutive patients with ACHD undergoing attempted catheter ablation in a large tertiary referral centre over a 15-year period. Acute procedural success rate and freedom from recurrence at 12 and 24 months were analysed.
Results. — From November 2004 to November 2019, 302 catheter ablations were performed in 221 patients with ACHD (mean age 43.6 ± 15.0 years; 58.9% male sex). The annual number of catheter ablations increased progressively from four to 60 cases per year (P < 0.001). Intra-atrial reentrant tachycardia/focal atrial tachycardia was the most common arrhythmia (n = 217, 71.9%). Over the study period, acute procedural success rate increased from 45.0% to 93.4% (P < 0.001). Use of irrigated catheters (odds ratio [OR] 4.03, 95% confidence interval [CI] 1.86—8.55), a three-dimensional mapping system (OR 3.70, 95% CI 1.72—7.74), contact force catheters (OR 3.60, 95% CI 1.81—7.38) and high-density mapping (OR 3.69, 95% CI 1.82—8.14) were associated with acute procedural success. The rate of freedom from any recurrence at 12 months increased from 29.4% to 66.2% (P = 0.001). Seven (2.3%) non-fatal complications occurred.
Conclusions. — The number of catheter ablation procedures in patients with ACHD has increased considerably over the past 15 years. Growing experience and advances in ablative technologies appear to be associated with a significant improvement in acute and mid-term outcomes.

MOTS CLÉS
Cardiopathies congénitales adultes ;
Ablation par cathéter ;
Résultats ;
Tendances

Résumé
Contexte. — Devant l'augmentation de la population d'adultes avec une cardiopathie congénitale (ACHD), une augmentation importante du nombre d'ablations par cathéter est attendue. Les données sur l'évolution des procédures d'ablation chez les ACHD, sur une large période de temps, sont rares.
Objectif. — L'objectif de cette étude était de décrire les tendances temporelles en volume et résultats des ablations par cathéters dans les ACHD.
Méthodes. — Étude rétrospective observationnelle incluant tous les patients ACHD consécutifs avec tentative d'ablation par cathéter dans un centre tertiaire pendant une période de 15 ans. Les taux de succès aigus et la survie sans récidive à 12 et 24 mois étaient analysés.
Résultats. — De novembre 2004 à novembre 2019, 302 ablations par cathéter ont été réalisées chez 221 patients ACHD (43,6 ± 15,0 ans; 58,9 % d'hommes). Le nombre annuel d'ablations a augmenté progressivement de 4 à 60 cas par an (p < 0,001). Les arythmies atriales organisées (réentrantes ou focales) étaient l'arythmie la plus fréquente (n = 217; 71,9 %). Au cours de l'étude, le taux de succès aigu augmentait de 45,0 % à 93,4 % (p < 0,001). L'utilisation de cathéters irrigués (OR 4,03, IC95 % 1,86—8,55), de système de mapping 3D (OR 3,70, IC95 % 1,72—7,74), de cathéters contact (OR 3,60, IC95 % 1,81—7,38) et de mapping haute densité (OR 3,69, IC95 % 1,82—8,14) étaient associés avec le succès aigu. Le taux de survie sans récidive à 12 mois augmentait de 29,4 % à 66,2 % (p = 0,001). Sept (2,3 %) complications non-fatales étaient survenues.
Conclusions. — Le nombre d'ablations par cathéter chez les patients ACHD a considérablement augmenté au cours des 15 dernières années. L'expérience accumulée et les progrès dans les techniques ablatives sont associés avec une amélioration significative des résultats à court et moyen termes.

Background

Advances in paediatric cardiology, especially surgical techniques, have resulted in an increasing number of patients with congenital heart disease (CHD) reaching adulthood, creating a new and steadily growing population of adults with congenital heart disease (ACHD), estimated at over 1.5 million patients in the USA alone [1].

The major improvement in life expectancy in this population is, however, tempered to some extent by late complications, especially the occurrence of atrial or ventricular cardiac arrhythmias [2,3]. Abnormal anatomy, postsurgical scarring and other systemic factors contribute to establishing a unique substrate for cardiac arrhythmia development [4]. Projections indicate that 50% of 20-year-old ACHD subjects will experience at least one atrial tachyarrhythmia during their lifespan [5], and sudden cardiac death remains an important mode of death in this specific population [6].

The experience with antiarrhythmic pharmacological therapy in ACHD has been disappointing, because of limited efficacy as well as potential mid- and long-term adverse effects in these relatively young patients [7—9]. Consequently, and with the growing and aging ACHD population, the number of catheter ablation procedures is expected to increase dramatically. Furthermore, the advent of catheter ablation and recent developments in ablative and mapping technologies may be associated with a significant improvement in outcomes [10—14]. However, data reporting experience and evolution of catheter ablation in patients with ACHD, over a significant period of time, remain scarce.

In the present paper, we aimed to describe temporal trends in volume and outcomes of catheter ablation procedures in patients with ACHD in a large tertiary centre.

Methods

Study design and data collection

This was a retrospective observational study including all consecutive patients with ACHD undergoing attempted catheter ablation at the Georges Pompidou European Hospital, Paris, France, between 1 November 2004 and 1 November 2019. Since 2001, the Georges Pompidou European Hospital has been a French national referral centre for ACHD, and includes a multidisciplinary team of cardiologists, interventional cardiologists, surgeons, imaging specialists, anaesthesiologists and electrophysiologists specifically trained in ACHD. All patients had recurrent symptomatic arrhythmias documented by electrocardiography. Written informed consent was obtained from all patients before catheter ablation. The study complies with the Declaration of Helsinki, and was approved by the local institutional review board.

All ACHD data are centralized on a computer software that allows exhaustive data gathering, including clinical information, medical examination findings, and follow-up with hospitalization and outpatient clinic reports. For each patient, baseline information included demographic characteristics, type of CHD, dates and types of previous cardiac surgeries, comorbidities, history of supraventricular and ventricular arrhythmias, pharmacological therapy, previous catheter ablation and cardiac imaging (echocardiography with or without cardiac magnetic resonance imaging or cardiac computed tomography). 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 reentrant tachycardia (AVNRT); junctional ectopic tachycardia (JET); atrioventricular node ablation (AVN); premature ventricular contraction (PVC); and ventricular tachycardia (VT). CHDs were classified as simple, moderate or complex according to the most recent European Society of Cardiology classification [15].

Catheter ablation procedure

Preprocedural transoesophageal echocardiography and/or cardiac computed tomography were performed systematically to rule out thrombus before catheter ablations of IART/FAT, AF, PVC and VT. Antiarrhythmic medication was in most cases discontinued for at least five half-lives before the procedure. Catheter ablation was performed under local anaesthesia, deep sedation or general anaesthesia, depending on case complexity and physician preference. Electroanatomical mapping with the CARTO® system (Biosense Webster, Irvine, CA, USA) was used in the majority of patients ($n = 218$). Conventional fluoroscopic guidance ($n = 41$) or electroanatomic mapping with the RHYTHMIA™ system ($n = 6$; Boston Scientific, Marlborough, MA, USA), which has been available in our hospital since February 2019, was used in other patients. Conventional fluoroscopic guidance was only used in some cases of typical atrial flutter, AVNRT, AVRT, pulmonary vein isolation with cryoablation or AVN ablation. A reference catheter was introduced into the coronary sinus when possible, or placed on the right atrium lateral wall, left atrial appendage (patients with atrial switch surgery) or left pulmonary artery (patients with lateral tunnel or extracardiac conduit Fontan). In patients in sinus rhythm at the beginning of the procedure, arrhythmia was induced by programmed atrial or ventricular stimulation or burst pacing. Isoproterenol infusion was administrated if necessary. Mechanisms and circuits of targeted arrhythmias were confirmed by activation mapping and entrainment manoeuvres. Ablations were performed with a variety of catheters, but we systematically collected the information on whether an irrigated and/or contact-force catheter was used or not. An irrigated catheter was used in the majority of procedures, except 44 (20 IART, 16 AVNRT, three pulmonary vein isolation with cryoablation, two AVRT, two AVN and one PVC ablation). Use of high-density mapping with PENTARAY® (Biosense Webster, Irvine, CA, USA) or ORION™ (Boston Scientific, Marlborough, MA, USA) catheters was also analysed. Final programmed atrial or ventricular stimulation performance was left to the discretion of the referent physician, and involved burst pacing and single to triple extrastimuli in at least two sites (high right atrium and coronary sinus in the atria, apex and right infundibulum in the ventricle) down to effective refractory period or 200 ms.

Follow-up

After the procedure, patients were monitored for at least 24 hours in the hospital. Twelve-lead electrocardiography and echocardiography were performed systematically before discharge. Oral anticoagulation, if started before ablation, was continued for at least 3 months after ablation. Based on current guidelines, long-term anticoagulation was continued in patients with moderate or complex CHD, whereas the CHA_2DS_2-VASc (cardiac failure, hypertension, Age ≥ 75 [Doubled], diabetes, stroke [Doubled] — Vascular disease, Age 65—74 and Sex category [Female]) score was used in simple CHD to guide the decision. However, anticoagulation could be withdrawn in patients free from recurrence and in the absence of other indication, or according to the relative risks of stroke and haemorrhagic complications, on a case-by-case basis [7,8]. The choice to pursue antiarrhythmic therapy after the procedure was at the physician's discretion. Patients were followed routinely at outpatient visits with electrocardiogram and 24-hour Holter recordings and/or pacemaker/defibrillator check at 3, 6 and 12 months, and then on an annual basis. Medical appointments were scheduled promptly in case of any symptoms suggestive of arrhythmia. For patients with recurrent symptoms not captured by electrocardiogram, 24-hour Holter recordings or implantable loop event recorder was offered. Recurrence was defined as any episode of documented arrhythmia lasting more than 30 seconds (except for PVC, where recording of PVCs with the same morphology was considered as a relapse).

Outcomes

Partial acute procedural success was defined as termination of clinical arrhythmia with subsequent verification of bidirectional conduction block across the critical isthmus/radiofrequency lesion line with additional arrhythmias induced not targeted or not successfully targeted or in the absence of final programmed stimulation performance.

Complete acute procedural success was defined as termination of clinical arrhythmia(s) with subsequent verification of bidirectional conduction block and non-inducibility of other arrhythmias or successful ablation of all secondary arrhythmias induced (except inducible AF). Final programmed stimulation performance was not required to consider complete acute procedural success when the targeted arrhythmia was AF, PVC or AVN.

Regarding patients managed before November 2018, we also analysed freedom from recurrence at 12 and 24 months, considering both targeted arrhythmia or any other arrhythmias.

Statistical analysis

Continuous data are presented as means ± standard deviations or medians (interquartile ranges). Categorical data are reported as numbers and percentages. We checked the linearity of quantitative variables using fractional polynomial regression. In the absence of linearity, continuous variables were dichotomized according to their median. Comparisons used the χ^2 test or Fisher's exact test for categorical variables, and Student's *t* test or the Mann-Whitney-Wilcoxon test, when appropriate, for continuous variables. Logistic regression models were used to identify factors associated with acute procedural success (complete and partial success). For analysis of temporal trends, we decided to arbitrarily divide this 15-year study into five periods of 3 years, beginning in November of each year. Linear time trends were tested with the use of logistic regression for binary variables and linear regression for continuous variables. Missing data were no more than 1%, except for systemic ventricular ejection fraction (5.0%), contact force (8.7%), type of catheter used (5.0%) and previous palliative shunt (9.7%). A two-tailed *P* value < 0.05 was considered statistically significant. Statistical analysis was performed using R software, version 3.6.3 (R Foundation for Statistical Computing, Vienna, Austria).

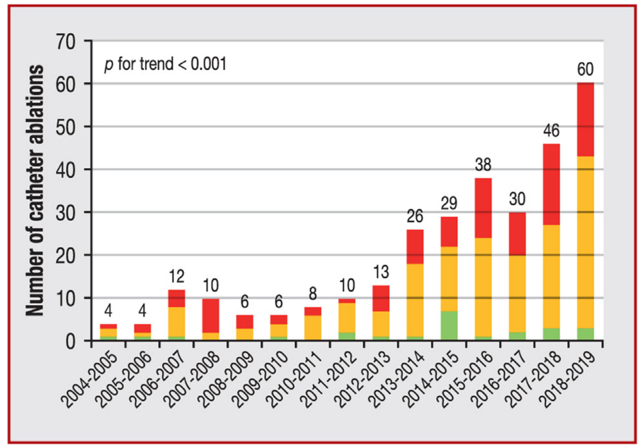

Figure 1. Annual number of catheter ablations in adults with congenital heart disease (ACHD). Ablations in simple CHD are represented in green, ablations in moderate CHD in orange and ablations in complex CHD in red.

Results

Study population

Over the study period, a total of 302 catheter ablations were performed in 221 patients with ACHD (mean age 43.6 ± 15.0 years; 58.9% male sex). The patients' general characteristics are presented in Table 1. Patients with moderate and complex CHD were younger than those with simple CHD (45.5 ± 15.4 and 38.2 ± 10.7 vs. 53.6 ± 19.0 years, respectively; $P < 0.001$), were more frequently male (54.0% and 70.2% vs. 45.8%; $P = 0.012$), had a higher number of cardiac surgeries (1.6 ± 0.9 and 1.8 ± 1.2 vs. 0.8 ± 0.5; $P < 0.001$), a lower mean systemic ventricular ejection fraction (54 ± 10% and 47 ± 13% vs. 55 ± 12%; $P < 0.001$) and more frequently had a history of hospitalization for heart failure (23.0% and 45.2% vs. 4.2%; $P < 0.001$). Moderate and complex CHD compared with simple CHD were also associated with a greater use of amiodarone (23.0% and 39.4% vs. 16.7%, respectively; $P = 0.006$) and number of antiarrhythmic agents tested (1.5 ± 0.9 and 2.0 ± 1.1 vs. 1.4 ± 0.8; $P = 0.001$). A total of 99 (32.8%) procedures were performed in patients with at least one previous catheter ablation.

The annual number of catheter ablations increased progressively from four to 60 cases per year (*P* for trend < 0.001, Fig. 1). Most of the catheter ablation procedures were performed in patients with moderate CHD ($n = 174$, 57.6%) or complex CHD ($n = 104$, 34.4%); only a minority were performed in patients with simple CHD ($n = 24$, 7.9%). The distribution of CHD severity was stable over the study (*P* for trend = 0.301) (Fig. 1). Tetralogy of Fallot ($n = 75$), D-transposition of the great arteries ($n = 31$), atrial septal defect ($n = 24$), atrioventricular septal defect ($n = 22$),

Table 1 General characteristics of patients according to congenital heart disease complexity.

	All ablations	Simple CHD	Moderate CHD	Complex CHD	*P*
	(*n* = 302)	(*n* = 24)	(*n* = 174)	(*n* = 104)	
Age (years)	43.6 ± 15.0	53.6 ± 19.0	45.5 ± 15.4	38.2 ± 10.7	< 0.001
Male sex	178 (58.9)	11 (45.8)	94 (54.0)	73 (70.2)	0.012
Number of cardiac surgeries	1.6 ± 1.0	0.8 ± 0.5	1.6 ± 0.9	1.8 ± 1.2	< 0.001
Previous palliative shunt	81 (29.7)	0 (0.0)	30 (19.6)	51 (53.1)	< 0.001
Systemic ventricular ejection fraction (%)	52 ± 12	55 ± 12	54 ± 10	47 ± 13	< 0.001
Previous hospitalization for heart failure	88 (29.1)	1 (4.2)	40 (23.0)	47 (45.2)	< 0.001
Pacemaker	50 (16.6)	2 (8.3)	28 (16.1)	20 (19.2)	0.47
Implantable cardioverter defibrillator	14 (4.6)	0 (0.0)	13 (7.5)	1 (1.0)	0.025
Targeted arrhythmia					
IART/FAT	217 (71.9)	15 (62.5)	126 (72.4)	76 (73.1)	0.57
AF	27 (8.9)	2 (8.3)	16 (9.2)	9 (8.7)	0.98
AVNRT	21 (7.0)	2 (8.3)	6 (3.5)	13 (12.5)	0.016
AVRT	9 (3.0)	2 (8.3)	7 (4.0)	0 (0.0)	0.017
VT/PVC	21 (7.0)	2 (8.3)	16 (9.2)	3 (2.9)	0.09
Other	7 (2.3)	1 (4.2)	3 (1.7)	3 (2.9)	0.48
Time from targeted arrhythmia diagnosis to procedure (months)	36.2 ± 74.2	39.5 ± 76.8	35.0 ± 74.0	37.4 ± 74.7	0.94
Previous catheter ablation	99 (32.8)	5 (20.8)	61 (35.1)	33 (31.7)	0.37
Cardiovascular risk factors					
Hypertension	33 (10.8)	3 (12.5)	24 (13.8)	6 (5.8)	0.10
Dyslipidaemia	34 (11.3)	2 (8.3)	24 (13.8)	8 (7.7)	0.32
Diabetes mellitus	7 (2.3)	1 (4.2)	5 (2.9)	1 (1.0)	0.30
Obesity (BMI > $30/m^2$)	44 (14.6)	0 (0)	35 (20.1)	9 (8.7)	0.002
Current smoking status	37 (12.3)	4 (16.7)	19 (10.9)	14 (13.5)	0.58
Coronary artery disease	5 (1.7)	3 (12.5)	0 (0.0)	2 (1.9)	0.001
Stroke	12 (4.0)	0 (0)	4 (2.3)	8 (7.7)	0.08
Medication use					
Beta-blocker	182 (60.3)	14 (58.3)	103 (59.2)	65 (62.5)	0.85
Amiodarone	85 (28.1)	4 (16.7)	40 (23.0)	41 (39.4)	0.006
Other antiarrhythmic drugs	61 (20.2)	6 (25.0)	33 (19.0)	22 (21.2)	0.74
ACE inhibitor or ARB	71 (23.5)	3 (12.5)	35 (20.1)	33 (31.7)	0.036
Diuretic	76 (25.2)	3 (12.5)	37 (21.3)	36 (34.6)	0.015
VKA	135 (44.7)	6 (25.0)	72 (42.0)	56 (53.8)	0.020
NOAC	38 (12.6)	13 (54.2)	49 (28.2)	23 (22.1)	0.007
Antithrombotic	85 (28.1)	2 (8.3)	23 (13.2)	13 (12.5)	0.89
Number of antiarrhythmic agents tested	1.7 ± 1.0	1.4 ± 0.8	1.5 ± 0.9	2.0 ± 1.1	0.001

Data are expressed as mean ± standard deviation or number (%). ACE: angiotensin-converting enzyme; AF: atrial fibrillation; ARB: angiotensin receptor antagonist; AVNRT: atrioventricular nodal reentrant tachycardia; AVRT: atrioventricular reentrant tachycardia; BMI: body mass index; CHD: congenital heart disease; FAT: focal atrial tachycardia; IART: intra-atrial reentrant tachycardia; NOAC: non-vitamin K antagonist oral anticoagulant; PVC: premature ventricular contraction; VKA: vitamin K antagonist; VT: ventricular tachycardia.

congenitally corrected transposition of the great arteries (*n* = 20), Fontan circulation (*n* = 19) and Ebstein anomaly (*n* = 18) were the most frequent underlying CHDs.

IART/FAT were the most common targeted arrhythmias (*n* = 217, 71.9%; 182 IART, 35 FAT), including 105 (48.4%) patients with only cavotricuspid isthmus (CTI)-dependent IART, 74 (34.1%) patients with only non-CTI-dependent IART/FAT and 30 (13.8%) patients with both CTI-dependent and non-CTI-dependent IART/FAT (uncertain circuit in eight patients). AF (*n* = 27, 8.9%), VT or PVC (*n* = 21, 7.0%), AVNRT (*n* = 21, 7.0%), AVRT (*n* = 9, 3.0%), JET (*n* = 4, 1.3%) and AVN (*n* = 3, 1.0%) were less prevalent. The mean number of targeted arrhythmias by procedure was 1.4 ± 0.8. The detail of targeted arrhythmias by CHD is provided in Fig. 2.

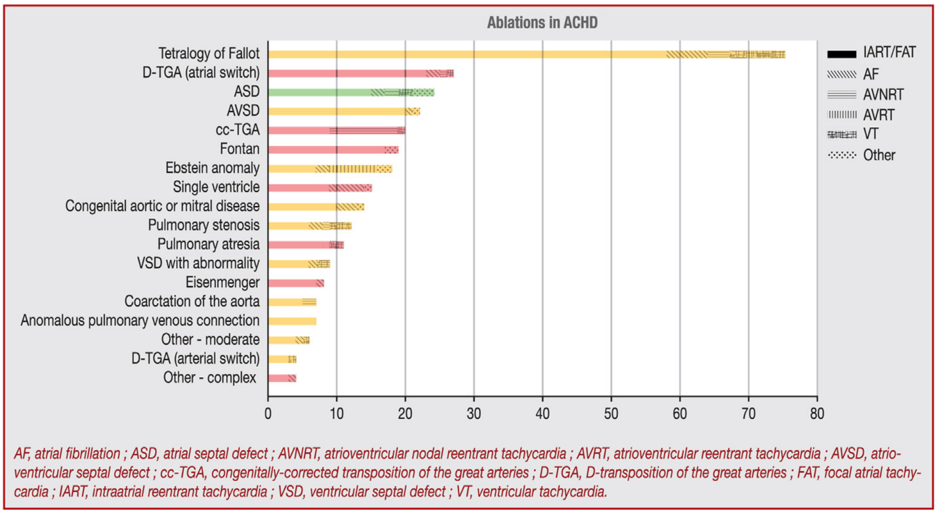

Figure 2. Number of catheter ablation procedures and targeted arrhythmias in different congenital heart diseases (CHDs). Ablations in simple CHD are represented in green, ablations in moderate CHD in orange and ablations in complex CHD in red. AF: atrial fibrillation; ASD: atrial septal defect; AVNRT: atrioventricular nodal reentrant tachycardia; AVRT: atrioventricular reentrant tachycardia; AVSD: atrioventricular septal defect; cc-TGA: congenitally corrected transposition of the great arteries; D-TGA: D-transposition of the great arteries; FAT: focal atrial tachycardia; IART: intra-atrial reentrant tachycardia; VSD: ventricular septal defect; VT: ventricular tachycardia.

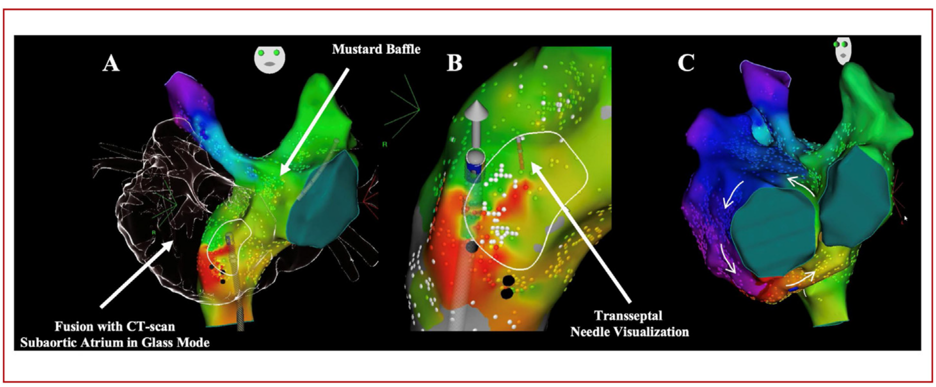

Figure 3. Example of a transbaffle puncture guided by three-dimensional (3D) anatomical mapping in a patient with atrial switch operation. A. 3D anatomical reconstruction of the pulmonary venous atrium and fusion with the computed tomography (CT) scan. B. The optimal site for transbaffle puncture is located and the transseptal needle is advanced and localized by the CARTO® system. C. The final activation mapping identifies an atrial flutter around the tricuspid annulus.

A transseptal/transtube/transbaffle puncture was performed in 69 (22.8%) procedures, including seven (10.1%) that required dilatation with an angioplasty balloon to introduce the sheath into the subaortic atrium. Perprocedural transoesophageal echocardiography was used in four (5.8%) patients, and others were guided by electroanatomical mapping and/or fluoroscopy (Fig. 3). A retrograde aortic approach was used in 22 (7.3%) procedures. A superior jugular access was performed in 13 (4.3%) procedures and a transhepatic puncture in one (0.3%) procedure. The use of irrigated catheters (from 30.0% to 94.8%; P for trend < 0.001), three-dimensional (3D) mapping systems (from 60.0% to 96.3%; P for trend < 0.001), contact force catheters (from 0.0% to 91.9%; P for trend < 0.001) and high-density mapping (from 0.0% to 71.9%; P for trend < 0.01) increased significantly during the study period (Fig. 4).

Acute procedural success

Acute procedural success rates were 87.5% in simple CHD, 87.1% in moderate CHD and 78.7% in complex CHD (P = 0.038 between moderate and complex CHD). Complete acute success rates were 41.7% in simple CHD, 49.4% in moderate CHD and 50.0% in complex CHD (P = not significant). Acute procedural success rates were 87.6% in IART/FAT (86.8% in IART vs. 91.4% in FAT; P = 0.63), 88.9% in AF, 84.2% in VT/PVC, 66.7% in AVRT and 61.9% in AVNRT.

Over this 15-year study period, acute procedural success increased from 45.0% to 93.4% (P for trend < 0.001), including complete acute procedural success from 10.0% to 66.2% (P for trend < 0.001) (Central illustration). During the same time, the performance of final programmed stimulation after ablation of the clinical arrhythmia increased

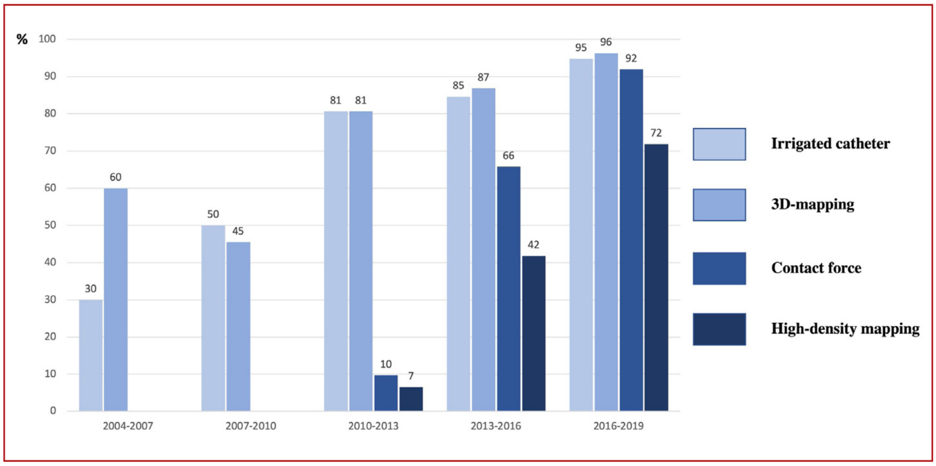

Figure 4. Evolution of use of ablative technologies. High-density mapping refers to mapping with PENTARAY® (Biosense Webster, Irvine, CA, USA) or ORION™ (Boston Scientific, Marlborough, MA, USA) catheters. 3D: three-dimensional.

from 20.0% (2004—2007) to 69.2% during the last 3 years (2017—2019) (*P* for trend < 0.001), reaching 81.4% in the last 12 months. When focusing on IART/FAT ablations, acute procedural success increased from 43.8% to 95.8% (*P* for trend < 0.001), including complete acute procedural success from 0.0% to 59.4% (*P* for trend < 0.001). Acute procedural success rates were similar in CTI-dependent IART versus non-CTI-dependent IART/FAT: 88.2% vs. 86.4% (*P* = 0.695); and 96.7% vs. 94.3% in the last time period (*P* = 0.565). The acute procedural success rate in patients with ASD and IART was 93.3% (100.0% in the last time period).

Use of irrigated catheters (odds ratio [OR] 4.03, 95% confidence interval [CI] 1.86—8.55), a 3D mapping system (OR 3.70, 95% CI 1.72—7.74), contact force catheters (OR 3.60, 95% CI 1.81—7.38) and high-density mapping (OR 3.69, 95% CI 1.82—8.14) were associated with acute procedural success.

12-month recurrence rate

The median follow-up time after catheter ablation was 20.5 (6.3—48.4) months, including 215 (71.2%) procedures with a follow up $\geq$ 12 months. Antiarrhythmic therapy (other than beta-blockers) was pursued in 68 (31.6%) patients. The rate of freedom from any recurrence at 12 months increased from 29.4% to 66.2% (*P* for trend = 0.001) and from 23.1% to 66.0% (*P* for trend = 0.005) when focusing on IART/FAT ablations. Among the 76 patients with at least one recurrence, 49 (64.5%) had a recurrence of the targeted arrhythmia, 25 (32.9%) had a different arrhythmia recorded and nine (11.8%) had both recurrence of the targeted arrhythmia and a different arrhythmia; the distinction between targeted arrhythmia or a different arrhythmia remained uncertain in 11 (14.5%) cases.

The overall 12-month and 24-month survival rates without any arrhythmia recurrence were 63.3% and 53.1%, respectively. In patients with acute procedural success and catheter ablation in the last period of time (2016—2019), the corresponding rates were 81.7% and 58.8%, respectively.

Overall, seven (2.3%) complications occurred, including: three minor vascular complications (one small groin haematoma, one arteriovenous fistula and one femoral artery dissection, without the need for interventional treatment or blood transfusion); one sepsis related to a lymphangitis; one complete atrioventricular block leading to pacemaker implantation; one traumatic severe aortic regurgitation diagnosed 2 months after a retrograde aortic approach in a patient with extracardiac Fontan requiring an aortic valve replacement; and one asymptomatic fistula between the right atrium and aorta observed during a cardiac surgery planned 2 weeks after an ablation procedure (probably caused by a traumatic transseptal puncture). Overall, 12 (4.0%) patients died and six (2.0%) underwent cardiac transplantation during follow-up. No death was related to a catheter ablation procedure.

Discussion

This study presents an overall picture of the temporal evolution of catheter ablation in ACHD from a large tertiary centre. Our findings demonstrate a considerable increase of the number of procedures over time, important changes in the technologies used (catheter and mapping systems) and a significant improvement in acute and mid-term outcomes.

Over a 15-year period, we noted a 15-fold increase in the annual number of catheter ablation procedures. Discouraging experiences with antiarrhythmic pharmacological therapies in ACHD have resulted in a preference for interventional approaches in most expert centres, and catheter ablation has been now presented as a first-line therapy in international guidelines, including in complex CHD [7—9]. This trend is set to continue as the ACHD population is steadily increasing year after year.

The majority of procedures were related to IART or FAT. Surgical incisions and anatomical obstacles predispose to the development of reentrant arrhythmias, which are by far the main mechanism encountered in patients with ACHD [16,17]. However, regarded as the next epidemic in the ACHD population, AF is already the leading presenting arrhythmia over the age of 50 years, and will probably represent a more important part of procedures in the near future [18,19]. Only small series on AF ablation in ACHD have been published so far, supporting feasibility and safety, although with modest results [20,21]. A greater appreciation of specific underlying mechanisms and substrates may contribute substantially to further improving AF ablation outcomes in this population.

Acute and 12-month success rates significantly improved over the study period, with up to 90% of acute procedural success. This improvement is associated in particular with advances in ablative technologies, namely irrigated radiofrequency, contact force catheters and 3D/high-density mapping systems. A few studies have suggested a benefit from irrigated ablation [13] and contact force catheters [11] in CHD. This may reflect the difficulties in creating transmural lesions in low-flow environments (that impair conductive cooling and limit power delivery of radiofrequency energy), as observed experimentally in certain types of surgical anatomies [22], as well as chronic volume and pressure loads that result in marked thickening of myocardial walls. The use of electroanatomical systems with high-density and ultra-high-density mapping improve the understanding of arrhythmia circuits and the identification of optimal ablation targets, particularly in more complex CHD with important myocardial remodelling, diffuse scar areas and regions of pre-existing block [16,23]. Acute success rates were lower in AVRT and AVNRT catheter ablations, probably explained by: (1) complex cases referred to our tertiary centre with previous failed ablations in some patients; and (2) the relatively modest number of these types of procedure, with results strongly impacted by a few failures.

Despite excellent acute and decent mid-term outcomes, the rate of recurrence remains significant. Different mechanisms or circuits are encountered relatively often, suggesting that recurrence may result from both non-durable previous ablation lesions, but also progressive atrial or ventricular remodelling, with development of different potential circuits [24,25]. The increase of final programmed stimulation after termination of the clinical arrhythmia, performed in more than 80% of recent procedures, emphasizes the growing awareness of the importance of considering multiple possible mechanisms or circuits [26]. Our definition of complete acute success, which implied non-inducibility or successful ablation of all other inducible arrhythmias, underlies the relatively modest rates of complete procedural success reported, because patients without final stimulation, but with successful ablation of the clinical arrhythmia, were considered as partial successes. However, the benefit associated with systematic final programmed stimulation in CHD remains poorly assessed, with only one retrospective study from our group, which reported recently that patients without ablation of all inducible non-clinical atrial arrhythmias had poorer outcomes [27]. This approach may help to improve long-term results, but more extensive ablation may also cause new iatrogenic areas of arrhythmogenesis where tissue is incompletely ablated or linear block is not completely or not durably achieved, as reported in patients after pulmonary vein isolation with additional linear ablations [28]. A promising approach to further improve outcomes is based on substrate identification for tailored treatment, including prophylactic ablations in the absence of other inducible arrhythmias. This has been described in particular in patients with repaired tetralogy of Fallot, where linear ablations in critical isthmus with abnormal slow conduction velocity involved in reentrant ventricular tachycardias were associated with favourable outcomes [29]. The value of chamber activation and conduction velocity analysis in arrhythmia or in sinus rhythm to identify potential isthmus has recently been confirmed in CHD and ischaemic heart disease [30,31].

Finally, we observed a relatively low proportion of complications related to catheter ablation, similar to those observed in recent series of complex catheter ablations in non-ACHD settings [32,33]. This finding is important when considering the complexity and duration of procedures with unusual venous access (superior, transhepatic), complex transseptal/transtube/transbaffle punctures or potential haemodynamic compromise as a result of arrhythmia in some CHDs. Whereas the risk of serious complication, albeit rare, has to be discussed with the patient, it reinforces that catheter ablation is a reasonable first-line therapeutic option in this population [7]. We reported two major complications in our series: one traumatic aortic regurgitation after a retrograde aortic approach requiring aortic valve replacement; and one complete atrioventricular block leading to a definitive pacemaker implantation. An asymptomatic fistula between the right atrium and the aorta was also observed during a surgery a few weeks after a catheter ablation procedure with a transseptal puncture in another patient. In patients with complex anatomy, remote magnetic navigation-guided ablation offers an effective and safe alternative, with excellent catheter manoeuvrability and stability and precise delineation of cardiac anatomy, and allows complete atrial mapping by the retrograde aortic approach [34,35].

Study limitations

We have to acknowledge some limitations. First, this was a single-centre retrospective study. All operators have had specific dedicated training and have developed expertise in catheter ablation in patients with ACHD, and this accumulated experience probably contributed to the improvement of outcomes observed, along with advances in technologies. However, none of the current operators was part of the team during the first half of the study period, suggesting that experience itself can only partly explain this improvement. Second, we present an exhaustive picture of catheter ablation procedures in ACHD from a large tertiary centre with, however, room for some selection bias, e.g. simple CHD (mainly atrial septal defects) may be under-represented. Third, selection of the mapping system and catheters was dependent on the operator's decision and availability. The vast majority of procedures (82.1%) were performed with the CARTO® system, which precludes comparisons with other systems (only six procedures were performed with the RHYTHMIA™ system). Fourth, we acknowledge a significant number of missing data in some variables, such as previous palliative shunt of systemic ejection fraction. This amount of missing data mainly relates to the oldest cases in patients referred for catheter ablation and usually managed in other centres. This does not affect our main results (temporal trends in terms of volume and outcomes), but may be considered as a limitation for a full understanding of such trends. Other data, such as fluoroscopy dosing and duration, were not collected systematically through the entire duration of this study. Hence, we were unable to provide a comprehensive analysis of changes in fluoroscopy use. Data on the last 5 years, however, revealed that whereas mean fluoroscopy duration was stable during this period (from 8.8 to 8.5 minutes; $P = 0.178$), the mean dose decreased significantly (from 1502 to 550 uGy/m^2; $P = 0.044$). Considering these limitations to this preliminary approach, we initiated in January 2020 a large prospective nationwide French multicentre registry to prospectively collect information on patients' characteristics, procedure details and outcomes, using a specific electronic Contact Research Form (NCT04202796).

Conclusions

In conclusion, the number of catheter ablation procedures in patients with ACHD has increased considerably over the last 15 years. Growing experience and recent advances in catheter and mapping technologies are associated with a significant improvement in acute and mid-term outcomes.

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Disclosure of interest

The authors declare that they have no competing interest.

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