Contemporary patients with congenital heart disease uniform atrial tachycardia substrates allow for clear ablation endpoints with improved long-term outcome

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ORIGINAL ARTICLE

Contemporary Patients With Congenital Heart Disease

Uniform Atrial Tachycardia Substrates Allow for Clear Ablation Endpoints With Improved Long-Term Outcome

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BACKGROUND: Poor outcome after atrial tachycardia (AT) radiofrequency catheter ablation (RFCA) in repaired congenital heart disease (CHD) has been attributed to CHD complexity. This may not apply to contemporary patients. The objective of our study was to assess outcome after RFCA for AT in contemporary patients with CHD according to prior atrial surgery and predefined procedural endpoints.

METHODS: Patients with CHD referred for AT RFCA to 3 European centers were classified as no atrial surgery/cannulation only, limited or extensive prior atrial surgery. Procedural success was predefined as termination and nonreinducibility for focal AT and bidirectional block across ablation lines for intra-atrial reentrant tachycardia and after empirical substrate ablation for noninducible patients. Patients were followed for AT recurrence and mortality.

RESULTS: Ablation was performed in 290 patients (41±17 years, 59% male; 3-dimensional mapping 89%, irrigated tip catheters 90%, transbaffle access 15%). In 197, 233 AT were targeted (196 intra-atrial reentrant tachycardia [64% cavotricuspid (mitral) isthmus–dependent, 33% systemic-venous incision–dependent] and 37 focal AT). In 93 noninducible patients, empirical substrate ablation was performed. Procedural success was achieved in 209 (84%) patients. AT recurred in 148 (54%) 10 (interquartile range, 0–25) months after RFCA. AT-free survival was significantly better in patients with no atrial repair/cannulation only and in patients with complete procedural success independently of CHD complexity. From 94 patients undergoing reablation, the initially targeted substrate had recovered in 64%.

CONCLUSIONS: In contemporary patients with CHD, outcome after AT ablation is associated with presence of prior atrial surgery and achievement of predefined procedural endpoints rather than CHD complexity. Techniques to improve lesion durability are likely to further improve long-term outcome.

GRAPHIC ABSTRACT: An online graphic abstract is available for this article.

Key Words: catheter ablation ■ congenital heart disease ■ mortality ■ tachycardia

Advances in surgical techniques have improved survival in contemporary patients with congenital heart disease (CHD). Late atrial tachycardias (AT) are common with a reported prevalence ranging from 15% to 75%, contributing to late morbidity and mortality.[1–7]

Radiofrequency catheter ablation (RFCA) is an important therapeutic option to control AT. Reported AT recurrence rates after RFCA are high, and repeated procedures are often required.[8–11] Ablation failure has been attributed to the complexity of the underlying cardiac

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WHAT IS KNOWN?

- Radiofrequency catheter ablation is an important therapeutic option to control atrial tachycardia (AT) in patients with congenital heart disease (CHD). However, recurrence rates are high, and repeated procedures are often required.
- Poor acute and long-term outcome after radiofrequency catheter ablation has been attributed to CHD complexity, noninducibility of the (presumed) clinical AT and difficult or unknown AT substrates.

WHAT THE STUDY ADDS

- In contemporary patients with CHD, long-term outcome after AT ablation is not dependent on the CHD complexity but on reaching predefined procedural endpoints.
- The high prevalence of 2 underlying, well-defined AT mechanisms and related substrates (cavotricuspid [mitral] isthmus–dependent flutter and systemic venous atrium incision–dependent intra-atrial reentrant tachycardia), which can be delineated without AT induction, allows empirical substrate ablation.
- The challenge of AT ablation in patients with CHD lies in creating durable ablative lesions, rather than in complex AT substrates.

Nonstandard Abbreviations and Acronyms

3D	3-dimensional
AT	atrial tachycardia
CT(M)I	cavotricuspid (mitral) isthmus
CT(M)IF	cavotricuspid (mitral) isthmus–dependent flutter
EAM	electroanatomical mapping
FAT	focal atrial tachycardia
IART	intra-atrial reentrant tachycardia
RFCA	radiofrequency catheter ablation
SVA	systemic venous atrium

defect, difficult access to the substrate, thickened atrial myocardium, noninducibility of the (presumed) clinical AT, and unknown AT substrates.[12–14]

However, previous data on acute and long-term outcome of RFCA for AT may not be valid for contemporary patients with CHD. The type and timing of surgical interventions for CHD have changed.[15–17] As a result, the complexity of CHD anatomy may no longer reflect the complexity of the AT substrate.

In addition, various technological developments have been established to facilitate RFCA, including improved transbaffle access, use of 3-dimensional electroanatomical mapping (3D-EAM), and irrigated tip catheters. Of interest, although the dominant reported AT mechanism is intra-atrial reentrant tachycardia (IART) involving the cavotricuspid (mitral) isthmus (CT[M]I), surgical incisions, and prosthetic material,[8,18–26] systematic evaluation of ablation endpoints, as widely accepted in patients with anatomically normal hearts, has not been performed or reported.

Therefore, the purpose of our study is to systematically evaluate the acute and long-term outcome of RFCA for AT in CHD using state-of-the-art technology, according to the presence and type of atrial surgical intervention and achievement of predefined procedural endpoints.

METHODS

Study Design and Patient Characteristics

The study population consisted of all consecutive patients with repaired CHD who underwent a first ablation procedure for symptomatic AT in 3 European high-volume tertiary referral centers (Department of Cardiology, Leiden University Medical Center, the Netherlands; Center for Electrophysiology, Bremen, Germany; Department of Cardiology, Aarhus University Hospital, Aarhus, Denmark) between 2006 and 2016.

Data regarding the underlying CHD and details of all prior surgical interventions were obtained from hospital records. CHD complexity was categorized as simple, moderate, or severe following the American College of Cardiology/American Heart Association 2018 guidelines.[27] In addition, patients were divided into 3 groups according to the complexity of the prior atrial surgical intervention. Group A consisted of patients with a right atrial cannulation site only but without an atrial incision, group B comprised patients with limited prior atrial surgery with a single right atrial incision for access with or without an additional suture line/patch closure of an atrial septal defect, and group C included patients with more extensive atrial surgery including >1 atrial incision and ≥2 additional suture lines with/without prosthetic material.

All available 12-lead ECGs, Holter registrations, internal loop recorder, and device interrogations were reviewed for documentation of spontaneous AT. In addition, medical records were reviewed for AT-related symptoms, prior antiarrhythmic medication, and admissions for cardioversions. Imaging studies performed within 6 months before ablation was assessed for biventricular function and residual lesions.

The Dutch Central Committee on Human-Related Research permits use of anonymous data without prior approval of an Institutional Review Board, if the data do not contain identifiers that could be traced back to the individual patient and if the data are obtained for patient care.

Programmed Electrical Stimulation, Electro-Anatomic Mapping, and Ablation

Procedures were performed under conscious sedation, deep sedation, or general anesthesia, dependent on patient and operator preference. A 3D-EAM system was always available and used when considered appropriate (CARTO [Biosense Webster] or Ensite NavX [St. Jude Medical]). Programmed electrical stimulation and EAM were performed according to our standard protocol (Supplement I in the Data Supplement).

In brief, activation and entrainment mapping was performed in patients with hemodynamically stable AT at baseline to elucidate the AT mechanism and to select ablation target sites. If AT was not present at baseline, programmed electrical stimulation was performed to induce AT, followed by activation/entrainment mapping. For unmappable AT (poorly tolerated, degenerating to atrial fibrillation) and noninducible patients, atrial substrate mapping was performed during sinus rhythm or CS/low systemic venous atrium (SVA) pacing to elucidate unexcitable areas as potential boundaries for reentrant circuits for empirical substrate ablation.

Classification of AT

ATs were classified according to their electrophysiological mechanism and activation pattern as IART or focal AT (FAT). Subsequently, and depending on the involved anatomic structures, IARTs were classified as incisional IART ($IART_{inc}$) and nonincisional IART. IART involving the atrial cannulation site was considered incisional. Nonincisional IART were further classified as CT(M)I–dependent flutter (CT[M]IF) or non-CT(M)IF. The location of the critical isthmus for the IART circuit or the site of FAT source in the SVA or in the PVA was determined and targeted by ablation (Supplement II and III in the Data Supplement).

Definition of Procedural Outcome

Acute procedural outcome was categorized according to predefined ablation endpoints in

1. Complete success:
   i. Inducible patients: termination by RF of all clinical and induced focal ATs and verification of bidirectional block along all ablation lines for clinical and induced IART and noninducibility of any AT at the end of the procedure (including isoproterenol administration).
   ii. Noninducible patients: Bidirectional conduction block across all ablation lines for empirical substrate ablation.
2. Partial success:
   i. Successful ablation of the clinical/presumed clinical AT (AT termination during ablation for focal AT or bidirectional block along ablation lines for IART) but other nonclinical AT remained inducible or bidirectional block along ablation lines for nonclinical ATs was not achieved.
3. Failure: the clinical AT could not be terminated or bidirectional block across ablation lines could not be demonstrated.
4. End point not tested: The predefined endpoints were not tested.

Reasons for acute ablation failure were analyzed.

Follow-Up

Patients were followed according to the standard clinical protocol of each participating center. This included at least 6-month interval follow-up visits with 12-lead ECG, 24-hour Holter recording, or implantable cardioverter defibrillator or pacemaker interrogation, if appropriate. Follow-up data were acquired from hospital records. If patients were not routinely followed at the ablation center, the referring hospital/physician was contacted. Patients were followed for AT recurrence (defined as any documented AT >30 s after ablation), hospital admissions, and mortality.

Statistical Analysis

Continuous data are presented as mean±SD, median with interquartile range, or median with range according to distribution. Categorical data are reported as percentage or frequencies. Continuous variables were compared using the 1-way ANOVA test with Bonferroni correction, Student t test, or the Mann-Whitney U test where appropriate. Categorical variables were compared using the $\chi 2$ test or Fisher exact test. Freedom from AT recurrence was estimated by the Kaplan-Meier method and compared among subgroups with log-rank test. Cox proportional hazards regression analysis was performed to detect any significant predictor of AT recurrence. All tests were 2-sided, and $P<0.05$ were considered significant. All analyses were performed with SPSS 23.0 (SPSS, Inc, Chicago, IL). The authors declare that all supporting data are available within the article and its Data Supplement.

RESULTS

Patient Characteristics

A total of 290 patients were included (170 [59%] male, mean age 41±17 years). Based on the presence and type of surgical intervention on atrial level, 43 (15%) patients were assigned to group A, 163 (56%) to group B, and 84 (29%) to group C. The type of CHD and details of the surgical interventions are listed in Table 1. The baseline characteristics of the patients are provided in Table 2.

ATs were documented in 279 (96%) patients: on 12-lead ECG in 222 (80%) patients, on Holter in 19 (7%) and on-device interrogation in 38 (13%) patients. The most common AT-related symptoms were dyspnea (n=140, 50%) and palpitations (n=124, 44%). Eight (3%) patients presented with syncope attributable to AT. In the 6 months preceding the ablation, 151 (52%) patients received antiarrhythmic drugs and 179 (62%) underwent ≥1 cardioversion. Thirteen (5%) patients had a history of atrial fibrillation.

First mapping and Ablation Procedure

Details of all 290 RFCA procedures are provided in Table 3 and Table I in the Data Supplement. A 3D-EAM system was used in 258 (89%) procedures. In 32 patients with a documented AT consistent with a typical cap binding complex dependent translation initiation factor, conventional mapping was performed without the use of a 3D-EAM system.

Inducible Patients

In 197 (68%) patients, a total of 288 ATs were present at baseline or were induced; ≥2ATs were inducible in 64 (22%) patients. The AT mechanism and source could be elucidated for 233 of the 288 ATs (81%) and was IART in 196 (84%) and FAT in only 37 (16%). Among the 196 IART, 126 (64%) were CT(M)IF, 65 (33%) were $IART_{inc}$, and only 5 (3%) were not related to CT(M)I or incisions.

Table 1. Type of Congenital Heart Disease and Surgical Interventions

Congenital heart defect	Type of repair	N
Group A: no atrial repair (or only cannulation)		
Tetralogy of Fallot	Total repair, transventricular	21
VSD	VSD closure, transventricular	8
Congenital aortic (valve) abnormalities	Aortic valve or artery surgery	6
Congenitally corrected transposition of the great arteries with or without VSD	No repair or only concomitant VSD closure (transventricular)	4
Ebstein anomaly	No repair	3
Pulmonary atresia+VSD+right aortic arch to systemic pulmonary collateral	Blade atrioseptostomy (transcatheter)	1
	Total	43
Group B: simple atrial repair		
ASD type I or II with or without VSD	Surgical ASD closure with or without VSD closure	61
Tetralogy of Fallot	Total repair, transatrial	41
Ebstein anomaly or mitral/tricuspid valve abnormalities	Surgical tricuspid valve repair	12
Partial abnormal drainage of pulmonary veins	Correction with single atrial patch	11
AVSD	AVSD closure	8
Transposition of the great arteries	Arterial switch procedure+surgical ASD closure	8
Congenital aortic (valve) abnormalities	Aortic valve surgery+surgical ASD/PFO closure or MVR	7
Pulmonary (valve) abnormalities/RVOTO with or without ASD type II	Pulmonary (valve) surgery with or without surgical ASD closure	7
Univentricular hearts	Surgical atrial septectomy+shunt procedures	6
Congenitally corrected transposition of the great arteries+ASD II	Only surgical ASD closure	1
VSD+coronary anomaly	VSD closure+aortic valve replacement (transatrial)	1
	Total	163
Group C: complex atrial repair		
Transposition of the great arteries	Atrial switch procedure (Mustard or Senning)	46
Univentricular hearts or double outlet RV+TGA or criss-cross heart	Classic total cavopulmonary connection	15
Univentricular hearts or double outlet RV+TGA	Total cavopulmonary connection with lateral tunnel	15
Total abnormal drainage of pulmonary veins	Total correction (with atrial tunneling)	4
Cc-TGA with valve anomalies	Double switch procedure	3
Ebstein anomaly, ASD type II, tricuspid regurgitation, PS	ASD closure, augmentation LA, resection RA wall, TVR	1
	Total	84

(cc)-TGA indicates (congenitally corrected) transposition of the great arteries; ASD, atrial septal defect; AVSD, atrioventricular septal defect; LA, left atrium; PS, pulmonary stenosis; RA, right atrium; RV, right ventricle; RVOTO, right ventricular outflow tract obstruction; TVR, tricuspid valve reconstruction; and VSD, ventricular septal defect.

Noninducible Patients

A total of 93 (32%) patients were noninducible or only inducible for unmappable ATs. In these patients, empirical substrate ablation was performed, targeting the CT(M)I in 78 (84%) patients, connecting the SVA incision to an unexcitable boundary in 11 (12%) and targeting both CT(M)I and an SVA isthmus in 4 (4%) patients.

Systemic Venous or Pulmonary Venous Substrates

In 56 out of 290 (19%) patients, access to the PVA was required for ablation: in 45 (80%) to target the CT(M)I, in 7 (13%) for non-CT(M)I linear lesions, and in 4 (7%) to ablate FAT. In 4 out of 290 (1%) patients, the PVA was accessed without subsequent ablation in the PVA. Access to the PVA was mainly obtained by transbaffle or transseptal puncture and was significantly more often required in patients with extensive atrial surgery: 7% versus 3% versus 62%, respectively ($P<0.0001$).

AT Substrates According to Atrial Anatomy and Surgical Atrial Interventions

The overall distribution of AT mechanisms did not differ according to the extent of atrial surgery (Figure 1A). However, specifically, patients with Fontan palliation had a higher incidence of $IART_{inc}$ typically involving the SVA (Figure 1B).

Procedural Outcome

Predefined procedural endpoints were tested in 250 (86%) patients. Complete success was achieved in 209 out of 250 (84%) patients: in 131 out of 162 (81%) inducible patients and in 78 out of 88 (89%) patients with empirical substrate ablation. Partial success was achieved in 18 out of 162 (11%) inducible patients. Ablation failed in 23 (9%) patients: in 13 out of 161 (8%)

Table 2. Baseline Characteristics

	All (n=290)	Group A (n=43)	Group B (n=163)	Group C (n=84)	*P* value
Age, y	41±17	49±14	43±18	33±11	<0.0001*†
Male gender, n (%)	170 (59%)	26 (61%)	91 (56%)	53 (63%)	0.528
CHD complexity‡					
Simple	64 (22%)	9 (21%)	55 (34%)	0 (0%)	<0.0001*†
Moderate	114 (39%)	25 (58%)	84 (52%)	5 (6%)	<0.0001*†
Great	112 (39%)	9 (21%)	24 (15%)	79 (94%)	<0.0001*†
Preserved SV function	172/200 (86%)	34/37 (92%)	100/110 (91%)	38/53 (72%)	0.002*
Preserved PV function	146/171 (85%)	30/34 (88%)	93/104 (89%)	23/33 (70%)	0.018*
Pacemaker before ablation	86 (30%)	7 (16%)	45 (28%)	34 (41%)	0.013†
Sinusarrest/sinusdysfunction	38 (44%)	2 (29%)	19 (42%)	17 (50%)	0.169
Third degree AV-block	24 (28%)	3 (43%)	13 (29%)	8 (24%)	0.169
Other	24 (28%)	2 (29%)	13 (29%)	9 (26%)	1.169
ICD before ablation	35 (12%)	8 (19%)	20 (12%)	7 (8%)	0.242
Secondary prevention	19 (54%)	5 (63%)	12 (60%)	2 (29%)	0.263
Number of cardiac surgeries	2 (1–3)	2 (1–3)	2 (1–3)	2 (1–3)	0.216
Age at first cardiac surgery, y	4 (1–13)	6 (4–9)	7 (2–22)	1 (0–2)	<0.0001*†§
Time since first cardiac surgery, y	28±14	38±13	26±15	27±11	<0.0001†§

ACC/AHA indicates American College of Cardiology/American Heart Association; AV, atrioventricular; CHD, congenital heart disease; ICD, implantable cardioverter defibrillator; PV, pulmonary ventricle; and SV, systemic ventricle.

*Significant difference between groups B and C.

†Significant difference between group A and C.

‡Classified according to the ACC/AHA 2008 guidelines for the management of adults with CHD.

§Significant difference between groups A and B.

inducible patients and in 10 out of 88 (11%) patients with empirical substrate ablation.

Reasons for ablation failure could be attributed to the following issues: (1) access: failure of baffle puncture (n=2) or limited catheter maneuverability (n=5); (2) inconclusive results of differential pacing to assess bidirectional block across linear lesions (n=4); (3) incomplete mapping due to massive chamber-size (n=1); (4) incomplete lesion generation, presumably due to extended hypertrophy/fibrosis; only unidirectional block along linear ablation lines could be achieved despite extensive ablation (n=9); (5) high risk for unintended damage to the specific conduction system (n=2).

Five (2%) procedures were terminated early because of hemodynamic instability (n=2), requirement of multiple unsuccessful external direct current-cardioversions for atrial fibrillation (n=2), or presence of a thrombus in the target atrium identified at the beginning of the procedure (n=1).

Major complications requiring intervention occurred in 2 patients (0.7%; one tamponade, one pneumothorax), both from group A.

Acute Outcome According to Surgical Atrial Intervention and Complexity of the CHD

There was no difference in acute outcome according to CHD complexity or presence and type of atrial surgery.

Table 3. Procedural Characteristics

	All (n=290)	Group A (n=43)	Group B (n=163)	Group C (n=84)	*P* value
Catheter type, irrigated tip	261 (90%)	41 (95%)	144 (88%)	76 (91%)	0.509
3D mapping system used	258 (89%)	29 (91%)	138 (85%)	81 (96%)	0.019*
Access pulmonary venous atrium	60 (21%)	3 (7%)	5 (3%)	52 (62%)	<0.0001*†
Transbaffle/transconduit	46 (72%)	0 (0%)	0 (0%)	46 (89%)	<0.0001*†
Transseptal	8 (13%)	3 (100%)	5 (100%)	0 (0%)	<0.0001*†
Retrograde	6 (12%)	0 (0%)	0 (0%)	6 (12%)	<0.0001*†
Targeted ATs, median (range)	1 (1–3)	1 (1–3)	1 (1–3)	1 (1–2)	0.360
Empirical substrate ablation only	93 (32%)	12 (30%)	51 (31%)	30 (36%)	0.638

3D indicates 3-dimensional; and AT, atrial tachycardia.

*Significant difference between groups B and C.

†Significant difference between group A and C.

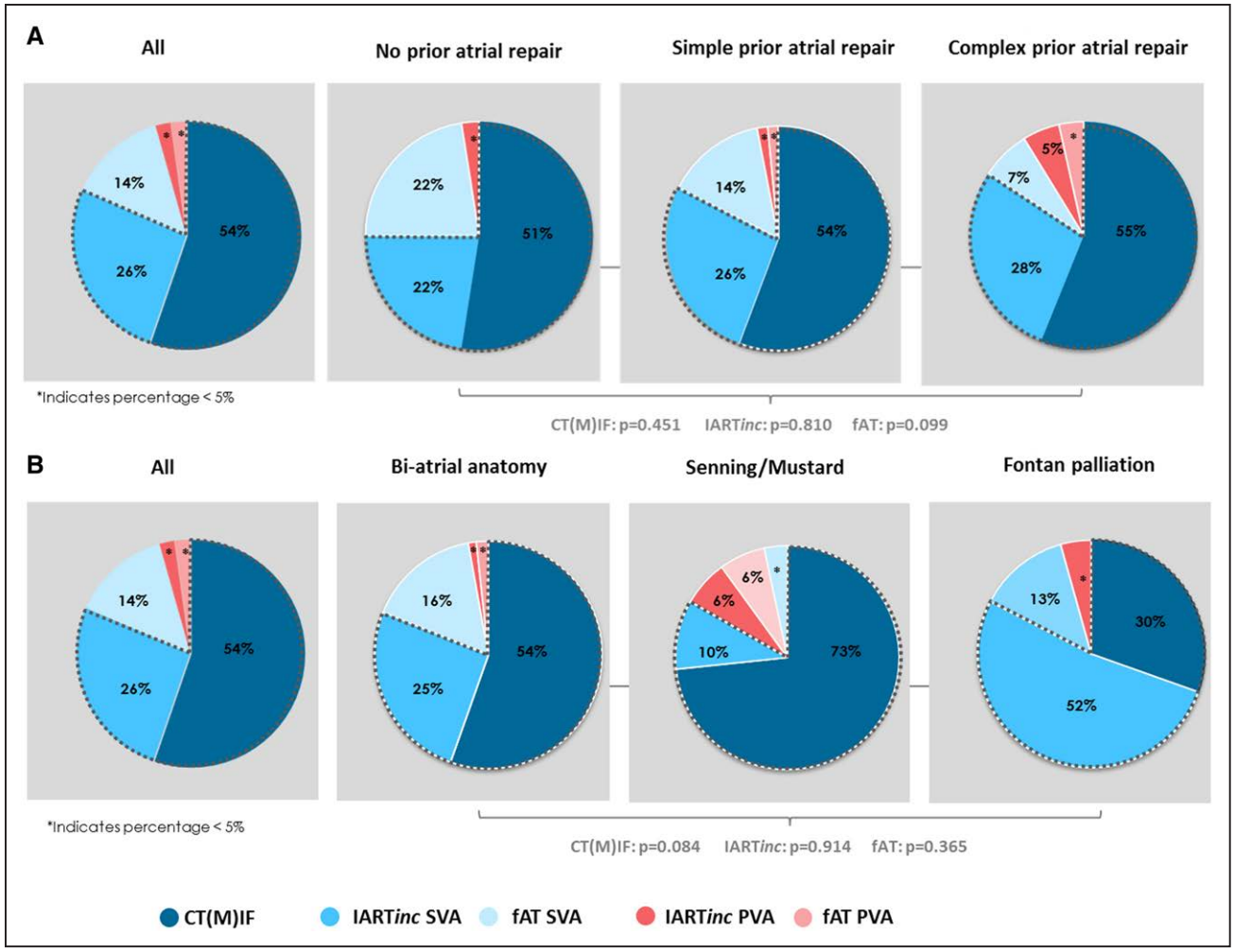

Figure 1. Atrial tachycardia (AT) mechanisms and substrate locations.
A, According to complexity of prior atrial surgery. **B**, According to specific surgical atrial interventions. Gray dashed delineation indicates cavotricuspid (mitral) isthmus–dependent flutter (CT(M)IF)+incisional intra-atrial reentrant tachycardia ($IART_{inc}$) located in the systemic venous atrium (SVA). The 5 (3%) non-CT(M)I and non $IART_{inc}$ are not included in this figure. FAT indicates sfocal AT; and PVA, pulmonary venous atrium.

In patients with more extensive surgery, the end point of ablation was less often tested which was driven by patients with classic Fontan palliation (Figure 2).

Long-Term Outcome

Twenty-nine (10%) patients were discharged on antiarrhythmic drugs. Fifteen patients were lost to follow-up. During a median follow-up of 34 (interquartile range, 13–60) months, 148 (54%) patients experienced recurrence of any AT after the first ablation procedure. Median time to recurrence was 10 (interquartile range, 0–25) months. Nineteen (7%) patients died during follow-up. The most common causes of death were heart failure (n=7 [37%]) and postoperative complications after surgery unrelated to RFCA (n=4 [20%]). Sustained AT-free survival was not different when evaluated according to the conventional classification of CHD complexity. However, AT-free survival was significantly better in patients with no prior atrial incision: 2-year AT-free survival was 68% compared to 42% after limited and 48% after extensive atrial repair (*P*=0.049, Figure 3A). Of note, no difference in AT-free survival was observed between patients with limited and extensive atrial surgery. AT-free survival was not different for specific atrial surgical interventions (Figure 3D).

The 1-year AT-free survival in patients inducible for only FAT was 43% compared to 55% in patients with other or multiple AT mechanisms. The 2-year AT-free survival in patients with only FAT was 34% compared with 48% in patients with other AT or multiple AT (*P*=0.075).

Freedom from sustained AT recurrence was significantly higher if complete procedural success was achieved compared to procedures with either partial success, failure, or not-tested endpoints (Figure 3C). Of importance, noninducible patients in whom successful empirical substrate ablation was performed had a similar good outcome compared to inducible patients with

Table 4. Univariable and Multivariable Predictors of AT Recurrence During Follow-Up

	Univariable			Multivariable		
Variables	HR	95% CI	*P* value	HR	95% CI	*P* value
Age, y	0.998	(0.99–1.01)	0.740	…	…	…
Male gender	1.13	(0.70–1.82)	0.631	…	…	…
CHD complexity	1.11	(0.59–2.11)	0.739	…	…	…
Atrial surgery complexity	2.85	(1.27–6.39)	0.011	1.98	0.69–5.73	0.207
History of AF	1.88	(0.18–19.53)	0.599	…	…	…
Depressed systemic ventricular function	1.26	(0.34–1.86)	0.592	…	…	…
Depressed pulmonary ventricular function	2.44	(1.00–6.00)	0.049	2.63	(0.98–6.36)	0.057
Multiple AT during procedure	1.39	(0.68–2.82)	0.365	…	…	…
Predefined end point reached	0.48	(0.28–0.82)	0.007	0.369	(0.17–0.80)	0.011

AF indicates atrial fibrillation; AT, atrial tachycardia; CHD, congenital heart disease; and HR, hazard ratio.

complete procedural success. Multivariable Cox regression analysis showed that complete procedural success (hazard ratio, 0.37 [95% CI, 0.17–0.80], *P*=0.011) was independently associated with better AT-free survival.

Redo Procedures

A second ablation was performed in 94 (32%) patients with a median of 10 (interquartile range, 0–25) months after the first procedure. Seventy-five patients (80%) were inducible for 92 AT (77% ART, 23% FAT). Of importance, the identified underlying AT substrate was identical with the previously targeted substrate in 64% of the patients.

DISCUSSION

To the best of our knowledge, this is the largest multicentre study reporting on acute and long-term outcome after radiofrequency catheter ablation (RFCA) for AT (AT) in a mixed cohort of consecutive, contemporary patients with CHD. Of importance, (1) patients were included on an intention-to-treat basis, (2) care was taken to elucidate underlying substrate and mechanism of all induced AT, (3) noninducible patients (with documented AT before the electrophysiological study) were included in the analysis and underwent substrate mapping followed by empirical substrate ablation, (4) transbaffle access was obtained whenever necessary to reach endpoints, (5) in the majority (89%) of the patients, currently accepted state-of-the-art endpoints for AT ablation were tested.

The findings can be summarized as follows: (1) thirty-one percent of the patients were not inducible or only inducible for unmappable AT requiring a substrate-based ablation approach despite prior AT documentation in the majority. (2) Except for Fontan palliation, the predominant AT substrate is similar across all CHD (*CT(M)IF* and *IARTinc* involving the SVA incision), which facilitates substrate-based ablation approaches. (3) Noninducible patients undergoing empirical substrate ablation had similar outcomes compared to successful ablation in inducible patients, which justifies empirical ablation in noninducible patients, provided that predefined endpoints are reached. (4) Complete procedural success according to currently accepted endpoints can be achieved in at least 84% of the patients independent of the extent of surgical atrial repair or complexity of the CHD with very low complication rates. (5) Despite advanced techniques, including routine transbaffle access, AT recurrence rates are still high but independent from the complexity of the CHD and specific subtypes like atrial switch operation and Fontan palliation. (6) AT-free survival is significantly better in patients without atrial surgical interventions and if complete procedural success has been achieved. (7) Noncomplete procedural success is independently associated with AT recurrence. (8) The identified substrate for recurrent AT after the first ablation was identical with the initial targeted substrate in two-thirds of patients with CHD who underwent a second mapping and ablation procedure, suggesting that lesion recovery is the main reason for AT recurrence.

AT in CHD

AT are the most common arrhythmias observed in patients with CHD and RFCA is an important therapeutic option for targeting these arrhythmias.[8,9,28]

Recent technical developments, such as 3D-EAM and the use of irrigated tip catheters, have facilitated ablation and enhanced procedural success.[12,13,15,23,24,26,29–32] In our cohort, the vast majority of ablation procedures were performed using modern technologies.

Substrates for AT

Besides the aging process itself, the coincidence of pathological remodeling and the presence of anatomic boundaries from surgical incisions, patch material, and valve annuli explains at least in part the high incidence of atrial arrhythmias in the congenital population.[29,33,34]

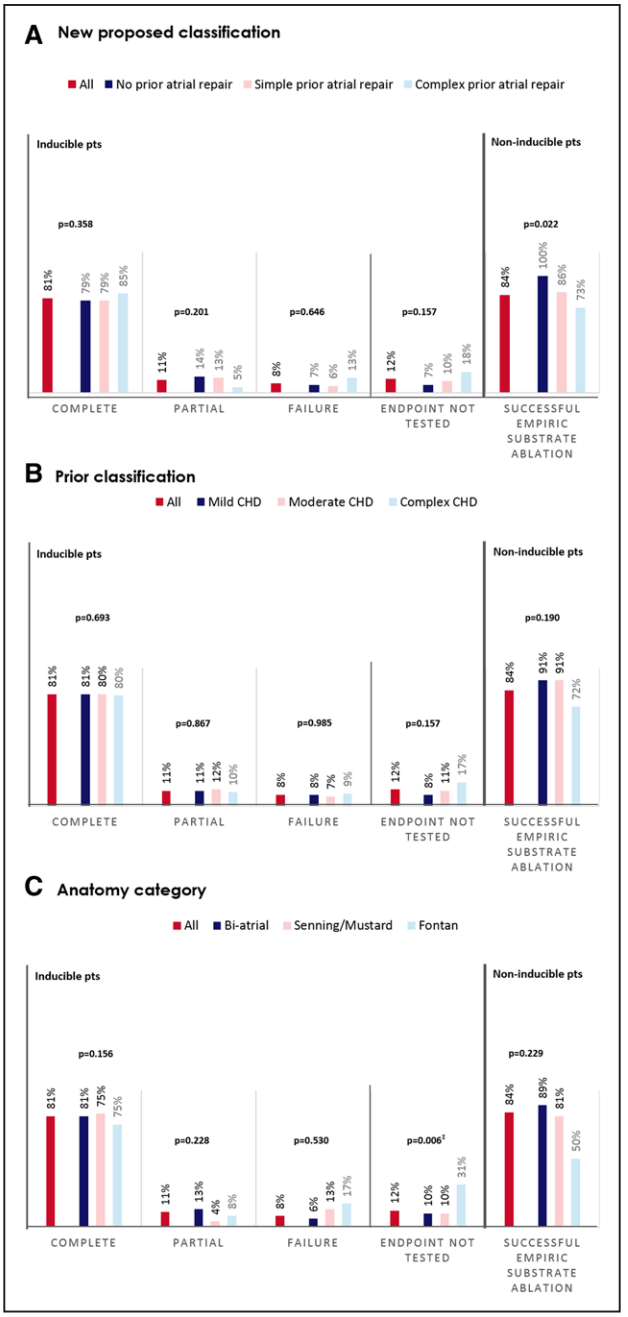

Figure 2. Acute procedural outcome.
A, According to surgery complexity categories, (**B**) according to conventional congenital heart disease (CHD) complexity categories, and (**C**) according to specific surgical categories. ‡Significant difference between group biatrial anatomy and Fontan palliation.

Although less complex atrial surgical interventions in combination with earlier hemodynamical improvement may influence AT substrate development, some uniform substrates remain.

The most important AT mechanism in our cohort was CT(M)IF which accounted for ≈50% of all AT regardless of surgical status (except Fontan palliation). The second most important AT mechanism was IART related to incisional scars within the SVA (25%), a substrate that can also be well delineated by 3D mapping. FAT were less frequently encountered: in our cohort, only 19 (7%) patients had only FAT.

Our findings are in line with previous studies reporting a similar distribution of AT substrates in patients with CHD.[20,22,24,30,35] However, several studies have also reported that non-CT(M)IF are more common than CT(M)IF in patients with complex CHD.[34,36] This may be partly explained by the number of Fontan patients included. In our cohort, non-CT(M)IF was only more common in patients after Fontan palliation. The high prevalence of the 2 dominant and well-defined substrates for the majority of AT across most CHDs allows a substrate-based ablation in noninducible patients with similar outcome compared to patients with inducible AT. These findings may even justify preventive surgical CT(M)I-ablation during the initial surgical repair or during re-interventions provided that bidirectional block can be achieved. In particular, patients in whom surgery prevents access to the AT substrate may benefit from concomitant surgical ablation.

Acute Ablation Outcome

A wide range of acute procedural success rates has been reported (Table II in the Data Supplement), related to different patient populations and ablation end point definitions.[8,13,18–20,22,23,25,26,30–32,34] The overall acute ablation success in our series (84%) was within the reported range of prior studies.

However, our study is the first to report outcome according to predefined endpoints. Bidirectional isthmus block is a well-established end point for CTI-ablation in anatomic normal hearts. However, the procedural end point is less clear for non-CT(M)IF for which AT termination during ablation is often considered as procedural success.[13,18–20,26,30]

In our study, the desirable end point for all IART was defined as bidirectional isthmus block in combination with noninducibility at the end of the procedure. These procedural endpoints were tested in 86% of all patients, including those with empirical substrate ablation, and could be achieved in the vast majority. Only in patients after classic Fontan palliation, operators more often refrained from reinduction mainly because of the length of the procedure due to multiple AT inducibility from severely diseased myocardium. Procedural failure tended to be also higher in patients after Fontan palliation (classic or lateral tunnel). Of note, these specific atrial surgical interventions will vanish in modern cohorts of patients with CHD with the introduction of extracardiac Fontan procedures. In patients with an extracardiac conduit, favorable 10-year freedom from new-onset late AT has been reported compared to atriopulmonary connection and lateral tunnel.[37] However, longer follow-up is needed to assess the long-term incidence of IART in patients with extracardiac conduits, in whom

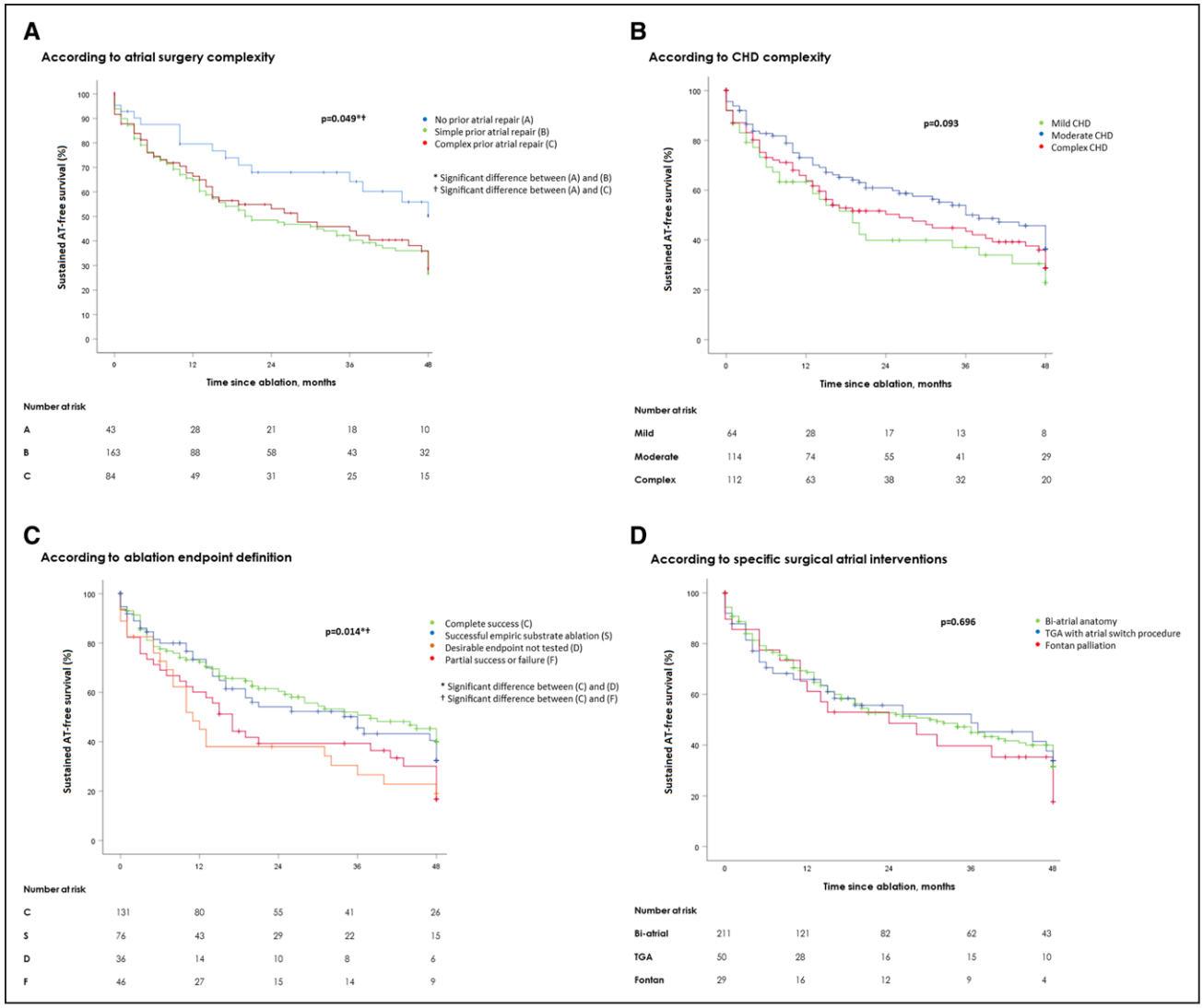

Figure 3. Atrial tachycardia (AT)-free survival after the first ablation procedure.
A, According to presence and complexity of prior atrial surgery, (**B**) according to conventional congenital heart disease (CHD) classification, (**C**) according to endpoint definition, and (**D**) according to specific surgical atrial interventions. Anatomy category TGA includes patients with congenitally corrected TGA after double switch procedure. TGA indicates transposition of the great arteries.

access to the CT(M)I may be even more challenging. Of importance, despite the consequent implementation of the predefined endpoints, complication rates were low. Only 2 major complications occurred in our patient cohort.

AT Recurrence

Despite high complete procedural success, AT recurrence rates were still high, affecting ≈50% of the population during a median follow-up time of 34 months. Previous studies have also described high AT recurrence rates. In particular, for patients with complex CHD, such as Fontan palliation, reported rates reached 85%.[13]

High AT recurrence rates in patients with CHD have been attributed to the complexity of the underlying cardiac defect, difficult access to the substrate, and thickened atrial myocardium.[12,13] In our cohort, long-term outcome was not dependent on the complexity of the underlying CHD, similar to a recent study reporting ablation outcome in a large, mixed CHD cohort.[32] However, patients without prior atrial surgery or a history of right atrial cannulation only performed significantly better on the long term compared with patients with limited or extensive atrial surgery. These findings suggest that any prior atrial incision facilitates (re)formation of arrhythmogenic atrial substrates. More complex atrial surgery had no further impact on long-term ablation outcome.

Of importance, long-term outcome in our cohort was significantly better if complete success was achieved, based on our predefined endpoints. Other previously described risk factors for AT recurrence, including older age, multiple unstable AT circuits, non-CT(M)IF, and history of AF, were not associated with AT recurrence in our study.[12,13,32] These findings support the importance of a

standardized approach to test for bidirectional isthmus block across all linear lesions and noninducibility at the end of all CHD ablation procedures.

Redo procedures were performed in 32% of our study cohort, on average only 10 months after the first ablation procedure. Compared with the first ablation procedure, the same substrate was targeted in 64% of all redo procedures. Previous studies have reported the same AT mechanisms and ablation site in only 38% to 50% of all redo procedures compared to the initial procedure.[13,21,34] The suggested mechanisms for AT recurrence were diffuse electrical alterations of atrial tissue, progressive atrial myopathy, or arrhythmogenicity of previous ablative lesions.[21,34] In contrast, our findings suggest that recurrence of AT might be mainly the consequence of lesion recovery, which may be partly explained by thickened atrial myocardium.

Advances in ablation catheter technologies have been developed to address the challenge of creating transmural durable ablation lesions. Higher power delivery in irrigated RF ablation has increased acute procedural success in patients with CHD.[26,38] Long, steerable sheaths improve catheter stability and contact and real-time contact force measurement are helpful for differentiating scar from noncontact sites.[39,40] Remote-controlled magnetic navigation and general anesthesia with high-frequency jet ventilation have been shown to improve catheter stability and might optimize ablation lesions.[19,41] Whether these techniques translate into more durable lesions and better outcome in patients with CHD requires further studies.

Limitations

Data for this study were retrospectively acquired in 3 different European tertiary referral centers. Follow-up visits and monitoring after ablation could, therefore, vary between patients. Asymptomatic cases of recurrent atrial arrhythmias could have been missed in patients without devices. All procedures were performed in tertiary referral centers by experienced operators with comprehensive expertise in CHD cases which might influence the generalization of the results.

Conclusions

The majority of contemporary patients with CHD have a CT(M)I or SVA incision–dependent IART allowing for (empirical) substrate ablation with well-defined procedural endpoints, independent of AT inducibility and CHD complexity. Long-term AT ablation outcome depends on the presence of atrial surgical interventions and achievement of predefined, complete procedural success. In experienced hands, the current challenge of AT ablation in CHD lies more in creating durable ablative lesions, rather than in difficult access or complex AT substrates.

Clinical Competencies

Competency in Medical Knowledge

In contemporary patients with CHD, long-term outcome after AT ablation is not dependent on the CHD complexity but on reaching predefined procedural endpoints.

The high prevalence of 2 underlying, well-defined AT mechanisms and related substrates (CT[M]I and SVA incision dependent IART), which can be delineated without AT induction allows empirical substrate ablation.

Competency in Patient Care (1)

The challenge of AT ablation in patients with CHD lies in creating durable ablative lesions, rather than in complex AT substrates.

Competency in Patient Care (2)

Surgical atrial incisions during initial repair of CHD should be avoided when possible, since long-term outcome is significantly better in patients without a history of prior atrial surgery or only right atrial cannulation.

Translational Outlook

This study has been performed retrospectively in 3 high-volume tertiary referral centers with expertise in patients with CHD. Large prospective studies applying the predefined endpoints for ablation would be desirable. New technologies for improvement of lesion formation should be evaluated in the CHD population.

ARTICLE INFORMATION

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Supplemental Materials

Supplemental Materials and Methods
Supplemental Results
Supplemental Tables I and II
References [42 and 43]

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