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Review

Technological Advances in Arrhythmia Management Applied to Adults With Congenital Heart Disease

Blandine Mondésert, MD,[a] Krishnakumar Nair, MD,[b] Christopher J. McLeod, MB, ChB, PhD,[c] and Paul Khairy, MD, PhD[a]

[a] *Electrophysiology Service and Adult Congenital Heart Disease Center, Montreal Heart Institute, Department of Medicine, Université de Montréal, Montreal, Quebec, Canada*

[b] *Division of Cardiology, University Health Network, Toronto General Hospital, Toronto, Ontario, Canada*

[c] *Electrophysiology Service, Mayo Clinic, Jacksonville, Florida, USA*

ABSTRACT

Arrhythmias are a leading cause of morbidity in adults with congenital heart disease. Numerous challenges to managing arrhythmias include vascular access issues, intracardiac shunts, unconventional locations of the conduction system, and anatomical complexities. Technological advances are improving our ability to diagnose and treat arrhythmias. Implantable loop recorders and various technologies developed for consumers to record electrocardiographic tracings using smartphone applications, watches, and dedicated portable devices are expanding our armamentarium of diagnostic tools. Remote magnetic-guided catheter ablation is enhancing access to otherwise difficult to reach arrhythmia substrates. Cryoablation allows perinodal arrhythmias to be safely treated in patients with displaced or difficult to predict locations of the atrioventricular conduction system. Interventions that minimize radiation exposure to near 0 levels are gaining interest and pulmonary

RÉSUMÉ

Les arythmies sont une des principales causes de morbidité chez les adultes atteints d'une cardiopathie congénitale. Les nombreux défis dans la prise en charge des arythmies comprennent les problèmes liés à l'accès vasculaire, les shunts intracardiaques, la configuration inhabituelle du système de conduction et les complexités anatomiques. Les avancées technologiques améliorent notre capacité à diagnostiquer et à traiter les arythmies. Les enregistreurs en boucle implantables et diverses technologies mises au point pour permettre aux consommateurs d'enregistrer des tracés électrocardiographiques au moyen d'applications pour téléphones intelligents, de montres ou d'appareils portables dédiés élargissent notre arsenal d'outils diagnostiques. L'ablation à distance par cathéter guidé magnétiquement améliore l'accès à des substrats anatomiques de l'arythmie qui seraient autrement difficiles à atteindre. La cryoablation permet de

Advances in the management of children and adults with congenital heart disease (CHD) have had a major effect on long-term survival,[1] such that the projected number of adults with CHD in Europe and North America now exceeds 3.5 million.[2-4] As adults with CHD age, arrhythmias ranging from sinus node dysfunction to ventricular fibrillation increase in prevalence.[5-7] Recommendations on the recognition and treatment of arrhythmias have been incorporated in Canadian, US, and European management guidelines for adults with CHD.[8-10] Moreover, expert societies recognized that there are numerous, sometimes unique, challenges and issues involved in managing arrhythmias in this patient population, such that an international panel was convened to provide detailed consensus-based recommendations.[11] Overcoming some of the challenges related to vascular access issues and anatomical complexities is highly dependent on available tools and technologies. Herein, we review technological advances that are revolutionizing the way arrhythmias are detected and treated in adults with CHD (Table 1).

Arrhythmia Detection

Ambulatory electrocardiogram monitoring

Detecting and accurately diagnosing arrhythmias remains the cornerstone of patient management. Class I recommendations have been proposed for standard electrocardiograms (ECGs), ambulatory ECG monitoring, cardiac event loop recorders, and implantable loop recorders.[11] Whereas a 12-lead ECG is an integral component of routine follow-up, ambulatory ECG monitoring is indicated when there is a need to clarify or exclude an arrhythmia, establish a

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Corresponding author: Dr Blandine Mondésert, Montreal Heart Institute, 5000 rue Bélanger, Montreal, Quebec H1T 1C8, Canada. Tel.: +1-514-376-3330.

E-mail: blandine.mondesert@icm-mhi.org

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vein isolation procedures to treat atrial fibrillation are increasingly performed. Cardiac implantable electronic devices compatible with magnetic resonance imaging have become the norm. Subcutaneous defibrillators and leadless pacemakers are providing effective solutions to patients in whom transvenous leads are contraindicated or not desired. His-bundle pacing is emerging as a viable option to provide more physiological pacing. Progressive advances in multicomponent communicating leadless devices carry the promise of providing leadless dual chamber pacing and cardiac resynchronization therapy in the near future. The safety of transvenous lead extraction procedures is likely to improve with advances such as the low-pressure balloon to manage superior vena cava lacerations. Awareness of these developments and referral to sites with dedicated expertise could contribute to further improving outcomes in adults with congenital heart disease.

traiter sans danger les arythmies périnodales chez les patients dont le système de conduction auriculoventriculaire est déplacé ou localisé de façon difficilement prévisible. Les interventions permettant de réduire au minimum l'exposition au rayonnement, à des niveaux presque nuls, suscitent de plus en plus d'intérêt, et les interventions d'isolement des veines pulmonaires pour le traitement de la fibrillation auriculaire sont de plus en plus pratiquées. Les dispositifs cardiaques électroniques implantables compatibles avec l'imagerie par résonance magnétique sont devenus la norme. Les défibrillateurs sous-cutanés et les stimulateurs cardiaques sans électrodes offrent des solutions efficaces aux patients chez qui les électrodes transveineuses sont contre-indiquées ou non souhaitées. La stimulation du faisceau de His s'affirme peu à peu comme une option viable de stimulation plus physiologique. Les avancées progressives dans la conception de dispositifs multicomposants de communication sans électrodes permettent d'espérer l'avènement prochain de traitements comme la stimulation double chambre et la resynchronisation cardiaque sans électrodes. L'innocuité des interventions d'extraction des électrodes par voie intraveineuse sera probablement améliorée grâce aux avancées comme l'utilisation du ballon à faible pression dans la prise en charge des lacérations de la veine cave supérieure. La connaissance de ces progrès et l'orientation vers des sites fondés sur une expertise spécialisée pourraient contribuer à la poursuite de l'amélioration des résultats thérapeutiques pour les adultes atteints de cardiopathie congénitale.

correlation with symptoms, assess risk, or determine appropriate therapy.[11]

Importantly, the yield of ambulatory ECG monitoring is dependent, in part, on the duration of screening. For example, in a retrospective series of adults with CHD, the prevalence of detected arrhythmias was twofold higher with 24-hour Holter monitoring compared with a standard ECG (31% vs 15%).[12] One-quarter of the patients with arrhythmias detected using Holter had unrevealing ECGs, and 80% of patients with detected arrhythmias were asymptomatic. In symptomatic patients, 37% experienced similar symptoms during Holter monitoring, thereby allowing for a diagnosis to be established. A second series assessed the value of Holter monitors in 189 patients with tetralogy of Fallot (n = 100), Fontan surgery (n = 51), or transposition of the great arteries with atrial baffles (n = 38).[13] The test was considered "clinically significant" if it prompted a change in therapy. By this definition, a modest (40%) sensitivity for routine monitoring was reported, with a high (96%) negative predictive value for future clinically significant arrhythmias. The diagnostic yield improved with older age.

In selected populations with syncope or at increased risk for atrial fibrillation (AF), the diagnostic yield of a 24-hour Holter monitor varied from 2% to 11%.[14,15] By increasing the monitoring period to 7-30 days, the detection of AF or syncopal events increased to 16-25%.[15,16] In a comparison of 24-hour Holter vs 14-day monitoring (Zio patch, IRhythm, San Francisco, CA) in 146 patients, 61 vs 96 arrhythmias were detected ($P < 0.001$).[17] Applying these monitoring strategies to children, 57% of detected arrhythmias occurred after 24 hours.[18] In another report, 29% of arrhythmias were recorded after > 48 hours.[19] In short, a substantial proportion of arrhythmias escape detection when monitoring is limited to 24 hours.

Table 1. Challenges and solutions in adults with CHD

Challenges in adults with CHD	Technological advancements
Diagnosis	Diagnosis
• Unproven arrhythmias • Stroke risk evaluation • Radiation exposure secondary to medical exams • Contraindication to MRI	• Long-term monitoring • Implantable cardiac monitoring • Low dose radiation exams, nonradiation exams (MRI) • MRI conditional devices
Treatment	Treatment
• Need for CIED but vascular obstructions or inaccessible cardiac chambers • Arrhythmias in patients without vascular access, inaccessible chambers, or difficult to reach substrates • Radiation exposure due to procedures • Structural, electrophysiological, surgical procedures at the same time	• Subcutaneous ICD • Leadless pacemaker • Extravascular devices • 3-D navigation systems • Remote magnetic-guided navigation • Low dose settings, zero fluoroscopic procedures • Heart team approach with combined procedures and multidisciplinary expertise
Follow-up	Follow-up
• Frequent in-clinic visit with high rate of no show	• Remote monitoring

CHD, congenital heart disease; CIED, cardiac implantable electronic device; ICD, implantable cardioverter-defibrillator; MRI, magnetic resonance imaging.

Loop recorders

Cardiac event loop recorders are typically indicated to establish whether or not sporadic symptoms are caused by transient arrhythmias; or whether cryptogenic stroke can be linked to subclinical atrial arrhythmia.[11] Where the index of suspicion for a malignant arrhythmia is high (eg, syncope of

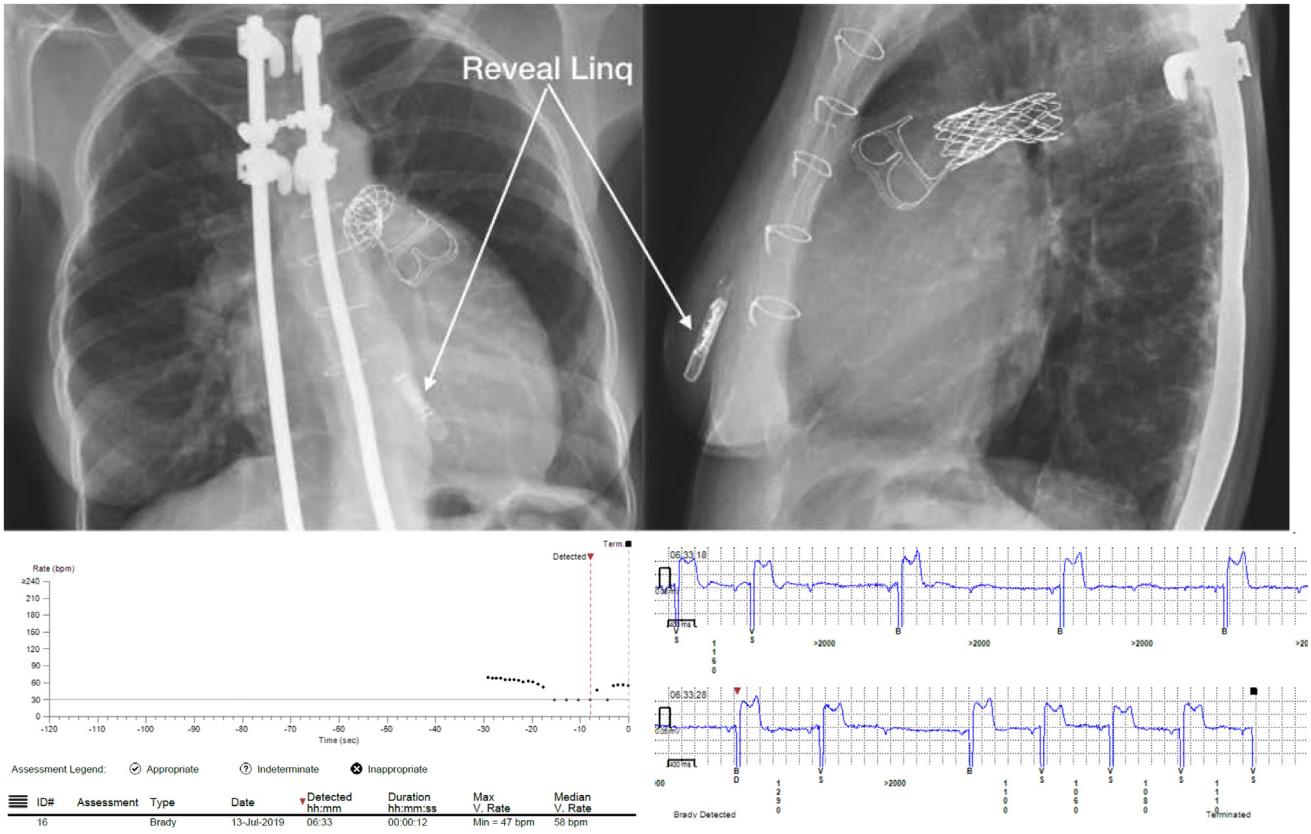

Figure 1. Implantable cardiac monitor in an adult with congenital heart disease. The **upper panel** shows radiographic posteroanterior and left lateral views of an implantable cardiac monitor in a 56-year-old patient with Turner syndrome, ventricular septal defect, and pulmonary stenosis, with a stent in the proximal pulmonary artery. The **lower panel** captures a 12-second complete atrioventricular block associated with dizziness. VS, ventricular sensed event.

unclear origin) but a symptom-rhythm correlation cannot be established by other means, implantable cardiac monitors (ICMs) can be of value (Fig. 1).[11] Modern ICMs are inch-long recording chips inserted subcutaneously in a parasternal location using local anaesthesia. The procedure can potentially be performed in an office setting, outside of an electrophysiology laboratory. ICMs offer longer-term monitoring (2-4 years) than standard external loop recorders. Data are stored automatically according to programmed parameters for brady- and tachyarrhythmias and upon patient activation. Technological advances are contributing to an enhanced power to detect arrhythmias using new algorithms for AF and bradyarrhythmias, filtering and detection processes, and novel self-learning intelligence. Moreover, home monitoring systems with or without cellphone capabilities add to the simplicity of using these devices, which might be particularly attractive to the young population with CHD.

In a retrospective cohort of 22 patients with CHD, the most frequent indication for an ICM was syncope followed by palpitations.[20] The ICM led to a diagnosis (either confirming or excluding arrhythmia) in 71% of patients. A more recent study of 94 patients with an ICM included 4 patients with CHD (with the others having other forms of structural heart disease or an inherited arrhythmia syndrome).[21] The diagnostic yield was 45% at 10 months, with a higher yield in patients with structural heart disease (60%). A higher rate of nonsustained ventricular tachycardia was observed in patients with structural heart disease (30%). Newer ICMs (Reveal LINQ [Medtronic, Minneapolis, MN]; Confirm Rx [Abbott, Chicago, IL]; Biomonitor2 [Biotronik, Berlin, Germany]) are smaller (1.2-5 cc), which is advantageous for smaller and dysmorphic adults (pectus excavatum) with CHD, and are also associated with lower bleeding and infection rates,[22] shorter procedural times (15 vs 23 minutes), and lower costs.[23]

Consumer-wearable ECG monitoring devices

Detecting atrial arrhythmias, particularly AF and intra-atrial re-entrant tachycardia, is important in adults with CHD for several reasons, including prevention of thromboembolic complications and heart failure.[24-26] There is growing interest in new technologies developed for consumers to record and monitor their own ECG tracings using smartphone applications, watches, and dedicated portable units.[27] These technologies empower patients to more actively participate in their health care. Consumer-wearable ECG monitoring is likely to progressively affect the care of adults with CHD considering the age bracket of this patient population,[28] the high prevalence of arrhythmias, and the practical, compact, and increasingly ubiquitous nature of these technologies.

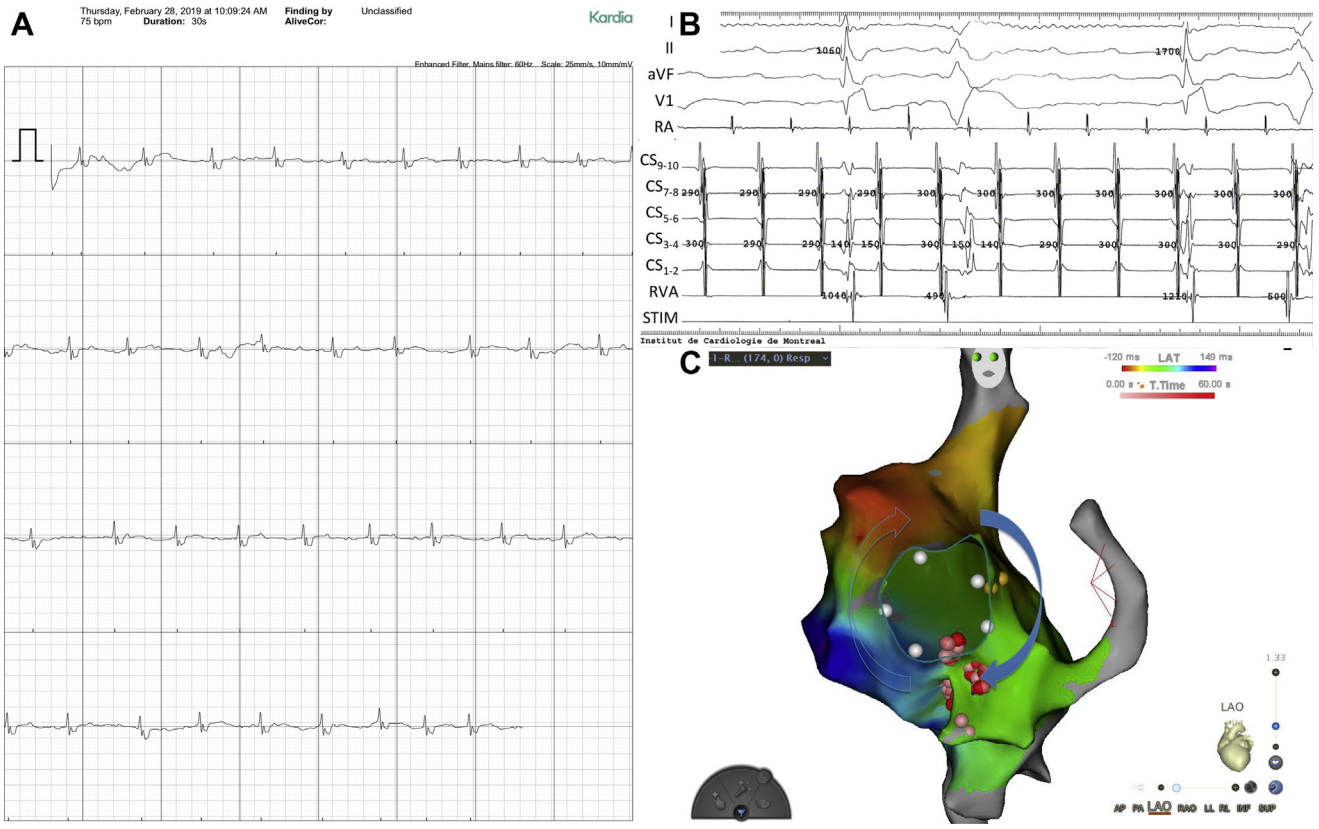

Figure 2. Arrhythmia captured by a smartphone-based application in a patient with tetralogy of Fallot. (**A**) A 34-year-old woman with surgically repaired tetralogy of Fallot captured her arrhythmia using the Kardia Mobile (AliveCor, Mountain View, CA) device with an iPhone app. The 30-second lead I tracing was classified as "undetermined." Upon review, it appeared consistent with intra-atrial re-entrant tachycardia with slow and variable atrioventricular conduction. An intra-atrial re-entrant tachycardia with a cycle length of 290 to 300 ms was confirmed in an electrophysiological study. (**B**) Surface electrocardiogram leads I, II, aVF, and VI followed by intracardiac recordings from the lateral right atrium, coronary sinus, and right ventricular apex. Electroanatomic mapping is depicted in (**C**) in a left anterior oblique view. Local activation times are colour-coded, with the site of earliest atrial activation in **white** and latest in **dark blue**.

The earliest use of smartphones to monitor cardiac activity was by means of photo plethysmography, whereby a heart rate was obtained by placing a finger over a camera lens and flash. The technology subsequently morphed into single-lead ECG recordings, typically by using 2 electrodes and an application to process the data. The first such technology by Kardia Mobile (AliveCor, Mountain View, CA) received Food and Drug Administration (FDA) 510(k) approval in December 2012. Its algorithms have subsequently been cleared by the FDA and received European Conformity to classify tracings as normal, interference, or AF. Shortly after, ECG Check (Cardiac Designs, Round Rock, TX), which is also compatible with iPhone and Android devices, followed suit (Fig. 2). D-Heart (D-Heart, Genova, Italy) is working on a smartphone-based technology to display an 8-lead ECG using adhesive electrodes, with the intention of targeting underserved areas of the world. Free-standing devices under development include the EPI Mini (EPI Mobile Health Solutions, Paragon, Singapore) and iHealth Rhythm (iHealth Labs, Mountain View, CA).

In adults with CHD, skin perfusion for heart rate readings can potentially be influenced by vascular anomalies and previous palliative shunts (eg, Blalock Taussig shunt). In addition, the ideal position of leads and monitors could vary according to cardiac malposition. Although several brands of fitness watches and bands measure pulse rates using photo plethysmography, the Apple Watch series 4 (Apple Inc, Cupertino, CA) is the first smart watch to receive FDA approval for its ECG sensor and AF detection algorithm. At the time of writing, this feature was only available in the United States and its territories of Puerto Rico, Guam, and the US Virgin Islands. The Apple Heart Study, a prospective single-arm observational study, self-enrolled 419,297 participants (NCT03335800).[29] Presented in abstract form at the 2019 American College of Cardiology Scientific Sessions, approximately 0.5% of participants received an irregular pulse notification.[30] Among those with notifications who followed up with ECG patch monitoring, one-third (34%) were found to have AF. Although a full-length report remains to be scrutinized, these preliminary results shed light on the potential for consumer-wearable technologies to affect patient care. Lower confidence limits for sensitivity and specificity values of 95.8% and 99.7%, respectively, were reported in study participants with newer devices with and without a history of AF.[31] The focus has thus far been on detecting AF, which is increasing in prevalence in adults with CHD.[32] Macro re-entrant atrial circuits are the most common sustained arrhythmias in adults with CHD and no wearable ECG algorithm has been validated for this purpose. Nevertheless, these technologies allow for users to record and share ECG tracings with their physicians thereby extending diagnostic capabilities beyond the realm of AF.

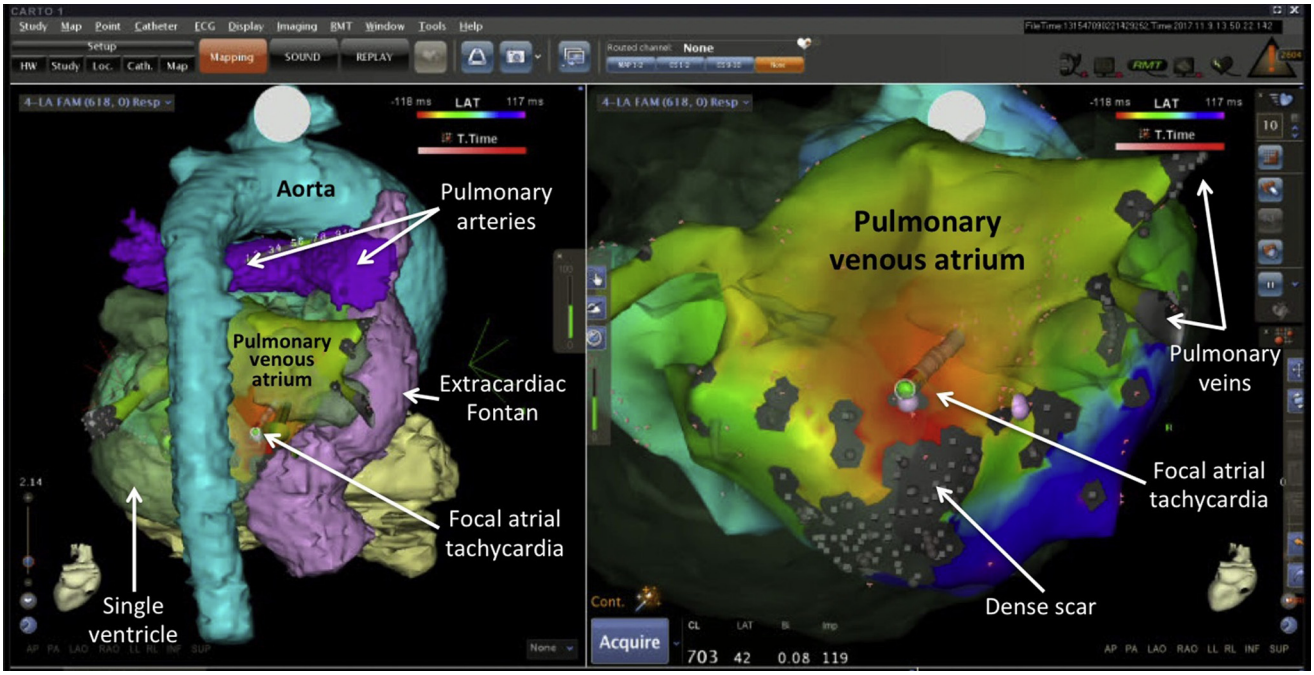

Figure 3. Remote magnetic-guided retrograde approach to catheter ablation in a patient with a single ventricle and extracardiac Fontan. Shown are posteroanterior views of electoanatomic mapping with computed tomography scan image integration of of a nonautomatic focal atrial tachycardia in a patient with a univentricular heart and extracardiac Fontan conduit. Retrograde aortic access to the pulmonary venous atrium was obtained using a soft and flexible magnetic-guided irrigated radiofrequency ablation catheter. In the **left panel**, note the location of the focal atrial tachycardia in the inferior portion of the pulmonary venous atrium, above the site where the inferior vena cava was transected and connected to the extracardiac conduit. On the **right panel**, the focal atrial tachycardia is seen bordering the dense scar, which is the presumed site of the transected and oversewn inferior vena cava.

Catheter Ablation

Remote magnetic-guided (remote magnetic navigation) catheter ablation

Catheter ablation plays a central role in the management of atrial and ventricular arrhythmias in adults with CHD.[11] However, catheter access to arrhythmia substrates can prove challenging because of vascular anomalies or complex anatomies.[33] Integration of 3-D imaging is deemed essential to providing an anatomic roadmap in such cases. An elegant technological solution that is well tailored to the CHD population is the use of remote magnetic navigation (RMN).[34] With this approach, soft and flexible mapping and radiofrequency ablation catheters can be steered toward otherwise unattainable areas. This system has been used to reach arrhythmias in pulmonary venous atria by means of a retrograde aortic approach, thereby overcoming limitations to venous access and obviating the need for complex transbaffle punctures (Fig. 3). Moreover, the risk of perforation is virtually eliminated by the soft catheters.[34,35] *In vitro* experiments have shown that the contact pressure generated by the current system (Niobe ES RMN System, Stereotaxis, St Louis, MO) can reach 20 g.[36] Limitations include costs and the inability to integrate multielectrode mapping as yet.

The literature on RMN in patients with CHD remains limited, on the order of approximately 200 patients, mostly on atrial arrhythmias. Safety and feasibility have been shown in those with complex CHD.[34,3537-43] Despite the small volumes and learning curves, reported acute success rates have ranged from 82% to 100%, with 67% to 100% freedom from arrhythmia recurrence at a mean follow-up of 4-20 months.[40] In addition to the advantages regarding access to arrhythmia substrates, shorter procedural and fluoroscopy times have been reported. After a learning curve, the mean fluoroscopy exposure time was reported to decrease from 40 to 1.6 minutes.[43] Although no cardiac perforation or pericardial effusion has been reported, the RMN system remains subject to standard complications related to vascular access, thromboemboli, and infections.[43] Larger studies are required to provide more accurate estimates of acute and long-term efficacy and complication rates. It also remains to be determined whether the favourable outcomes reported for RMN-guided ventricular tachycardia ablation in non-CHD patients[44] can be mirrored in the adult CHD population.

Cryoablation

In addition to issues related to catheter access, another challenge encountered in adults with CHD is the ablation of perinodal arrhythmias in the context of displaced or difficult to predict locations of the atrioventricular conduction system. Distinct from radiofrequency ablation, cryoablation (Medtronic CryoCath LP, Montreal, QB) allows for reversible electrophysiological effects before permanent tissue destruction. Moreover, adhesion of the catheter tip to the endocardial

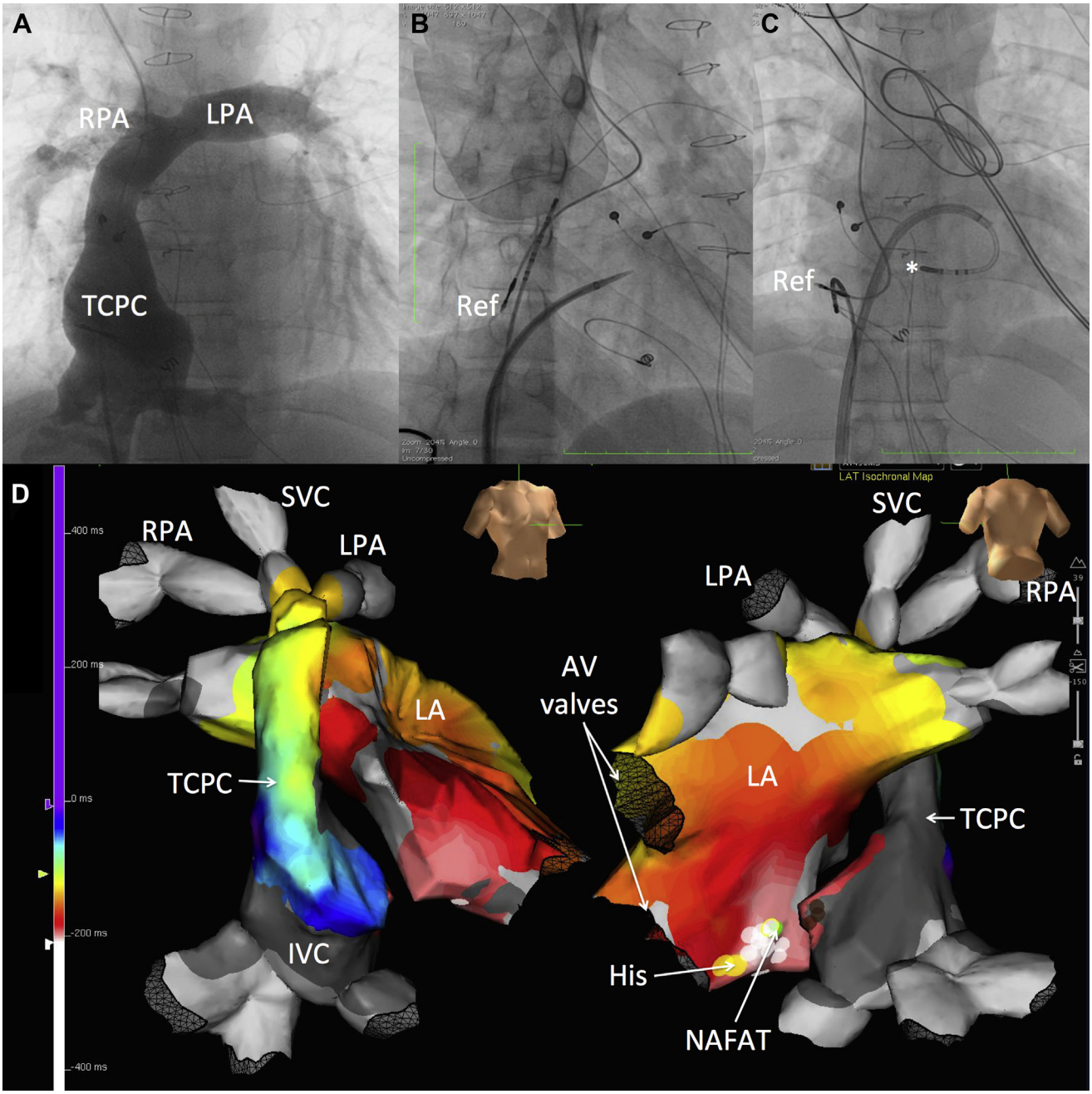

Figure 4. Cryoablation of a para-Hisian nonautomatic focal atrial tachycardia (NAFAT) through a transbaffle puncture in a patient with a double-inlet left ventricle and intracardiac lateral tunnel total cavopulmonary connection (TCPC) Fontan. Contrast angiography of the intracardiac TCPC Fontan is shown in (**A**). A right anterior oblique view of the transseptal needle is shown in (**B**). A reference catheter (Ref) consisting of a transvenous pacemaker lead was screwed onto the lateral wall of the TCPC via the right internal jugular vein. Position of the cryocatheter at the site of successful ablation of the NAFAT using transbaffle access is shown in (**C**) (**asterisk**). (**D**) Three-dimensional electroanatomic maps of the TCPC and neo-left atrium (LA) in anterior and posterior views. His bundle recordings are marked by the **yellow circles**. The site of successful cryoablation of the peri-Hisian NAFAT is indicated by the **green circle**. AV, atrioventricular; LPA, left pulmonary artery; RPA, right pulmonary artery; SVC, superior vena cava. Reproduced from Ávila et al.[49] with permission from Elsevier.

surface enhances catheter stability, a feature particularly advantageous in the setting of perinodal arrhythmias.[45-48]

In adults with CHD who underwent cryoablation for atrial arrhythmias, recurrence rates ranging from 6% to 10% were reported at a follow-up of 24-26 months.[47,48] In a single-centre case series, cryoablation proved to be safe and moderately effective in ablating perinodal arrhythmias in patients with single-ventricle physiology (Fig. 4), congenitally corrected transposition of the great arteries, atrioventricular septal defects, and complete transposition of the great arteries with an atrial baffle.[49] Cryoablation was acutely successful in 75% of targeted arrhythmias, with no procedural complications. In the remaining cases, cryoablation was deemed useful in showing safety before effective crossover to radiofrequency ablation.[49] It

is, therefore, thought to be helpful in localizing and eliminating slow pathway inputs to atrioventricular nodes that are not within the usual confines of Koch's triangle and in ablating septal circuits and perinodal or peri-Hisian focal tachycardias.

Zero fluoroscopy

Three-dimensional electroanatomic mapping systems allow for catheter ablation procedures to be performed with 0 or near 0 radiation exposure. Radiation exposure is a matter of concern to all patients, as promulgated by the "as low as reasonably achievable" principle.[50] Nevertheless, there is increased awareness about further minimizing radiation exposure to vulnerable subgroups such as children, pregnant women, and CHD patients who require multiple interventions (electrophysiological and hemodynamic) during a lifespan. The Carto Univusystem (Biosense-Webster Inc, Irvine, CA) was assessed in 55 patients with CHD who required 63 ablation procedures.[51] In this setting, the system was associated with a median fluoroscopy time of 8 seconds, median total dose area product of 55 cGy/cm^2, and median effective dose of 0.136 mSv. Overall, 89% of ablation procedures were performed with an effective dose < 1 mSv.

Periprocedural imaging with ultrasound technologies such as intracardiac echocardiography and transesophageal echocardiography can also contribute to a reduction in fluoroscopy dose, as reported in a non-CHD population with ablation for AF or ventricular tachycardia.[52] Additional simple precautions such as limiting cine acquisition, adjusting the height of the table, reducing the frame rate, lowering the radiation dose per pulse, and collimation could have a major effect on reducing radiation exposure to the patient and personnel.[50] Age at exposure and higher dose of radiation received remain primary determinants in conferring carcinogenic risk—a distinct consideration in the younger population of CHD patients.[53] For example, the lifetime attributable risk of radiation-induced cancer was projected to be 25 per 1000 procedures in girls exposed to > 10 mSv at younger than 1 year of age and decreased with a lower dose and older age.[54]

Ablation of atrial arrhythmias

With AF poised to become the next arrhythmic epidemic to strike adults with CHD after intra-atrial re-entrant tachycardia,[24] there is a growing interest in AF ablation procedures centred on pulmonary vein isolation (PVI) in this patient population.[25] Outcomes for catheter ablation have improved considerably since the introduction of 3-D electroanatomic mapping systems and irrigated or large electrode-tip catheters capable of creating deeper lesions.[55]

The largest series of PVI-based AF ablation consists of 57 patients with an average age of 51 years, 61% of whom had simple, 18% moderate, and 21% complex forms of CHD.[56] When PVI failed to achieve sinus rhythm, additional linear lesions were performed, occasionally supplemented by ablation of complex fractionated atrial electrograms. Arrhythmia-free survival rates with or without antiarrhythmic drugs were 63% at 1 year and 22% at 5 years, which appear to be lower than in the general population.[57,58] Moreover, an 8% complication rate was reported, which exceeds that observed in contemporary series of patients without CHD. Thus, although the feasibility of PVI has been described in the rare patient with complex CHD,[57,58] current data are insufficient to claim efficacy and safety outcomes equivalent to that in patients without CHD. A greater appreciation of underlying mechanisms and electrophysiological substrates might contribute substantially to further improving outcomes in adults with CHD and AF.[25]

In addition to consistent improvements in management of AF, technological advances have improved mapping of complex scar-related atrial arrhythmias—namely, smaller electrodes in multipolar configurations (64 × 0.4 mm electrodes, Intellamap Orion [Boston Scientific, Boston, MA]; 20 × 1 mm electrodes, Pentaray Catheter [Biosense-Webster Inc]; HDGrid [Abbott]). This advance provides improved mapping resolution and accuracy where definition of diseased, fragmented electrograms is central to the clinical tachyarrhythmia—and pivotal in contrast to the patient with a normal myocardial substrate.[59] In a series of 12 adults with CHD in which the Rhythmia mapping system (Boston Scientific) was used in 15 procedures (including 1 ventricular tachycardia), complete mapping was achieved in only 44% of cases, primarily because of dilated chambers.[60] Three patients (25%) had recurrences during a median follow-up of 12 months.[60] Although such newer technologies require further study, they highlight the challenges in creating durable lesions in adults with CHD. For adults with CHD and arrhythmias who undergo cardiac surgery, concomitant intraoperative ablation could be considered.[61,62]

Complex venous and cardiac anatomy is frequently a major issue in planning, mapping, and executing ablation for the scar-related or focal arrhythmias in the patient with repaired CHD, and definition of anatomy is crucial. Pre-emptive imaging with computed tomography, magnetic resonance imaging (MRI), or contrast venography has become standard in most centres that perform these procedures, along with continued advances in image integration. This latter feature allows for a manual or automated computed tomography segmentation process, providing detailed anatomic 3-D image integration highlighting discrete anatomic structures (Cartoseg, Biosense-Webster; Fig. 3).

Ablation of ventricular arrhythmias

Sudden cardiac death of presumed arrhythmic etiology is a leading cause of mortality in adults with CHD.[5,63] An interplay of factors including surgical scars and slow conducting myocardial tissue can result in critical electrical isthmuses that favour re-entrant ventricular tachycardia. Over the years, catheter ablation has played an increasingly important role in managing ventricular arrhythmias in adults with CHD, with acute success rates of 80%-85% and recurrence rates of 6%-15% at 3-5 years of follow-up.[64,65] As a general rule, ventricular tachycardia ablation is not considered a substitute for an implantable cardioverter-defibrillator (ICD) in high-risk patients.

Cardiac Implantable Electronic Devices

Compatibility with MRI

Most novel cardiac implantable electronic devices (CIEDs) are now MRI conditional, which is important to adults with

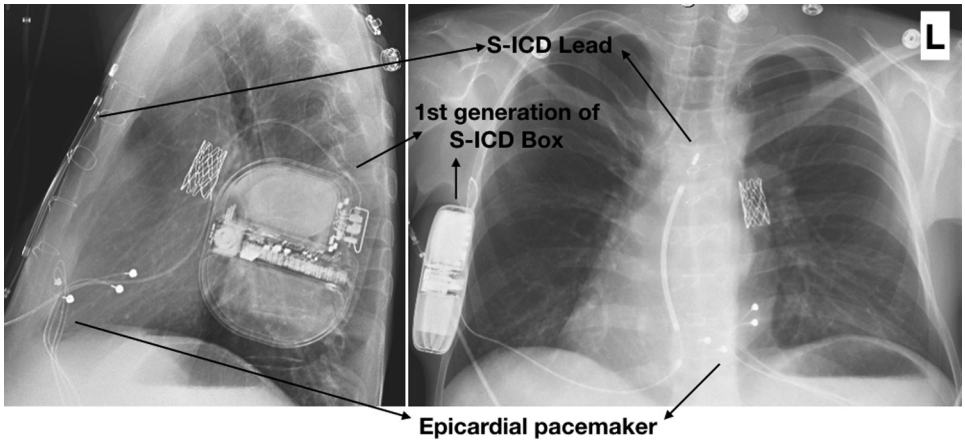

Figure 5. Subcutaneous implantable cardioverter-defibrillator (S-ICD) in a Fontan patient with dextrocardia. Shown are radiographic posteroanterior (**right**) and left lateral (**left**) views of a right-sided implant of a first-generation S-ICD (1010, Cameron Health) in a 26-year-old patient with dextrocardia and a total cavopulmonary connection Fontan. The S-ICD was implanted after a successfully resuscitated cardiac arrest. The patient had a previous epicardial pacemaker implanted for sinus node dysfunction. The leads and pacemaker were truly dedicated bipolar devices rendering it impossible for unipolar pacing to be programmed, which could potentially induce double counting and inappropriate shock. Screening and testing were performed with and without pacing. L, left.

CHD who often require magnetic resonance imaging to assess cardiovascular and extracardiac manifestations of their disease. In such cases, the only restrictions for MRI scanning related to the CIED are epicardial, dysfunctional, or abandoned leads, which unfortunately remain problematic for many adults with CHD. MRI compatible epicardial leads are of interest but have yet to be developed. There is also a growing literature on MRI scanning in patients with non-MRI conditional

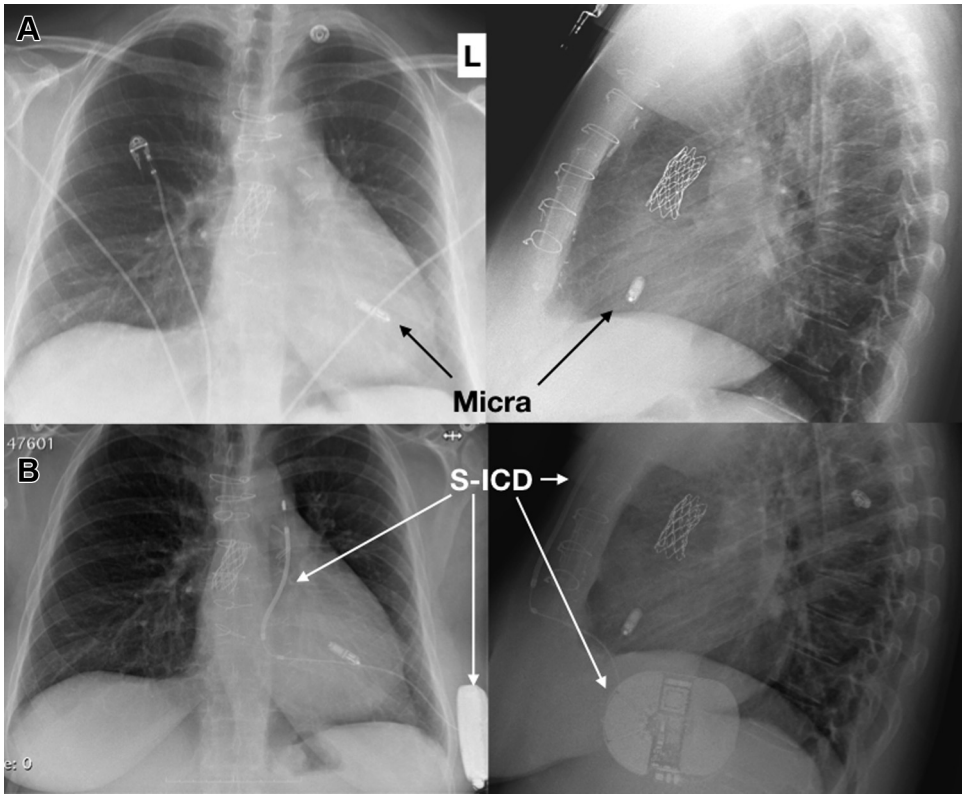

Figure 6. Leadless pacemaker (**A**) combined with a subcutaneous implantable cardioverter-defibrillator (S-ICD) (**B**) in an adult with congenital heart disease. (**A**) Radiographic images in posteroanterior and left lateral views of a leadless pacemaker implanted in a 44-year-old patient with a partial atrioventricular septal defect, superior vena cava syndrome, and subclavian vein thrombosis after endocarditis of the tricuspid valve due to pseudomonas aeruginosa. An S-ICD was subsequently implanted (**B**) in the context of a resuscitated cardiac arrest. No interaction between the two devices was observed. L, left.

CIEDs.[66] With appropriate precautions, MRI scanning is feasible and safe. Nevertheless, for cardiovascular indications, artifacts created by the CIED remains an important issue that could hamper image interpretation, yet technological advances related to gradient-echo sequencing has allowed for improved image quality even in the context of devices, intracardiac leads, and thoracic 1.5 Tesla magnetic resonance imaging.[67,68] Importantly, current iterations of newer technologies including the ICM, leadless pacemaker, and subcutaneous ICD (S-ICD) are also MRI conditional. Extraction of older leads to render a CIED system MRI conditional remains a class IIb indication.[69]

Newer technologies

The vascular access issues and complex anatomies that render catheter ablation procedures challenging could likewise impede transvenous lead implantation in adults with CHD.[70] In some instances, epicardial lead implantation has traditionally been the only reasonable option available. Over the past decade, leadless and/or nontransvenous devices have emerged as suitable alternatives in selected patients. These devices have the potential to favourably affect complications related to transvenous lead systems including pericardial effusion, pneumothorax, lead dislodgement, lead fracture, venous thrombosis, stroke related to an intracardiac shunt, pocket infection, endocarditis, and subpulmonary atrioventricular valve regurgitation.[71-73] Some of these complications are more common in young and active patient populations and can have catastrophic consequences.

S-ICDs. The first human implantation of an S-ICD was in 2008. Progressive improvements have since been made to preimplantation testing methods, detection algorithms, programming capabilities, implantation procedures, and MRI compatibility. Although the major cohort studies (ie, **I**nvestigational **D**evice **E**xemption [IDE] and **E**valuation o**f**Fact**o**r**s** Impac**t**ing C**l**inical Outcome and Cost **E**ffectivene**ss** of the S-ICD [EFFORTLESS S-ICD] Registry) did not exclude patients with CHD, only a limited number (ie, N = 19) of such patients were enrolled.[74-76] A few studies have reported on the initial experience with the S-ICD specifically in adults with CHD.[77,78] The need for thorough screening has been identified as an important issue to mitigate the risk of inappropriate shocks due to T-wave oversensing, which is particularly problematic in patients with wide QRS complexes, as is typical of tetralogy of Fallot. New algorithms, including Smart Pass (Boston Scientific), and dual-zone programming have resulted in a reduction in the rate of inappropriate shock from 14% to 3.5% in the latest reports.[79,80] Another issue relevant to adults with CHD is the compatibility of the S-ICD with preexisting transvenous, leadless, and epicardial pacemakers because of the high prevalence of coexisting bradyarrhythmias. Initial reports suggest that, when appropriately programmed, these devices can indeed be compatible with the important exception of unipolar pacemaker leads.[81]

In many respects, adults with CHD who require a defibrillator are ideal candidates for the S-ICD by virtue of limited transvenous access and/or contraindications such as intracardiac shunts (Fig. 5).[82] In the past, such patients might have otherwise received a more complex epicardial ICD system that is prone to a higher failure rate.[83] Randomized trials (**Pr**ospective, R**a**ndomize**d** Comparison of Subcu**t**ane**o**us and T**r**ansvenous **I**mpl**an**table Cardioverter Defibrillator Therapy Trial [PRAETORIAN] and **A**void **T**ransvenous **L**eads in **A**ppropriate **S**ubjects [ATLAS]) are currently under way to compare S-ICDs with standard transvenous systems.[84,85] Results should be available in 2020-2021.

Leadless pacemakers. Although the notion of leadless pacing dates back to the 1970s, a transcatheter pacing system was first introduced in 2012 with the heralded benefits of avoiding lead- and device pocket-related complications (first with Nanostim from Abbott[86] and then with Micra [Medtronic Inc, Dublin, Ireland][87,88]). Published data on leadless pacemakers in adults with CHD remain limited,[89] in part because only single-chamber ventricular pacemakers are currently available and most adults with CHD and pacemaker indications require dual chamber devices. Studies to combine the leadless ventricular pacemaker with an accelerometer-based atrial sensor are ongoing to provide atrioventricular synchronous pacing.[90,91] Leadless pacemakers might be particularly well suited to adults with CHD who have vascular abnormalities of the superior veins or venous obstructions as a result of longstanding transvenous leads (Fig. 6). The implantation technique requires femoral venous access. Exceptionally, case reports have described the safe implantation of leadless pacemakers using a jugular venous approach.[92]

Longevity of leadless pacemakers is estimated to be approximately 10 years, depending on the pacing rate and output, but long-term studies are lacking. Issues regarding replacements and extractions years later require clarification. Despite the absence of a dedicated tool for leadless pacemaker extractions, reports have described successful device removal up to 2 years after implantation.[93] Encapsulation could pose a major challenge to successful extraction. Although it might be technically feasible to add new leadless pacemakers in the event of battery depletion, the question of how many devices can be implanted safely in a subpulmonary ventricle before compromising function remains unanswered.

His bundle pacing. His bundle pacing (HBP), initially described in the late 1970s,[94,95] has recently emerged as a viable option to provide more physiological pacing. Despite the newfound interest in reviving and perfecting this technology, HBP has already been featured in management guidelines. In 2018, the American College of Cardiology/American Heart Association/Heart Rhythm Society guidelines on bradycardia and cardiac conduction delay expressed a preference for "more physiological" pacing (ie, cardiac resynchronization therapy [CRT] or HBP) in patients with atrioventricular block, > 40% ventricular paced beats, and an ejection fraction between 36% and 50% to prevent heart failure.[96] Studies are currently comparing HBP with CRT in patients with standard CRT indication.[97] Currently, HBP is not recommended as an alternative to CRT because of the variability in recruitment of the left bundle and in the absence of consistent data that this approach reduces mortality and hospitalizations and improves quality of life.[98] Recent data on

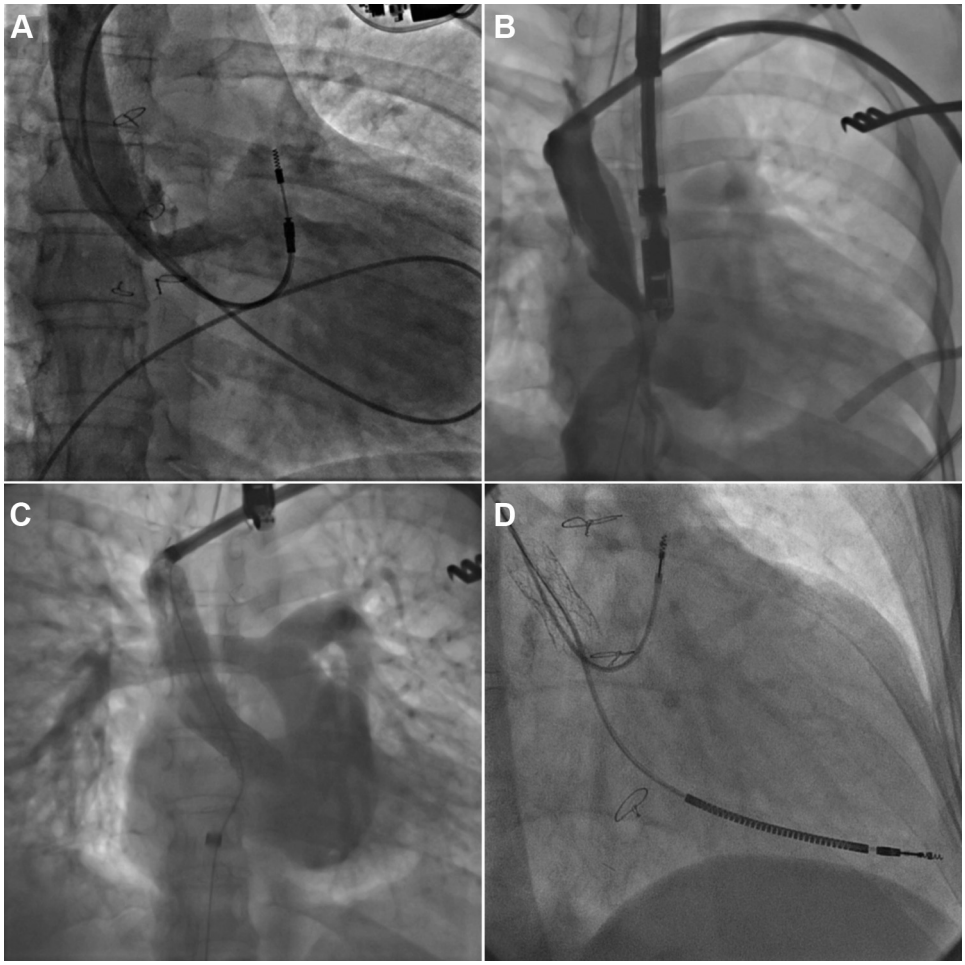

Figure 7. Lead extraction. Extraction of a single-chamber atrial pacemaker and implantation of a dual chamber implantable cardioverter-defibrillator was performed in a 35-year-old individual with transposition of the great arteries and Mustard surgery. (**A**) Angiography revealed stenosis of the superior limb of the Mustard baffle. Shown in (**B**), the stenosis persisted despite laser lead extraction. Stenting of the baffle is shown in (**C**), followed by implantation of the implantable cardioverter-defibrillator in (**D**).

HBP and left bundle branch pacing have emerged indicating a high rate of crossover to CRT.[99,100] Techniques and indications remain to be refined.

HBP has been reported in 1 patient with congenitally corrected transposition of the great arteries.[101] If studies prove favourable, it could potentially become the preferred mode of pacing in subgroups of adults with CHD who require dual chamber pacing or have a CRT indication. Complexities in identifying appropriate sites to capture the His bundle or left bundle branch area in adults with CHD include anatomical obstacles (eg, atrial switch), displaced or difficult to predict locations of the atrioventricular conduction system, postoperative complete atrioventricular block, and ventricular septal defect patches or closure devices.

Emerging technologies. Leadless pacing is now a reality. Progressive advances will continue to broaden the population base that stands to benefit from this technology. It is only a matter of time before multicomponent communicating leadless devices capable of performing atrial pacing, dual chamber pacing, and CRT become available. The Wise-CRT system (EBR Systems Inc, Sunnyvale, CA) combines a systemic ventricular free wall endocardial leadless pacemaker with a subcutaneous ultrasonic transmitter synchronized to a conventional right-sided pacing system.[102] A large multicentre investigational device exemption clinical trial approved by the FDA is currently under way.[103] If proven effective, this type of system obviates the need for coronary sinus access to pace a systemic ventricle and could, therefore, be of particular interest to patients in whom the coronary sinus is not accessible, malformed, or does not lead to a systemic ventricle (eg, congenitally corrected transposition of the great arteries, complete transposition with an atrial baffle, and selected candidates with univentricular hearts).

Other anticipated technological advances include expanding the S-ICD from a shock box device into a combined pacing and defibrillation system. Prototypes implanted in animals have shown the ability for a leadless pacemaker to communicate with an S-ICD.[104,105] Although these 2 technologies have already been combined in humans without interactions (Fig. 6),[81] the ability of the devices to communicate and integrate their functions could allow for such features as

antitachycardia pacing to treat monomorphic ventricular tachycardia and back-up ventricular pacing in the event of bradycardia. The first implantations in humans and accompanying clinical studies are anticipated in the latter half of 2019.

Additional emerging technologies include an extravascular ICD (Medtronic) that combines an investigational retrosternal pacing and defibrillation lead implanted by means of a small incision (1-3 cm) into the virtual space below the sternum, with an S-ICD placed over the left lateral thorax. Such a device could allow back-up and antitachycardia pacing. The ability to pace, sense, and defibrillate using the retrosternal lead has been shown in a study of 79 patients.[106] The 20 first human implantations have been reported at the Late Breaking Trial in Heart Rhythm Society meeting in San Francisco in May 2019, without intraprocedural complications, but with 4 withdrawals after implantation because of lack of a safety margin in defibrillation threshold.[107] Significant challenges might be encountered in the population of adults with CHD because of previous cardiac surgeries, fibrosis, a reduction in the virtual retrosternal space, and/or issues related to thoracic deformities (eg, pectus excavatum). Optimal adoption of some of these newer technologies will require a heart team approach that includes electrophysiologists, adult CHD specialists, surgeons, structural cardiologists, and echocardiographers.

Lead Extraction

As the population of adults with CHD grows and ages, transvenous lead extraction procedures are increasingly required (Fig. 7). Several reports have shown feasibility and safety in adults with CHD by using a stepwise approach that uses various tools (eg, laser, mechanical, and rotational sheaths; single or double snares) and access sites (eg, subclavian, femoral, and jugular).[108,109] In adults with CHD, combined tools and approaches are often required because of the young age at implantation, number of leads, lengthy time since implantation, and anatomical complexities (eg, obstructed conduits or baffles). Complications such as pericardial effusion are less common in adults with CHD because of previous surgeries. However, adults with CHD might be more prone to the complication of subpulmonary atrioventricular valve regurgitation,[110,111] particularly those with a less compliant mitral valve in the subpulmonary ventricle (ie, congenitally corrected or complete transposition of the great arteries with an atrial baffle).[108]

A feared complication of transvenous lead extraction is laceration of the superior vena cava (SVC), with ensuing rapid intrathoracic hemorrhage. A low pressure compliant balloon inflated in the SVC (Bridge Occlusion Balloon, Spectranetrics, Colorado Springs, CO) and inserted over a wire through femoral venous access was developed to prevent rapid bleeding and allow for a $\geq$ 30-minute period to stabilize the patient and repair the SVC if needed. Retrospective studies in a non-CHD population have yielded impressive results, with all patients alive despite SVC lacerations.[112] Applicability of this technology to adults with CHD might be limited by femoral venous access issues. Although bridge balloons have been implanted in animal models through a superior approach, the technique has not yet been reported in humans.

Conclusion

There are numerous technical challenges to managing arrhythmias in adults with CHD including vascular obstructions and anomalies, stenotic baffles and conduits, intracardiac shunts, and lack of direct access to chambers of interest after surgical repair. Fortunately, technological advances are permitting an increasing number of adults with CHD and arrhythmias to be diagnosed and managed safely and effectively. Considering the multitude of issues encountered, in many respects adults with CHD stand to benefit most from technological progress in catheter ablation and CIEDs. Awareness regarding these advances and referral to sites with dedicated expertise in managing arrhythmias in adults with CHD could potentially contribute to further improving outcomes in this unique and diverse patient population.

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References

1. Khairy P, Ionescu-Ittu R, Mackie AS, et al. Changing mortality in congenital heart disease. J Am Coll Cardiol 2010;56:1149-57.
2. van der Linde D, Konings EE, Slager MA, et al. Birth prevalence of congenital heart disease worldwide: a systematic review and meta-analysis. J Am Coll Cardiol 2011;58:2241-7.
3. Warnes CA, Liberthson R, Danielson GK, et al. Task force 1: the changing profile of congenital heart disease in adult life. J Am Coll Cardiol 2001;37:1170-5.
4. Baumgartner H. Geriatric congenital heart disease: a new challenge in the care of adults with congenital heart disease? Eur Heart J 2014;35:683-5.
5. Silka MJ, Hardy BG, Menashe VD, Morris CD. A population-based prospective evaluation of risk of sudden cardiac death after operation for common congenital heart defects. J Am Coll Cardiol 1998;32:245-51.
6. Gatzoulis MA, Hechter S, Siu SC, Webb GD. Outpatient clinics for adults with congenital heart disease: increasing workload and evolving patterns of referral. Heart 1999;81:57-61.
7. Engelfriet P, Boersma E, Oechslin E, et al. The spectrum of adult congenital heart disease in Europe: morbidity and mortality in a 5 year follow-up period. Eur Heart J 2005;26:2325-33.
8. Silversides CK, Marelli A, Beauchesne L, et al. Canadian Cardiovascular Society 2009 Consensus Conference on the management of adults with

congenital heart disease: executive summary. Can J Cardiol 2010;26:143-50.

9. Stout KK, Daniels CJ, Aboulhosn JA, et al. 2018 AHA/ACC guideline for the management of adults with congenital heart disease: a report of the American College of Cardiology/American Heart Association task force on clinical practice guidelines. J Am Coll Cardiol 2019;73:e81-192.

10. Baumgartner H, Bonhoeffer P, De Groot NM, et al. ESC Guidelines for the management of grown-up congenital heart disease (new version 2010). Eur Heart J 2010;31:2915-57.

11. Khairy P, Van Hare GF, Balaji S, et al. PACES/HRS expert consensus statement on the recognition and management of arrhythmias in adult congenital heart disease: developed in partnership between the Pediatric and Congenital Electrophysiology Society (PACES) and the Heart Rhythm Society (HRS). Endorsed by the governing bodies of PACES, HRS, the American College of Cardiology (ACC), the American Heart Association (AHA), the European Heart Rhythm Association (EHRA), the Canadian Heart Rhythm Society (CHRS), and the International Society for Adult Congenital Heart Disease (ISACHD). Can J Cardiol 2014;30:e1-63.

12. Rodriguez FH, Moodie DS, Neeland M, Adams GJ, Snyder CS. Identifying arrhythmias in adults with congenital heart disease by 24-h ambulatory electrocardiography. Pediatr Cardiol 2012;33:591-5.

13. Czosek RJ, Anderson J, Khoury PR, et al. Utility of ambulatory monitoring in patients with congenital heart disease. Am J Cardiol 2013;111:723-30.

14. Kapoor WN, Hammill SC, Gersh BJ. Diagnosis and natural history of syncope and the role of invasive electrophysiologic testing. Am J Cardiol 1989;63:730-4.

15. Bang OY, Ovbiagele B, Kim JS. Evaluation of cryptogenic stroke with advanced diagnostic techniques. Stroke 2014;45:1186-94.

16. Krahn AD, Klein GJ, Yee R. Recurrent syncope. Experience with an implantable loop recorder. Cardiol Clin 1997;15:313-26.

17. Barrett PM, Komatireddy R, Haaser S, et al. Comparison of 24-hour Holter monitoring with 14-day novel adhesive patch electrocardiographic monitoring. Am J Med 2014;127:95.e11-7.

18. Pradhan S, Robinson JA, Shivapour JK, et al. Ambulatory arrhythmia detection with ZIO® XT patch in pediatric patients: a comparison of devices. Pediatr Cardiol 2019;40:921-4.

19. Karaoğuz MR, Yurtseven E, Aslan G, et al. The quality of ECG data acquisition, and diagnostic performance of a novel adhesive patch for ambulatory cardiac rhythm monitoring in arrhythmia detection. J Electrocardiol 2019;54:28-35.

20. Kenny D, Chakrabarti S, Ranasinghe A, et al. Single-centre use of implantable loop recorders in patients with congenital heart disease. Europace 2009;11:303-7.

21. Sakhi R, Theuns D, Bhagwandien RE, et al. Value of implantable loop recorders in patients with structural or electrical heart disease. J Interv Card Electrophysiol 2018;52:203-8.

22. Mittal S, Sanders P, Pokushalov E, et al. Safety profile of a miniaturized insertable cardiac monitor: results from two prospective trials. Pacing Clin Electrophysiol 2015;38:1464-9.

23. Kanters TA, Wolff C, Boyson D, et al. Cost comparison of two implantable cardiac monitors in two different settings: Reveal XT in a catheterization laboratory vs. Reveal LINQ in a procedure room. Europace 2016;18:919-24.

24. Ebrahim MA, Escudero CA, Kantoch MJ, et al. Insights on atrial fibrillation in congenital heart disease. Can J Cardiol 2018;34:1531-3.

25. Waldmann V, Laredo M, Abadir S, Mondésert B, Khairy P. Atrial fibrillation in adults with congenital heart disease. Int J Cardiol 2019;287:148-54.

26. Laredo M, Waldmann V, Khairy P, et al. Age as a critical determinant of atrial fibrillation: a two-sided relationship. Can J Cardiol 2018;34:1396-406.

27. Cheung CC, Krahn AD, Andrade JG. The emerging role of wearable technologies in detection of arrhythmia. Can J Cardiol 2018;34:1083-7.

28. Olson KE, O'Brien MA, Rogers WA, Charness N. Diffusion of technology: frequency of use for younger and older adults. Ageing Int 2011;36:123-45.

29. Turakhia MP, Desai M, Hedlin H, et al. Rationale and design of a large-scale, app-based study to identify cardiac arrhythmias using a smartwatch: the Apple Heart Study. Am Heart J 2019;207:66-75.

30. Turakhia M, Perez M, Desai M. Results of a large-scale app-based study to identify atrial fibrillation using a smartwatch: the Apple Heart Study. J Am Coll Cardiol 2019;73:19. LB-20253.

31. Apple Inc: Using Apple Watch for arrhythmia detection. Available at, https://www.apple.com/healthcare/site/docs/Apple_Watch_Arrhythmia_Detection.pdf.

32. Labombarda F, Hamilton R, Shohoudi A, et al. Increasing prevalence of atrial fibrillation and permanent atrial arrhythmias in congenital heart disease. J Am Coll Cardiol 2017;70:857-65.

33. Khairy P, Poirier N. The extracardiac conduit is not the preferred Fontan approach for patients with univentricular hearts. Circulation 2012;126:2516-25.

34. Ernst S. Robotic approach to catheter ablation. Curr Opin Cardiol 2008;23:28-31.

35. Wu J, Pflaumer A, Deisenhofer I, et al. Mapping of intraatrial reentrant tachycardias by remote magnetic navigation in patients with d-transposition of the great arteries after Mustard or Senning procedure. J Cardiovasc Electrophysiol 2008;19:1153-9.

36. Bessiere F, Zikry C, Rivard L, Dyrda K, Khairy P. Contact force with magnetic-guided catheter ablation. Europace 2018;20:ii1-4.

37. Wu J, Pflaumer A, Deisenhofer I, et al. Mapping of atrial tachycardia by remote magnetic navigation in postoperative patients with congenital heart disease. J Cardiovasc Electrophysiol 2010;21:751-9.

38. Ernst S, Babu-Narayan SV, Keegan J, et al. Remote-controlled magnetic navigation and ablation with 3D image integration as an alternative approach in patients with intra-atrial baffle anatomy. Circ Arrhythm Electrophysiol 2012;5:131-9.

39. Akca F, Bauernfeind T, Witsenburg M, et al. Acute and long-term outcomes of catheter ablation using remote magnetic navigation in patients with congenital heart disease. Am J Cardiol 2012;110:409-14.

40. Ueda A, Suman-Horduna I, Mantziari L, et al. Contemporary outcomes of supraventricular tachycardia ablation in congenital heart disease: a single-center experience in 116 patients. Circ Arrhythm Electrophysiol 2013;6:606-13.

41. Akca F, Onsesveren I, Jordaens L, Szili-Torok T. Safety and efficacy of the remote magnetic navigation for ablation of ventricular tachycardias–a systematic review. J Interv Card Electrophysiol 2012;34:65-71.

42. Suman-Horduna I, Babu-Narayan SV, Ueda A, et al. Magnetic navigation in adults with atrial isomerism (heterotaxy syndrome) and supraventricular arrhythmias. Europace 2013;15:877-85.

43. Roy K, Gomez-Pulido F, Ernst S. Remote magnetic navigation for catheter ablation in patients with congenital heart disease: a review. J Cardiovasc Electrophysiol 2016;27(suppl 1):S45-56.

44. Qian P, De Silva K, Kumar S, et al. Early and long-term outcomes after manual and remote magnetic navigation-guided catheter ablation for ventricular tachycardia. Europace 2018;20(suppl 2):ii11-21.

45. Dubuc M, Roy D, Thibault B, et al. Transvenous catheter ice mapping and cryoablation of the atrioventricular node in dogs. Pacing Clin Electrophysiol 1999;22:1488-98.

46. Gaita F, Haissaguerre M, Giustetto C, et al. Safety and efficacy of cryoablation of accessory pathways adjacent to the normal conduction system. J Cardiovasc Electrophysiol 2003;14:825-9.

47. Insulander P, Bastani H, Braunschweig F, et al. Cryoablation of substrates adjacent to the atrioventricular node: acute and long-term safety of 1303 ablation procedures. Europace 2014;16:271-6.

48. Insulander P, Bastani H, Braunschweig F, et al. Cryoablation of atrioventricular nodal re-entrant tachycardia: 7-year follow-up in 515 patients-confirmed safety but very late recurrences occur. Europace 2017;19:1038-42.

49. Ávila P, Bessière F, Mondésert B, et al. Cryoablation for perinodal arrhythmia substrates in patients with congenital heart disease and displaced atrioventricular conduction systems. JACC Clin Electrophysiol 2018;4:1328-37.

50. Thibault B, Macle L, Mondesert B, et al. Reducing radiation exposure during procedures performed in the electrophysiology laboratory. J Cardiovasc Electrophysiol 2018;29:308-15.

51. Cano O, Sauri A, Plaza D, et al. Evaluation of a near-zero fluoroscopic approach for catheter ablation in patients with congenital heart disease [e-pub ahead of print]. J Interv Card Electrophysiol https://doi.org/10.1007/s10840-018-0467-3.

52. Sadek MM, Ramirez FD, Nery PB, et al. Completely nonfluoroscopic catheter ablation of left atrial arrhythmias and ventricular tachycardia. J Cardiovasc Electrophysiol 2019;30:78-88.

53. Williams D. Radiation carcinogenesis: lessons from Chernobyl. Oncogene 2008;27(suppl 2):S9-18.

54. Journy N, Dreuil S, Rage E, et al. Projected future cancer risks in children treated with fluoroscopy-guided cardiac catheterization procedures. Circ Cardiovasc Interv 2018;11:e006765.

55. Triedman JK, Alexander ME, Love BA, et al. Influence of patient factors and ablative technologies on outcomes of radiofrequency ablation of intra-atrial re-entrant tachycardia in patients with congenital heart disease. J Am Coll Cardiol 2002;39:1827-35.

56. Sohns C, Nurnberg JH, Hebe J, et al. Catheter ablation for atrial fibrillation in adults with congenital heart disease: lessons learned from more than 10 years following a sequential ablation approach. JACC Clin Electrophysiol 2018;4:733-43.

57. Frankel DS, Shah MJ, Aziz PF, Hutchinson MD. Catheter ablation of atrial fibrillation in transposition of the great arteries treated with Mustard atrial baffle. Circ Arrhythm Electrophysiol 2012;5:e41-3.

58. Kirubakaran S, Rajani R, Linton N, et al. Catheter ablation for persistent atrial fibrillation in a patient with previous repair of total anomalous pulmonary venous connection. Circ Arrhythm Electrophysiol 2013;6:e54-5.

59. Xue Y, Liu Y, Liao H, et al. Evaluation of electrophysiological mechanisms of post-surgical atrial tachycardias using an automated ultra-high-density mapping system. JACC Clin Electrophysiol 2018;4:1460-70.

60. Ernst S, Cazzoli I, Guarguagli S. An initial experience of high-density mapping-guided ablation in a cohort of patients with adult congenital heart disease. Europace 2019;21(suppl 1):i43-53.

61. Stulak JM, Suri RM, Burkhart HM, et al. Surgical ablation for atrial fibrillation for two decades: are the results of new techniques equivalent to the Cox maze III procedure? J Thorac Cardiovasc Surg 2014;147:1478-86.

62. Gutierrez SD, Earing MG, Singh AK, et al. Atrial tachyarrhythmias and the Cox-maze procedure in congenital heart disease. Congenit Heart Dis 2013;8:434-9.

63. Gatzoulis MA, Balaji S, Webber SA, et al. Risk factors for arrhythmia and sudden cardiac death late after repair of tetralogy of Fallot: a multicentre study. Lancet 2000;356:975-81.

64. van Zyl M, Kapa S, Padmanabhan D, et al. Mechanism and outcomes of catheter ablation for ventricular tachycardia in adults with repaired congenital heart disease. Heart Rhythm 2016;13:1449-54.

65. Laredo M, Frank R, Waintraub X, et al. Ten-year outcomes of monomorphic ventricular tachycardia catheter ablation in repaired tetralogy of Fallot. Arch Cardiovasc Dis 2017;110:292-302.

66. Shah AD, Morris MA, Hirsh DS, et al. Magnetic resonance imaging safety in nonconditional pacemaker and defibrillator recipients: a meta-analysis and systematic review. Heart Rhythm 2018;15:1001-8.

67. Buendía F, Cano Ó, Sánchez-Gómez JM, et al. Cardiac magnetic resonance imaging at 1.5 T in patients with cardiac rhythm devices. Europace 2011;13:533-8.

68. Schwitter J, Gold MR, Al Fagih A, et al. Image quality of cardiac magnetic resonance imaging in patients with an implantable cardioverter defibrillator system designed for the magnetic resonance imaging environment. Circ Cardiovasc Imaging 2016;9:e004025.

69. Wilkoff BL, Love CJ, Byrd CL, et al. Transvenous lead extraction: Heart Rhythm Society expert consensus on facilities, training, indications, and patient management: this document was endorsed by the American Heart Association (AHA). Heart Rhythm 2009;6:1085-104.

70. Khairy P. EP challenges in adult congenital heart disease. Heart Rhythm 2008;5:1464-72.

71. Lee DS, Krahn AD, Healey JS, et al. Evaluation of early complications related to de novo cardioverter defibrillator implantation insights from the Ontario ICD database. J Am Coll Cardiol 2010;55:774-82.

72. Schleifer JW, Pislaru SV, Lin G, et al. Effect of ventricular pacing lead position on tricuspid regurgitation: a randomized prospective trial. Heart Rhythm 2018;15:1009-16.

73. Olde Nordkamp LR, Postema PG, Knops RE, et al. Implantable cardioverter-defibrillator harm in young patients with inherited arrhythmia syndromes: a systematic review and meta-analysis of inappropriate shocks and complications. Heart Rhythm 2016;13:443-54.

74. Weiss R, Knight BP, Gold MR, et al. Safety and efficacy of a totally subcutaneous implantable-cardioverter defibrillator. Circulation 2013;128:944-53.

75. Lambiase PD, Barr C, Theuns DA, et al. Worldwide experience with a totally subcutaneous implantable defibrillator: early results from the EFFORTLESS S-ICD Registry. Eur Heart J 2014;35:1657-65.

76. Burke MC, Gold MR, Knight BP, et al. Safety and efficacy of the totally subcutaneous implantable defibrillator: 2-year results from a pooled analysis of the IDE study and EFFORTLESS registry. J Am Coll Cardiol 2015;65:1605-15.

77. Moore JP, Mondesert B, Lloyd MS, et al. Clinical experience with the subcutaneous implantable cardioverter-defibrillator in adults with congenital heart disease. Circ Arrhythm Electrophysiol 2016;9:e004338.

78. Ferrero P, Ali H, Barman P, et al. Entirely subcutaneous defibrillator and complex congenital heart disease: data on long-term clinical follow-up. World J Cardiol 2017;9:547-52.

79. Brisben AJ, Burke MC, Knight BP, et al. A new algorithm to reduce inappropriate therapy in the S-ICD system. J Cardiovasc Electrophysiol 2015;26:417-23.

80. Theuns D, Brouwer TF, Jones PW, et al. Prospective blinded evaluation of a novel sensing methodology designed to reduce inappropriate shocks by the subcutaneous implantable cardioverter-defibrillator. Heart Rhythm 2018;15:1515-22.

81. Mondesert B, Dubuc M, Khairy P, et al. Combination of a leadless pacemaker and subcutaneous defibrillator: first in-human report. HeartRhythm Case Rep 2015;1:469-71.

82. Khairy P, Landzberg MJ, Gatzoulis MA, et al. Transvenous pacing leads and systemic thromboemboli in patients with intracardiac shunts: a multicenter study. Circulation 2006;113:2391-7.

83. Radbill AE, Triedman JK, Berul CI, et al. System survival of non-transvenous implantable cardioverter-defibrillators compared to transvenous implantable cardioverter-defibrillators in pediatric and congenital heart disease patients. Heart Rhythm 2010;7:193-8.

84. Olde Nordkamp LR, Knops RE, Bardy GH, et al. Rationale and design of the PRAETORIAN trial: a Prospective, RAndomizEd comparison of subcuTaneOus and tRansvenous ImplANtable cardioverter-defibrillator therapy. Am Heart J 2012;163:753.e2-60.e2.

85. Mondesert B, Bashir J, Philippon F, et al. Rationale and design of the randomized prospective ATLAS study: Avoid Transvenous Leads in Appropriate Subjects. Am Heart J 2019;207:1-9.

86. Reddy VY, Knops RE, Sperzel J, et al. Permanent leadless cardiac pacing: results of the LEADLESS trial. Circulation 2014;129:1466-71.

87. Reynolds D, Duray GZ, Omar R, et al. A leadless intracardiac transcatheter pacing system. N Engl J Med 2016;374:533-41.

88. El-Chami MF, Al-Samadi F, Clementy N, et al. Updated performance of the Micra transcatheter pacemaker in the real-world setting: a comparison to the investigational study and a transvenous historical control. Heart Rhythm 2018;15:1800-7.

89. McCanta AC, Morchi GS, Tuozo F, et al. Implantation of a leadless pacemaker in a pediatric patient with congenital heart disease. HeartRhythm Case Rep 2018;4:506-9.

90. Chinitz L, Ritter P, Khelae SK, et al. Accelerometer-based atrioventricular synchronous pacing with a ventricular leadless pacemaker: results from the Micra atrioventricular feasibility studies. Heart Rhythm 2018;15:1363-71.

91. Garweg C, Splett V, Sheldon TJ, et al. Behavior of leadless AV synchronous pacing during atrial arrhythmias and stability of the atrial signals over time-results of the MARVEL Evolve subanalysis. Pacing Clin Electrophysiol 2019;42:381-7.

92. Saleem-Talib S, van Driel V, Chaldoupi SM, et al. Leadless pacing. Going for the jugular. Pacing Clin Electrophysiol 2019;42:395-9.

93. Curnis A, Cerini M, Mariggio D, et al. First-in-human retrieval of chronically implanted Micra transcatheter pacing system. Pacing Clin Electrophysiol 2019;42:1063-5.

94. El-Sherif N, Amay YLF, Schonfield C, et al. Normalization of bundle branch block patterns by distal His bundle pacing. Clinical and experimental evidence of longitudinal dissociation in the pathologic his bundle. Circulation 1978;57:473-83.

95. Zanon F, Ellenbogen KA, Dandamudi G, et al. Permanent His-bundle pacing: a systematic literature review and meta-analysis. Europace 2018;20:1819-26.

96. Kusumoto FM, Schoenfeld MH, Barrett C, et al. 2018 ACC/AHA/HRS guideline on the evaluation and management of patients with bradycardia and cardiac conduction delay: a report of the American College of Cardiology/American Heart Association task force on clinical practice guidelines and the Heart Rhythm Society. J Am Coll Cardiol, in press.

97. Keene D, Arnold A, Shun-Shin MJ, et al. Rationale and design of the randomized multicentre His Optimized Pacing Evaluated for Heart Failure (HOPE-HF) trial. ESC Heart Fail 2018;5:965-76.

98. Exner DV, Birnie DH, Moe G, et al. Canadian Cardiovascular Society guidelines on the use of cardiac resynchronization therapy: evidence and patient selection. Can J Cardiol 2013;29:182-95.

99. Upadhyay GA, Vijayaraman P, Nayak HM, et al. On-treatment comparison between corrective his bundle pacing and biventricular pacing for cardiac resynchronization: a secondary analysis of his-sync [e-pub ahead of print]. Heart Rhythm https://doi.org/10.1016/j.hrthm.2019.05.009.

100. Vijayaraman P, Naperkowski A, Subzposh FA, et al. Prospective evaluation of feasibility, electrophysiological and echocardiographic characteristics of left bundle branch area pacing, S-LBCT03-01 - HRS LBCT 2019. San Francisco.

101. Kean AC, Kay WA, Patel JK, Miller JM, Dandamudi G. Permanent nonselective His bundle pacing in an adult with L-transposition of the great arteries and complete AV block. Pacing Clin Electrophysiol 2017;40:1313-7.

102. Reddy VY, Miller MA, Neuzil P, et al. Cardiac resynchronization therapy with wireless left ventricular endocardial pacing: the SELECT-LV study. J Am Coll Cardiol 2017;69:2119-29.

103. Auricchio A, Delnoy PP, Butter C, et al. Feasibility, safety, and short-term outcome of leadless ultrasound-based endocardial left ventricular resynchronization in heart failure patients: results of the wireless stimulation endocardially for CRT (WiSE-CRT) study. Europace 2014;16:681-8.

104. Tjong FVY, Brouwer TF, Koop B, et al. Acute and 3-month performance of a communicating leadless antitachycardia pacemaker and subcutaneous implantable defibrillator. JACC Clin Electrophysiol 2017;3:1487-98.

105. Tjong FVY, Koop BE. The modular cardiac rhythm management system: the EMPOWER leadless pacemaker and the EMBLEM subcutaneous ICD. Herzschrittmacherther Elektrophysiol 2018;29:355-61.

106. Boersma LVA, Merkely B, Neuzil P, et al. Therapy from a novel substernal lead: the ASD2 study. JACC Clin Electrophysiol 2019;5:186-96.

107. Haqqani H, Kotschet E, Shaw D, et al. Understanding outcomes with the S-ICD in primary prevention patients with low ejection fraction (UNTOUCHED) study: high conversion efficacy and low adverse

event rate during the first 30 days; S-LBCT02-05 - HRS LBCT 2019. San Francisco.

108. Gourraud JB, Chaix MA, Shohoudi A, et al. Transvenous lead extraction in adults with congenital heart disease: insights from a 20-year single-center experience. Circ Arrhythm Electrophysiol 2018;11: e005409.

109. Fender EA, Killu AM, Cannon BC, et al. Lead extraction outcomes in patients with congenital heart disease. Europace 2017;19:441-6.

110. Birgersdotter-Green U, Dawood FZ. Transvenous extraction of pacemaker and defibrillator leads and the risk of tricuspid valve regurgitation: making a case for thoughtful lead management. JACC Clin Electrophysiol 2018;4:1429-30.

111. Park SJ, Gentry JL 3rd, Varma N, et al. Transvenous extraction of pacemaker and defibrillator leads and the risk of tricuspid valve regurgitation. JACC Clin Electrophysiol 2018;4:1421-8.

112. Tsang DC, Azarrafiy R, Pecha S, et al. Long-term outcomes of prophylactic placement of an endovascular balloon in the vena cava for high-risk transvenous lead extractions. Heart Rhythm 2017;14:1833-8.