The Fontan operation has been the primary technique for surgical palliation of patients with single ventricle physiology since its eponymous description in 1971. Early modifications incorporated the morphological right atrium within the systemic venous-pulmonary circulation, although in its adopted role as the subpulmonary chamber the right atrium hindered rather than contributed to efficient pulmonary blood flow and provided an ideal electroanatomic substrate for atrial arrhythmia that contributed to long-term morbidity and mortality. To overcome these inherent limitations, in 1988, de Leval pioneered a novel surgical variant of the original Fontan procedure, channeling inferior vena caval blood flow directly to the pulmonary artery via an intracardiac baffle created within the posterolateral aspect of the right atrium, generating a pulmonary venous atrium from the remaining morphological right and left atria. Subsequently, the extracardiac connection has been increasingly used. Although these modifications have improved the hemodynamic profile and reduced arrhythmia burden in the short term, arrhythmia remain an important longer-term complication.

By its nature, the total cavopulmonary connection (TCPC) limits access to a significant proportion of atrial myocardium using a standard percutaneous approach. Anterograde access to the pulmonary venous atrium via a fenestration in the intracardiac baffle or a transbaffle puncture is possible in some cases, but allow only a single catheter approach that may significantly hinder accurate determination of arrhythmia mechanism and ablation. The purpose of this study was to determine the varied arrhythmia mechanisms after the TCPC and the feasibility, safety, and success of ablation.

**Background**—The ability to identify and ablate different arrhythmia mechanisms after the total cavopulmonary connection has not been studied in detail.

**Methods and Results**—After obtaining Institutional Review Board approval according to institutional guidelines, consecutive patients after a total cavopulmonary connection undergoing electrophysiology study over a 6-year period were included (2006–2012). Arrhythmia mechanism was determined, and the procedural outcome was defined as complete, partial success, or failure. A 12-point arrhythmia severity score was calculated for each patient at baseline and on follow-up. Fifty-seven procedures were performed on 52 patients (18.4±11.8 years; 53.0±27.2 kg). Access to the pulmonary venous atrium was necessary in 33 procedures, via fenestration (16) or transbaffle puncture (17), and in 2 cases, an additional retrograde approach was used. In total, 80 arrhythmias were identified in 47 cases: macroreentrant (n=25) or focal atrial tachycardia (n=8), atrioventricular nodal reentry tachycardia (n=13), reentry via an accessory pathway (n=4) or via twin atrioventricular nodes (n=4), ventricular tachycardia (n=5), and undefined atrial tachycardia (n=21). Procedural outcome in 32 patients who underwent ablation was complete success (n=25), partial success (n=3), failure (n=3), or empirical ablation (n=1). After successful ablation, there was a significant decrease in arrhythmia score over 18.2 (4–32) months follow-up, with a sustained trend even in the face of arrhythmia recurrence (50%).

**Conclusions**—Arrhythmia mechanism post total cavopulmonary connection is highly varied, encompassing simple and more complex substrates, documentation of which facilitates a strategic approach to invasive arrhythmia management. Despite the anatomic limitations, successful and clinically meaningful ablation is possible. (Circ Arrhythm Electrophysiol. 2015;8:318-325. DOI: 10.1161/CIRCEP.114.001758.)

**Key Words:** arrhythmia • catheter ablation • congenital heart disease • electrophysiology mapping • Fontan procedure • total cavopulmonary connection
WHAT IS KNOWN

• Atrial arrhythmias are a common source of morbidity in patients after the Fontan operation.
• Although recent surgical modifications decrease or delay the arrhythmia burden, it was unclear how anatomic constraints and surgical intervention affected arrhythmia mechanisms and the ability to map and ablate these arrhythmias.

WHAT THE STUDY ADDS:

• This is the largest published experience to date of catheter mapping and ablation in the total cavopulmonary connection population, demonstrating varying arrhythmia mechanisms.
• Specific mechanisms identified included varying forms of macroreentrant and focal atrial tachycardia, varying forms of atrioventricular nodal reentry, and twin nodal tachycardia.
• Despite the limited access to the pulmonary venous atrium, mapping and ablation are possible with an associated measurable improvement in arrhythmia symptoms, even though a high rate of recurrence was documented.

Methods

Data from the case records of all patients after TCPC palliation undergoing invasive electrophysiology studies (EPS) over a 6-year period (March 2006–March 2012) was collected. This study period was based on a stable operator and institutional procedural experience in invasive electrophysiological assessment of the TCPC patients and familiarity with mapping and ablative technologies, thereby minimizing these as potential confounders in our analysis. All studies were performed on clinically defined indications at Boston Children’s Hospital.

Electrophysiology Study

Electrophysiology studies were performed using standard electrophysiological mapping system (Prucka, GE Medical Systems, Milwaukee, WI) with electroanatomic mapping (CARTO, Biosense Webster, Diamond Bar, CA) used where indicated by clinical need. Intra cardiac echo was used on 18 (32%) cases being used in the major-...
during the application of energy in the absence of atrial ectopy and subsequent failure to reinduce the previously identified tachycardia or noninducibility alone if ablation was performed during sinus rhythm.

Procedural case success was considered complete if all inducible arrhythmia mechanisms were successfully ablated and partial if some, but not all, arrhythmia substrates were eliminated. Arrhythmia recurrence was defined by documented arrhythmia on either ECG or pacemaker telemetry.

**Clinical Arrhythmia Severity Score**
Arrhythmia burden during the 3 months before EPS was assessed using a clinically relevant 12-point scoring system subdivided into 4 categories (Table). An arrhythmia score was calculated for each patient at baseline and on each clinical encounter during follow-up where data were available.

**Follow-Up and Adverse Events**
Adverse events were defined as any anticipated or unanticipated event for which injury could or did occur as a consequence of performing the electrophysiological study and assigned a severity level as trivial, minor, moderate, major, or catastrophic. Pre- and postprocedure pulse oximetry data were obtained from clinic visits and follow-up encounters when available, and patient or physician concerns regarding worsening cyanosis were collected.

**Statistical Analysis**
The Kolmogorov–Smirnov test was used to assess normal distribution. Variables with approximately normal distribution were expressed using mean (standard deviation) and those with nonparametric distribution using median (interquartile range). Comparison between clinical arrhythmia scores at baseline and follow-up was made using the Wilcoxon signed-rank test.

**Results**

**Patient Demographics**
In total, 57 electrophysiological procedures were performed in 52 patients (age 18±11.8 years; weight 53±27.2 kg), of whom 48 had an intracardiac and 4 an extracardiac TCPC. Two patients had undergone prior surgical conversion from an atrio-pulmonary Fontan with concomitant arrhythmia surgery, and 5 patients had a repeat EPS during the study period. Arrhythmia had been documented before in 45 patients, and 21 antiarrhythmic agent had been used in 38, including amiodarone (n=6). The clinical indications for EPS were palpitations (n=33), syncope with (n=4) or without palpitations (n=2), documented arrhythmia (n=10), cardiac arrest (n=2), and asymptomatic ventricular preexcitation (n=1). Eleven patients had permanent atrial (n=10) or dual chamber (n=1) pacemakers implanted. Overall follow-up of >3 months was available in 42 patients (81%) with no follow-up in 10 (19%).

**Catheterization Data**
The mean cavopulmonary pressure measured in 46 patients was 16±4.1 mm Hg. Access to the pulmonary venous atrium was required on 33 occasions and was achieved via a fenestration (n=16), using a transbaffle needle (n=14) or radiofrequency puncture (n=3). A retrograde aortic approach was used in combination with the transbaffle approach in 2 cases.

**Arrhythmia Mechanism and Ablation**
Eighty distinct arrhythmia substrates (CL, 312±78ms) were induced in 47 patients further defined as follows:

**Macreorentrant Atrial Tachycardia**
Twenty-five different circuits (CL, 277±55ms) were identified in 17 patients (range 1–4 per patient) using activation mapping alone (13) or in combination with entrainment mapping (12). Using activation mapping, 92%±5% of the tachycardia CL could be accounted for. The cavotricuspid isthmus or CTI (cavitriarial in L-looped ventricles) was critical to 14 circuits (56%), all of which were successfully ablated at this site, either within both the intracardiac baffle and pulmonary venous atrium (10) or in the pulmonary venous atrium alone (4; Figure 1). A further 11 circuits (44%) were independent of the CTI, of which 8 were located and successfully ablated within the intracardiac baffle and 3 were confined to the pulmonary venous atrium. Of the latter, 2 were successfully ablated at the mitral isthmus and posterolateral chamber, respectively, and a third circuit appeared dependent on an inaccessible section of the anterior morphological right atrium. In the 5 patients without a CTI-dependent circuit, 2 had empirical CTI ablation as part of the overall ablative strategy.

**Focal Atrial Tachycardia**
Eight focal tachycardias (CL, 380±57ms) were identified in 5 patients using activation mapping of sustained tachycardia in 7 cases and P-wave morphology during atrial ectopy in 1 case where tachycardia could not be sustained. Six foci were within the intracardiac tunnel and 2 in the pulmonary venous atrium (Figure 2). All 7 sustained tachycardias were successfully ablated.
AVNRT
Thirteen different AVNRT patterns were seen in 8 patients, of which 7 were typical (VA interval 33–65ms) and 6 were atypical (VA interval 176–260ms). Four patients had both typical and atypical patterns, 1 had 2 atypical patterns (Figure 3A) and 1 had typical AVNRT in the upper of twin AV nodes. During programmed atrial stimulation, dual AV nodal physiology as defined by recognized criteria was seen in only 1 patient. Using single ventricular premature beats in tachycardia at progressively shorter coupling intervals to ventricular refractoriness (maximal V1–V2 interval achieved 110–180 ms), atrial reset was not encountered in any patient. Transient 2:1 AV block was seen in 2 patients during tachycardia without change in the VA interval. Ablation was attempted in 7 of 8 patients using radiofrequency alone (n=2), cryotherapy alone (n=3), or both (n=2), with successful modification of AV nodal conduction properties in 6 patients.

Accessory Pathway Mediated AVRT
Orthodromic AVRT was seen in 4 patients. Two patients had manifest preexcitation on surface ECG, 1 of whom was asymptomatic with rapid pathway conduction demonstrable on a prior limited study. The pathway refractory period was 280 ms in both cases. Both cases with concealed pathways showed VA conduction that was nondecremental and resistant to adenosine. AVRT was induced in each case, although the preexcitation index was calculated in only 1 case (70 ms) because of hemodynamic instability or CL variability in the others. A single accessory pathway was seen in each patient (2 posteroseptal and 2 left posterior), and ablation was successful in all 4 cases. Of note, both patients with concealed pathways had undergone prior ablation of manifest pathways located at different anatomic sites.

Twin AV Nodal Tachycardia
Twin AV nodes facilitated 4 patterns of reentrant tachycardia in 3 patients who all had the anatomic triad of atrial isomerism, atrioventricular septal defect, and discordant VA connections. In 2 cases, anterograde conduction was exclusively via the superior AV node during tachycardia and via either the superior or inferior AV node in a single case (Figure 3C). Ablation was successfully performed in 1 patient and deferred in 2 because of the risk of atrioventricular block in minimally symptomatic patients.

Other Atrial Arrhythmias
An additional 21 atrial arrhythmias were induced in 14 patients, which led to hemodynamic instability (n=2), were not considered clinically relevant (n=6), degenerated to atrial fibrillation necessitating cardioversion (n=1), or were non sustained (n=12). These were not mapped in sufficient detail to define mechanism nor were ablation performed.

Ventricular Tachycardia
Ventricular tachycardia was recorded in 5 patients, 2 of them with previously documented ventricular tachycardia. The 3 remaining had a history of syncope and were inducible via ventricular drive trains with 3 extrastimuli. One patient underwent ablation for repeated episodes of monomorphic ventricular tachycardia, despite amiodarone therapy, which was ultimately unsuccessful. The clinical relevance of ventricular tachycardia in the other 4 patients remains uncertain. None of these patients had atrial arrhythmias identified during the study.

Noninducible Patients
Of the 5 patients with no inducible arrhythmias, 4 patients were symptomatic with atrial tachycardia pre-EPS, with tachycardia documented in 3 patients on prior noninvasive assessment. The fifth patient, who had no prior arrhythmia history but known severe ventricular dysfunction and prior cardiac arrest, underwent empirical CTI ablation based on the possibility of rapidly conducted atrial tachycardia.

Patient Outcomes
Ablation and Arrhythmia Recurrence
Overall, 32 of the 52 patients underwent ablation, complete procedural success was achieved in 25 patients (76%), partial success in 3 (9%), failure in 3 (9%), and empirical ablation in 1 (3%). Five patients had second procedures in this time. One patient did not undergo ablation on the first EPS, but subsequently had a successful ablation. Four had second procedures for arrhythmia recurrence at 8 days, 2, 11, and 39 months all following acutely successful ablation procedures. The same arrhythmia mechanism was seen in 1, but a different mechanism in 3. The second procedure was successful in 2, partially successful in 1, and no ablation performed in the final patient because of induction of only nonspecific atrial arrhythmia. Including patients who underwent 2 procedures, of the 28 patients who had an initial ablation with either complete...
or partial success, follow-up data were available for 22 (79%), of whom 11 (50%) had documented arrhythmia recurrence.

**Clinical Arrhythmia Severity Score**

Over a median follow-up of 18.2 (4–33) months in 45 patients, 5 (2–8) arrhythmia scores were recorded per patient. Arrhythmia scores are displayed in Figure 4. Scores at follow-up in those with documented arrhythmia recurrence were higher than those without, although a trend in reduction from preprocedure scores was still evident at >24 months follow-up despite recurrence. In those with no arrhythmia recurrence,
the median arrhythmia score at 24 months remained at \( \leq 1 \), with the loss of statistical significance likely relating to small numbers.

**Adverse Events**

Two major adverse events occurred during the study. A 47-year-old man died 6 days after an unsuccessful procedure after the onset of a wide complex tachycardia from which he could not be resuscitated. A 31-year-old male suffered a pulmonary embolus to the left lung diagnosed on thoracic CT scan, from which he made a full recovery. In addition, 1 patient who had previously suffered an out-of-hospital cardiac arrest before EPS died from multiorgan failure 1 month later, having undergone an empirical cavotricuspid isthmus ablation during that admission. Minor adverse events included 2 cases of transient atrioventricular block after AVNRT and AVRT ablations, respectively, and 1 case each of groin hematoma and femoral venous bleeding postprocedure.

There were 4 patients in whom an arbitrary drop in the pulse oximetry of >5% was recorded when the preprocedure saturation was compared with that during follow-up clinic encounters. Two of them had a transbaffle puncture performed during the procedure and 2 did not, and no study patients had worsening cyanosis recorded as 1 of their main follow-up complaints or as a concern from their referring cardiologist.

Figure 4. Clinical arrhythmia severity score at baseline and during follow-up. The \( P \) value for comparison between baseline and the postprocedure encounters is displayed under the time interval. EPS indicates electrophysiology studies.
Discussion

These findings represent the largest published experience of catheter ablation after the TCPC reported to date, providing novel information on both arrhythmia mechanism in a heterogeneous population with single ventricle physiology and the feasibility of detailed mapping despite the anatomic constraints. The major findings are as follows: first, arrhythmia mechanism is highly varied, encompassing reentrant circuits, focal atrial tachycardia, and the more common substrates, atrioventricular nodal, and atrioventricular reentry using either an accessory pathway or second AV node. Second, despite limited catheter access to the pulmonary venous atrium, successful mapping, mechanistic determination, and delivery of ablation lesions is possible. Third, using a clinically relevant arrhythmia scoring system, successful ablation is associated with a reduction in score with a trend that persisted even in the presence of arrhythmia recurrence.

Arrhythmia Mechanism

A mechanism for reentrant arrhythmias after the intracardiac TCPC was first proposed using animal models. Suture lines created along the posterolateral wall of the right atrium created a line of intercalated conduction block, permitting the development of a reentrant circuit using the tricuspid annulus as the anterior central barrier, analogous to classical atrial flutter where the cristaterminalis acts as the posterior obstacle. Reentry could be induced acutely using programmed extrastimuli or was initiated spontaneously by atrial extrastyles. Initiation of tachycardia could be prevented by creation of a further line of fixed block between the suture line and the tricuspid annulus to interrupt the circuit. The data presented here would support the clinical relevance of peri-tricuspid circuits and 6 of 8 focal tachycardias were located within the intracardiac baffle, suggesting that the hemodynamic burden imposed by the pulmonary circulation has the ability to remodel a small section of atrial myocardium, including the crista terminalis sufficiently to facilitate arrhythmia.

Interestingly, 8 of the 11 non-CTI dependent reentrant circuits and 6 of 8 focal tachycardias were located within the intracardiac baffle, suggesting that the hemodynamic burden imposed by the pulmonary circulation has the ability to remodel a small section of atrial myocardium, including the crista terminalis sufficiently to facilitate arrhythmia.

More simple substrates, including AVNRT and AVRT, via either an accessory pathway or a second AV node were prevalent, accounting for 21 different arrhythmias in 15 patients. Those with relatively slow cycle length and 1:1 AV relationship may seem similar to focal atrial tachycardia, although accurate differentiation can be performed using simple pacing maneuvers, such as the A-V response on cessation of pacing. The emergence of more common arrhythmia substrates and specifically AVNRT may reflect the natural history of congenital cardiac surgery over the last 3 decades, where palliative surgery was offered to infants with increasingly complex cardiac disease potentially involving the intrinsic conduction system. In this study, 4 of 8 patients with AVNRT had both typical and atypical variants, much higher than would be typically seen in patients with a normal heart. Such mechanisms should be actively considered in the presence of a 1:1 AV relationship and may be highlighted by those with recurrent, spontaneously terminating arrhythmia.

Empirical ablation at sites of slow conduction and low electrogram amplitude with a view to prevent further arrhythmia recurrence was not routinely performed during this study. It was our practice to address all inducible arrhythmias where possible. The decision to undertake such an ablative strategy should be balanced between the true potential for future arrhythmia reduction and the potential for incomplete, proarrhythmic lesions and should be performed in a highly individualized manner.

Patient Outcomes

Despite advances in arrhythmia mapping and ablative technology, arrhythmia recurrence remains significant in the TCPC population, a major issue in prior iterations of the Fontan procedure. Five patients had a second procedure during the study period, with a different mechanism seen in 3. This suggests an ongoing process of remodeling and arrhythmogenesis secondary to the underlying hemodynamic limitations of the circulation, as noted in previous reports. However, the wisdom of using arrhythmia recurrence as the only marker of success for electrophysiology study and catheter ablation has been questioned previously, prompting the development of the arrhythmia scoring system used here. The persistent improvement seen in those who underwent ablation, and the sustained trend even in the face of arrhythmia recurrence, supports the notion that symptomatic improvement is not driven only by complete arrhythmia elimination.

Two serious adverse events occurred during the study; a pulmonary embolus presumably related to thrombus developing within the intracardiac baffle after the ablation and a fatal arrhythmic storm several days after a failed procedure. These serve as a reminder of the potential instability of patients after single ventricular palliation and the importance of vigilant peri-procedural care. Despite the potential issues related to catheter stability during ablation and potential for anomalous locations of the atrioventricular conducting system within these patients, only 2 cases of transient AV block occurred. Synchronous dual chamber pacing in the single ventricle population not only necessitates epicardial lead placement with the associated procedural morbidity, but may be associated with significant decrease in ventricular function and change in morphology secondary to the dyssynchronous effects of single site pacing. Cryoablation with the benefits of catheter adhesion may limit the potential for AV block.

Study Limitations

This study is a retrospective analysis of 52 patients undergoing clinically necessitated electrophysiology studies and ablation. The specific approach to each case was based on operator preference rather than a predetermined protocol. Limited number of catheters within the pulmonary venous atrium during tachycardia prevented the use of certain pacing maneuvers that may have provided additional benefit in mechanistic
determination, for example, assessment of the postpacing interval corrected for AH delay to differentiate AVNRT from AVRT.\textsuperscript{20} The analysis of the arrhythmia score on the subgroup of patients with arrhythmia recurrence was limited by the fact that a documented arrhythmia itself would by definition increase ≥1 point and by ≤3 the total score. In this setting, the fact that there was a strong sustained trend of lower arrhythmia scores would suggest improvement in the overall clinical status that was reflected on the other measured components of the scale. Finally, because of the referral pattern to our institution, follow-up data are not uniform or complete.

Conclusions
Arrhythmia mechanism after the total cavopulmonary connection is varied and relates to the underlying anatomy, surgical procedures, and ongoing hemodynamic effects on atrial myocardiun. Despite the anatomic limitations imposed, successful mapping and ablation are possible with sustained clinical benefit. Based on the findings reported here, a sequential approach to arrhythmia mechanistic determination may be adopted.

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Video 1: Demonstration of most common uses of intracardiac echocardiography (ICE) during diagnostic and ablative procedures in patients following total cavopulmonary connection.

Intracardiac echocardiography (ICE) provides detailed definition of the cardiac anatomy, specifically the position of the atrioventricular valves, which may act as central obstacles to conduction in reentrant circuits. Additionally ICE may help identify the precise location of baffle fenestrations guiding catheter access to the pulmonary venous chamber, and demonstrate good tissue contact at during radiofrequency ablation.