Anatomical Substrates and Ablation of Reentrant Atrial and Ventricular Tachycardias in Repaired Congenital Heart Disease

Charlotte Brouwer,¹ Mark G Hazekamp² and Katja Zeppenfeld¹

1. Department of Cardiology, Leiden University Medical Centre, The Netherlands; 2. Department of Cardiothoracic Surgery, Leiden University Medical Centre, The Netherlands

Abstract

Advances in surgical repair techniques for various types of congenital heart disease have improved survival into adulthood over the past decades, thus exposing these patients to a high risk of atrial and ventricular arrhythmias later in life. These arrhythmias arise from complex arrhythmogenic substrates. Substrate formation may depend on both pathological myocardial remodelling and variable anatomical boundaries, determined by the type and timing of prior corrective surgery. Accordingly, arrhythmogenic substrates after repair have changed as a result of evolving surgical techniques. Radiofrequency catheter ablation offers an important therapeutic option but remains challenging due to the variable anatomy, surgically created obstacles and the complex arrhythmogenic substrates. Recent technical developments including electroanatomical mapping and image integration for delineating the anatomy facilitate complex catheter ablation procedures. The purpose of this review is to provide an update on the changing anatomical arrhythmogenic substrates and their potential impact on catheter ablation in patients with repaired congenital heart disease and tachyarrhythmias.

Keywords

Ablation, arrhythmogenic substrate, atrial tachycardia, congenital heart disease, electroanatomical mapping, tachyarrhythmias, ventricular tachycardia

Disclosure: The authors have no conflicts of interest to declare.

Acknowledgements: The authors thank Ron Slagter for his help in designing and preparing Figure 1.

Received: 16 February 2016 **Accepted:** 19 May 2016 **Citation:** *Arrhythmia & Electrophysiology Review* 2016;5(2):150–60 DOI: 10.15420/AER.2016.19.2

Access at: www.AERjournal.com

Correspondence: Katja Zeppenfeld, MD, PhD, Leiden University Medical Centre, Department of Cardiology, C5-P, PO Box 9600, 2300 RC Leiden, The Netherlands. E: K.Zeppenfeld@lumc.nl

The reported incidence of congenital heart disease (CHD) depends on the number of trivial lesions included, such as atrial and ventricular septal defects (ASDs and VSDs). Moderate-to-severe CHD numbers remain stable with 6 per 1,000 live births.¹ Survival into adulthood has improved dramatically over the last 25 years and has been driven mainly by a decreased mortality in moderate and severe forms of CHD in childhood, including tetralogy of Fallot, truncus arteriosus, atrioventricular septal defect (AVSD), transposition of the great arteries (TGA) and univentricular hearts. For individuals born between 1990 and 1992 survival to the age of 18 was 78 % for tetralogy of Fallot, 77 % for AVSD, 71 % for TGA and 49 % for the heterogeneous group of patients with univentricular hearts.²

Improved surgical outcome during infancy increases the risk of late complications such as atrial and ventricular arrhythmias, thus contributing to morbidity and mortality later in life.^{3,4} Arrhythmias may be part of the underlying disease but may also be the consequence of the type of corrective surgery and the age at which it was performed (see Table 1).

Areas of dense fibrosis owing to surgical incisions as well as patch material, valve annuli and veins can form regions of conduction block that create anatomical isthmuses of myocardial bundles.^{5,6} Interstitial fibrosis due to longstanding cyanosis, pressure and/or

volume overload, ageing and pathological hypertrophy may provide the substrate for slow conduction within these anatomically defined isthmuses.^{7,8} In particular, the duration of right atrial volume overload and right ventricular pressure overload have been associated with structural remodelling.^{7,9}

The coincidence of both of these specific features – anatomical boundaries and pathological remodelling over time – in adult patients with CHD may explain the high incidence of atrial and ventricular reentrant arrhythmias.

Radiofrequency catheter ablation (RFCA) is an important therapeutic option for targeting these arrhythmias as drug refractoriness and unsuccessful antitachycardia pacing are often encountered.^{10,11} However, RFCA remains challenging due to the variable anatomy with occasionally difficult or limited access (occluded femoral vessels, interrupted inferior vena cava (IVC), surgically created obstacles, prostheses and baffles), the sometimes hypertrophied myocardium and a complex and highly variable arrhythmogenic substrate that is dependent on the original malformation and the type of repair that has been performed.^{8,12,13} The purpose of this review is to provide an update on the changing anatomical substrate found in contemporary patients with repaired CHD and its impact on catheter ablation.

Type and Timing of Surgery and its Impact on Atrial and Ventricular Arrhythmias

Surgical approaches and the timing of intervention in various types of CHD have changed over the past decades and are likely to affect the incidence and the potential substrate for arrhythmias (see *Figure 1*).

The first clinical surgical closure of an ASD was performed in 1948.¹⁴ Between 1948 and 1953 many methods of surgical repair were explored until Gibbons introduced the cardiopulmonary bypass in the mid-1950s. After its introduction, surgical ASD closure with direct sutures or with the use of a pericardial patch became widely accepted as the gold standard for ASD closure.¹⁴ Nowadays, minimally invasive surgical approaches using a limited oblique incision in the right atrium are increasingly used. Over recent decades, percutaneous device closure, which was originally described by King and Mills in 1974, has become an established alternative to surgery in selected patients with suitable anatomy.¹⁵

The arrhythmia burden after repair of ASD is substantial regardless of the type of closure performed, particularly when repair is performed during adulthood.^{16–19} In a large retrospective cohort of 213 patients after surgical ASD closure 2.3 % of patients developed new onset atrial arrhythmias and 60 % of patients with preoperative atrial flutter or fibrillation continued to have arrhythmias post-surgery after a follow-up period of 3.8 years.¹⁶ A retrospective study of 184 patients after percutaneous device closure demonstrated new-onset arrhythmias in 3.3 % of patients 4 months after repair.¹⁹ Silversides et al. reported an annual risk of new-onset atrial arrhythmias of 1 % in 101 patients after percutaneous ASD closure.¹⁸

The first intracardiac repair of tetralogy of Fallot was performed in 1954 by Lillehei on a 10-month-old boy. Subsequent series of early interventions reported a high perioperative mortality that led to the introduction of a 'two-stage repair' with a palliative shunt followed by total repair later in childhood.

Total repair included (patch) closure of the perimembranous or less frequently observed muscular VSD and relief of the infundibular or valvular right ventricular outflow tract (RVOT) obstruction. This repair was initially performed through a vertical or transverse right ventriculotomy often combined with the use of an RVOT or a large transannular patch to augment the restrictive RVOT. Right ventriculotomy and the use of a transannular patch with resulting pulmonary regurgitation and chronic volume overload often lead to right ventricle (RV) dilatation and dysfunction. Consequently, a combined transatrial–transpulmonary approach has been introduced, which is now usually performed early in life. The arrhythmia burden in repaired tetralogy of Fallot is considerable and increases markedly after the age of 45. The prevalence of AT was 20.1 % in a recent multicentre study, the majority classified as intra-atrial reentry tachycardia (IART).²⁰ A significant number of patients had atrial fibrillation (AF), which is more likely in older patients with left ventricular dysfunction and left atrial dilatation. The vast majority of ventricular arrhythmias documented in repaired tetralogy of Fallot patients are monomorphic and fast ventricular tachyarrhythmias (VT) with a reported prevalence of 14.2 %.²⁰ The modern approach of earlier repair using a transatrial–transpulmonary intervention is likely to have an important impact on the potential substrate and the incidence of ventricular arrhythmias.

The classic Fontan procedure, which is a direct atriopulmonary connection designed in 1971 for patients with tricuspid atresia has

Table 1: Approximate Risk for Arrhythmias in Various Congenital Heart Defects

Type of CHD	IART	AP	AF	MSVT	VA/SCD
ASD	++		+		
VSD	+			+	
CoA			+ residual		++
AVSD	+				
Ebstein's anomaly	++	+++			+
TOF	++			++	++
TGA (atrial switch)	+++			+	++
ccTGA	+	++			+
LVOTO					++
Fontan classic	+++		+		+
Fontan lateral tunnel	+				

*complex D-TGA; + = low risk; ++ = medium risk; +++ = high risk; AP = accessory pathway; AF = atrial fibrillation; ASD = atrial septal defect; AVSD = atrioventricular septal defect; (cc) TGA = (congenitally corrected) transposition of the great arteries; CHD = congenital heart disease; CoA = coarctation of the aorta; IART = intra-atrial reentrant tachycardia; LVOTO = left ventricular outflow tract obstruction; MSVT = monomorphic ventricular tachycardia; SCD = sudden cardiac death; TOF = tetralogy of Fallot; VA = ventricular arrhythmia; VSD = ventricular septal defect.

led to progressive systemic venous atrium (SVA) dilatation. With the aim of improving pulmonary blood flow it has been replaced by modifications to the procedure, which have also been applied to other forms of single ventricle circulation, such as hypoplastic right and left heart syndromes as well as other univentricular hearts.

One of the modifications is the lateral tunnel technique, introduced in 1988. It uses an intra-atrial patch to create a baffle to link the IVC to the superior vena cava (SVC), which is then connected to the pulmonary artery.²¹ The remaining morphological right and left atria serve as the pulmonary venous atrium (PVA). The extracardiac conduit-type Fontan described in 1990 consists of a direct extracardiac connection between the IVC and the right pulmonary artery using a Gore-Tex® conduit.²² The lateral tunnel has resulted in a significant decrease in late atrial tachyarrhythmias (AT) with a 15-year AT-free survival of 87 % compared with 61 % after the classic Fontan. If adjusted for the duration of follow-up the event-free survival was similar for the lateral tunnel and the extracardiac conduit Fontan in a recent paediatric cohort.²³ However, considering the young population and the time dependency of an evolving arrhythmogenic substrate, a longer follow-up is required.

The Fontan operation and its modifications do not require ventricular incisions or patch material. Accordingly, monomorphic VT are unlikely and ventricular arrhythmias may be mainly attributed to impaired function and pathological remodelling of the systemic ventricle.

In dextro-transposition of the great arteries (D-TGA), there is a concordant atrioventricular (AV) connection in combination with ventriculoarterial discordance, with the aorta connecting to the morphological RV, and the pulmonary trunk to the morphological left ventricle (LV). It can occur in an isolated form (simple TGA) or in association with other congenital malformations (complex TGA: VSD in approximately 40 %, or less frequently in combination with pulmonary outflow tract obstruction). Senning performed the first atrial switch operation in 1959 using the atrial septum to create a baffle to redirect the blood flow from the caval veins to the LV. The RV remains the systemic ventricle. The Mustard procedure, introduced

Figure 1: Schematic Overview of Prior and Modern Surgical Approaches in Various Types of Congenital Heart Disease and Resulting Anatomical Isthmuses for Tachyarrhythmias (Blue Lines)

1. Surgical techniques for repair of Tetralogy of Fallot. Left panel: A. transventricular approach with large transannular patch; B. Right Ventricular incision and ventricular septal defect (VSD) closure with patch; C. Four potential anatomical isthmuses for VT are indicated. Right panel: D. transatrial-transpulmonary approach with a small transannular patch and VSD closure with patch preventing isthmus 1 and 2. Two potential isthmuses for atrial tachycardia are indicated. The remaining anatomical isthmus 3 for ventricular tachyarrhythmias depends on the size of the VSD (E, F). Isthmus 4 not shown. 2. Fontan surgical techniques: A. atriopulmonary connection; B. lateral tunnel, C. extracardiac tunnel. The cavotricuspid isthmus (CTI) is indicated. 3. Surgical techniques for transposition of the great arteries. Left panel: Mustard procedure (above) showing the variable spatial relationship between the ostium of the coronary sinus and the baffle. Consecutive surgical steps of the Senning procedure (below). Ablation of the CTI (indicated) after Mustard and Senning procedures often acquires access to the both atria. Right panel: modern arterial switch operation.

in 1964, uses a baffle from pericardium or synthetic material. Both procedures predispose patients to sinus node dysfunction and late AT with an incidence of 60 % and 24 %, respectively, at 20 years post-surgery.²⁴ Simple TGA does not require incisions of the ventricles or patch material, which have been associated with monomorphic VT. However, in complex TGA, VSD patch closure, ventricular incisions and resection of outflow tract obstruction may result in anatomical boundaries facilitating macroreentrant VT as in patients with repaired tetralogy of Fallot.

Since 1975, anatomical correction with the arterial switch operation, first described by Jatene et al., has become the treatment of choice. During this procedure, the aorta and pulmonary trunk are disconnected from their arterial roots and 'switched' to connect to the correct ventricle.²⁵ The prevalence of AT after the arterial switch remains low: in a reasonably large series only 3/65 (4.6 %) patients had a history of atrial flutter in adulthood.²⁶ To determine whether the arterial switch operation also influences the potential substrate for monomorphic VT in complex TGA a longer follow-up is required.

Atrial Tachyarrhythmias

ATs are the most common arrhythmias observed in unselected patients with CHD, with a reported prevalence of 15 %.²⁷ The frequency is highest after Fontan palliation and after atrial switch operation, followed by ASD closure and repaired tetralogy of Fallot (see Figure 2).²⁸ Ageing plays an important role with a lifetime risk of 50 % once a CHD patient has entered the adult population.²⁷

The dominant underlying mechanism is intraatrial (macro) reentrant:

- Cavotricuspid isthmus dependent flutter (CTIDF), which accounts for 40–60 % of all AT;
- Incisional IART using a suture line/prosthetic material as central obstacle, often involving the right lateral atriotomy (20–40 %), or, more rarely;
- Macro-reentrant or localised reentrant AT independent from these structures.^{29,30}

Of importance, CTIDF and IART often coexist and are not distinguishable on surface electrocardiograms (ECGs).³¹ Considering the high incidence of CTIDF in patients with corrected CHD empirical cavotricuspid isthmus (CTI) ablation has been considered in non-inducible patients.³²

Although less frequent, non-automatic focal atrial tachycardias (FATs) do occur, accounting for 5–10 % of all AT.^{29,33,34} These non-automatic FATs are indistinguishable from macroreentrant by routinely applied noninvasive means. Foci are predominantly found in the SVA and may be due to microreentry or triggered activity.³⁵ Body surface mapping is an interesting new technology, but whether it allows reliable differentiation between AT mechanisms in the presence of atrial scarring requires further investigation.

Mapping and Ablation

3D-electroanatomical mapping (EAM) to facilitate RFCA procedures has been successfully used for AT in patients with CHD.^{5,12,13,29,36,37} In patients with incessant or reproducibly inducible and haemodynamically tolerated AT, activation mapping can be performed to identify a focal source with a centrifugal spread of activation³⁵ or to record the continuous sequence of activation covering the cycle length of a (macro-) reentrant AT.⁵ Zones of slow conduction can be identified and entrainment mapping can be used to confirm participation within the reentry circuit.^{5,31}

Considering the complex and variable anatomy with multiple potential reentry circuits, a substrate-based approach facilitated by 3D mapping may be useful in selected patients. This method can also be applied in those who have an otherwise unmappable AT due to an inability to induce the clinically documented AT, multiple and changing circuits or haemodynamically poorly tolerated AT. The latter is more often encountered in patients with Fontan circulation or poor function of the systemic ventricle after the atrial switch operation. In particular the longer cycle length of IART may lead to 1:1 conduction and haemodynamic compromise (see Figure 3).^{5,38} 3D voltage and activation mapping can be performed during stable sinus rhythm to identify boundaries of potential reentry circuit isthmuses. Sites with no atrial potential distinguishable from noise (generally ≤ 0.03 mV) and/or sites at which high output pacing (10 mA/2 ms) can be considered as dense scar or unexcitable tissue.^{5,39}

Contact force measurement or catheter visualisation by intracardiac echocardiography (ICE) may be helpful to exclude poor contact and to identify true unexcitable scar. Delineation of unexcitable tissue may be important as far field electrograms up to 0.3 mV may mimic viable myocardium at sites with transmural fibrosis.⁴⁰ Unexcitable sites can be displayed together with the caval veins, valve annuli and lines of double potentials. Double potentials may be located between the caval veins and the posterolateral SVA consistent with the crista terminalis but may also indicate atriotomy and suture lines.^{29,33} After

delineation of all boundaries that create intervening isthmuses potentially related to AT, these isthmuses can be targeted by a linear RFCA lesion connecting the unexcitable boundaries during SR.

Considering the percutaneous access difficulties, particularly of the CTI in patients after complex surgical repair such as Fontan or atrial switch procedures, intra-operative transection of the CTI during initial repair could be a reasonable and desirable consideration in the future in selected patients.

Technical Developments

The use of an irrigated tip catheter has increased acute procedural success in patients with CHD.^{36,41} Long, steerable sheaths and real-time contact force measurement may be particularly helpful for differentiating between scar and non-contact sites in severely diseased and dilated atria after the classic Fontan. Whether this technique translates into more confluent and durable lesions and better outcome requires further studies.

Image integration (multi-slice computed tomography, cardiac MR) can facilitate ablation by visualising the complex anatomy and its relation to the catheter position. Late gadolinium enhancement cardiac MR may also be performed pre-procedurally to identify a potential arrhythmic substrate by visualising regions of myocardial fibrosis.^{42,43} However, whether anatomical isthmuses related to VT can be visualised by current magnetic resonance imaging (MRI) technology requires further evaluation.

ICE and its real-time integration with EAM may have additional advantages as it can facilitate real-time acquisition of the anatomy and landmark visualisation.³⁸ ICE can also facilitate transseptal and baffle puncture and help to monitor tissue contact.¹³

Non-contact mapping allowing simultaneous recordings of >3000 virtual electrograms has been successfully applied to elucidate the mechanism of right AT in a small group of patients, the majority after ASD closure.⁴⁴ In patients with Fontan circulation who may benefit most from rapid mapping of multiple and often poorly tolerated AT, non-contact mapping was hampered by the size of the SVA with inaccurate scar delineation and appeared an inferior method to EAM.⁴⁵ A promising new technology is high-density multi-electrode contact mapping with small and narrow-spaced electrodes. This is likely to facilitate substrate mapping by fast and accurate delineation of areas of slow conduction and small re-entry circuits in briefly tolerated AT.

Remote-controlled magnetic navigation (RMN) systems can potentially overcome navigation difficulties in CHD by providing improved catheter stability and manoeuvrability, reproducible catheter movement and precise delineation of cardiac anatomy.^{10,46} Irrigated tip RMN catheters and a fully integrated 3D electroanatomical system for superimposing EAM maps on the fluoroscopic reference images are now available.^{47,48} Use of RMN systems in combination with 3D electroanatomical systems has been reported to be safe and effective for ablation in patients with variable CHD complexities.^{10,46,48-50} Several studies suggest a significant reduction in fluoroscopy time using RMN, especially in patients with complex CHD.^{10,48,50} Whether RMN is superior to conventional mapping requires randomised trials that are unlikely to be available in the near future.

Endpoint of Ablation

Different definitions of procedural success and ablation endpoints have been applied and follow-up data acquisition varies between groups.

Figure 2: Prevalence of Supraventricular and Ventricular Tachyarrhythmias in Congenital Heart Disease, Classified According to Main Diagnosis

ASD = atrial septal defect; AVSD = atrioventricular septal defect; TGA = transposition of the great arteries. Data from the Dutch national CONCOR registry.²²

Figure 3: Procedural Workflow for Atrial Tachycardia Ablation in a Classic Fontan Patient with a Haemodynamically Poorly Tolerated Atrial Tachycardia

A. Induced clinical atrial tachycardia (AT) with 1:1 conduction. B. Schematic overview of classic Fontan anatomy and right lateral view of the anatomic shell of the systemic venous atrium (SVA), derived from electroanatomical mapping integrated with MSCT (left ventricle, hypoplastic right ventricle (not segmented), aortic root and coronary arteries). Unexcitable boundaries are indicated by black lines. C. Right lateral view of bipolar voltage and activation map during sinus rhythm. Voltage and activation time is colour-coded according to colour bar; grey tags indicate unexcitable tissue and blue tags indicate double potentials. Continuous conduction is shown (white arrows) through a low bipolar voltage area between two unexcitable boundaries. With the catheter placed at the site indicated by the white circle, the AT could be briefly reinduced. Entrainment at this site (not shown) confirmed participation in the re-entry circuit. D. Electroanatomical map of the SVA showing connection of the unexcitable boundaries by RF applications (red line). Red tags indicate ablation sites. E. Activation map after ablation during pacing from the SVA close to the line. White arrows indicate the changed activation sequence after the linear RF ablation lesions connecting unexcitable boundaries consistent with unidirectional conduction block.

Accordingly, a wide range of acute procedural success rates (63–95 %) and outcome data have been reported. Outcomes are difficult to compare. They are dependent on patient population and the experience of the centres and operators. Table 2 provides an overview of the more recently published series.^{10,12,13,33,41,44,46,50-53} A bidirectional isthmus block is an established endpoint for CTIDF and has improved long-term outcome in patients after atrial switch operations.⁵⁴ The procedural endpoint is less clear for IART for which termination during ablation is still often considered as 'procedural success' with or without non-inducibility at the end of the procedure.^{33,34,41,46,51,53} AT recurrence rates after RFCA are considerably high, ranging from 20–45 % at short-term follow-up. However, they can reach 85 % for complex CHD such as Fontan palliation, even if complete procedural success (defined as termination of all targeted IART and non-inducibility) has been achieved.⁵³ The mechanism of AT recurrences may differ from the initial AT mechanism.^{12,13,33,37,46,51-53}

Table 2: Overview of Recent Literature Concerning Atrial Tachycardia Ablation in Patients with Repaired Congenital Heart Disease

Author, Year	Location	Year of Inclusion	CHD Type (n)	Method	Imaging	Patients (n)	AT, no	AT, mean cl	AT type (n)	Acute Success (%)	Definition Endpoint	Recurrence After Any (Successful) Ablation (%)	Mean FU Time (Months)
Correa, 2015	Boston, US	2006–12	Fontan (52) Extracard. (4) Intracard. (48)	AM	ICE	52	80	312	CTIDF (14) IART (11) FAT (8) Other (21)	CTIDF (100) IART (81) FAT (100) All (84)	TDA + NI	50 (16)	18
Correa, 2013	Boston, US	2006–10	Fontan Classic (52) Modern (37) TGA Mustard (16) Senning (13)	NP	–	90	170	NP	IART (78) FAT (22) Other (70)	81	NI and/or DB (not specified)	30 (NP)	12
Ueda, 2013	London, UK	2007–12	ASD, Ebstein, Fontan, Mustard, TOF, VSD	AM, LL	CMR	116	228	NP	CTIDF (47) IART (87) FAT (43) Other (51)	86	NI	21 (NP)	20
Akca, 2012	Rotterdam, the Netherlands	2007–11	AoS (1), ASD (4), AVSD (2), Ebstein (6), PD (1), PS (2), TA (4), TGA (10), TOF (3), VSD (3)	RMIN, AM	–	36	59	NP	CTIDF (5) IART (19) FAT (13)	86 IART (81) FAT (88)	NI	19 redo 39 (NP)	26
Mah, 2011	Boston, US	1997–2010	TOF (59)	AM, SM	–	95	127	303 (IART)	CTIDF (50) IART (45) FAT (13) EAT (4)	CTIDF (94) IART (84) FAT (92) EAT (100)	TDA in all + NI in 32 IART/CTIDF/ FAT + DB in 34 CTIDF/IART/FAT	34 (NP)	NP
De Groot, 2010	Leiden, the Netherlands	2000–04	ASD (11), CoA (2), Ebstein (1), Fontan (14), TGA (4), TOF (10), Valvular (9), VSD (2)	AM, SM	–	53	54	288 (IDAF) 309 (IART) 380 (FAT)	CTIDF (27) IART (22) FAT (5)	66 IART (55) FAT (100)	CTIDF: DB IART/FAT: TDA	55 (NP)	60

(Continued)

Table 2 (Continued): Overview of Recent Literature Concerning Atrial Tachycardia Ablation in Patients with Repaired Congenital Heart Disease

Author, Year	Location	Year of Inclusion	CHD Type (n)	Method	Imaging	Patients (n)	AT, no	AT, mean cl	AT type (n)	Acute Success (%)	Definition Endpoint	Recurrence After Any (Successful) Ablation (%)	Mean FU Time (Months)
Yap, 2010	Toronto, Canada	1993–2009	ASD (21), AVSD (9), Fontan (21), Other (14), TGA (21), TOF (18), VSD (5)	AM, SM, LL	–	130	118	NP	IART	63	TDA, NI	57 (48)	40
Wu, 2010	Munich, Germany	2006–08	ASD (2), Ebstein (1), Fontan (9), Mustard (2), Senning (4)	RMN, AM	–	22	26	321	CTIDF (8) IART (14) FAT (2)	95	TDA (TGA) NI (Fontan) DB (simple CHD)	9 (NP)	8
Peichl, 2009	Prague, Czech Republic	2004–07	(cc)TGA (4), Fontan (3) VSD (1)	AM, SM	ICE	7	12	320	CTIDF (4) IART (6) FAT (2)	100	DB (CTIDF)	28 (NP)	23
Liew, 2008	London, UK	2002–07	APV (1), ASD (9), TGA (1), TOF (1)	AM, SM	–	12	12	NP	CTIDF (1) IART (9) FAT (1) Other (1)	88	TDA, NI DB (Linear lesions)	33 (36)	26
Triedman, 2005	Boston, US	2002–03	Fontan (9) other biventricular (20)	SM	–	27	67	312	CTIDF (27) IART (40)	66	TDA+ NI + DB	19 (NP)	6

AT = atrial tachycardia; AM = activation mapping; AoS = aortic stenosis; APV = anomalous pulmonary vein drainage; ASD = atrial septal defect; AVSD = atrioventricular septal defect; CHD = congenital heart disease; CMR = cardiac magnetic resonance imaging; CoA = coarctation of the aorta; (cc)TGA = (congenitally corrected) transposition of the great arteries; CTIDF = cavotricuspid isthmus dependent flutter; CTI = cavotricuspid isthmus; DB = demonstrated bidirectional conduction block along the ablation line; EAT = ectopic atrial tachycardia; EM = entrainment mapping; FAT = focal atrial tachycardia; FU = follow-up; IART = intra-atrial reentrant tachycardia; ICE = image integration; LL = linear lesions; NI = non-inducibility after ablation; NP = data not provided; PD = patent ductus; PS = pulmonary stenosis; RMN = remote magnetic navigation; SM = substrate mapping; TA = tricuspid atresia; TDA = termination during ablation; TOF = tetralogy of Fallot; VSD = ventricular septal defect.

Figure 4: Retrograde Approach for Access to the Pulmonary Venous Atrium in a Patient with Cavotricuspid Dependent Atrial Flutter After a Senning Procedure for d-Transposition of the Great Arteries

Right posterior oblique view of the bipolar voltage map of the systemic venous atrium (SVA) integrated with 3D anatomic data of the pulmonary venous atrium (PVA) acquired with intracardiac echocardiography (ICE). Bipolar voltages are colour coded: low voltages (<0.5 mV) are displayed in red. Green dots indicate double potentials, red dots indicate radiofrequency (RF) lesions. The PVA was accessed using a retrograde approach. Linear RF lesions connecting the tricuspid valve annulus and the inferior caval vein resulted in cavotricuspid dependent atrial flutter (CTDF) termination. Insets show catheter position during termination of the tachycardia on fluoroscopic right and left oblique views. IART = intra-atrial reentry tachycardia; ICV = indicates inferior caval vein; LAO = left anterior oblique view; PVs = pulmonary veins; RAO = right anterior oblique view; SCV = superior caval vein. Adapted with permission from den Uijl et al.³⁸

In a small series of 16 patients with various CHD all identified isthmuses based on electroanatomical substrate mapping were targeted, regardless of whether an AT was related to it. Unidirectional conduction block was applied as lesion endpoint. This approach was successful for 28 in 29 identified isthmuses. During a median follow-up of 14 months, only one new macro-reentrant AT was documented in one patient.⁵ The appealing concept of substrate-based ablation needs to be evaluated prospectively in a larger population.

Right Lateral Atriotomy

After right lateral atriotomy for ASD closure, repair of tetralogy of Fallot or as a part of many other corrective surgeries, the most common macro-reentrant circuit is a CTI-dependent flutter (52–71 %), followed by a macro-reentrant circuit with the lateral incision as central obstacle (21–31 %).^{29,33,34} Regardless of the initial ablation site >50 % of all recurrences occurred at either the CTI or the lateral SVA scar supporting an empirical linear ablation between the lateral SVA scar and the IVC.³³

Fontan Circulation

After classic Fontan operation patients may encounter multiple IART circuits at various locations due to progressive SVA enlargement and time-dependent development of low-voltage areas that may serve as reentry circuit borders.^{5,55}

CTI-dependent flutter (or cavomitral in L-looped ventricles) usually requires access to the PVA, either by a pre-existing fenestration, a trans-baffle puncture or, rarely, via a retrograde access.⁵¹ In patients with lateral tunnels, circuits may be localised to the low right atrium even in the absence of the tricuspid valve. Pericaval reentry is common with an area of slow conduction associated with the lower margin of the crista terminalis or low SVA surgical scars (e.g. cannulation site),

which can often be terminated by focal ablation.⁵⁶ Although pericaval reentry, which is typically slower than periannular reentry, can also be ablated by transecting the CTI-isthmus between the IVC and the hypoplastic or atretic valve, the latter may be more challenging due to an ambiguous anatomy and the risk of AV node injury.

In a series of 52 patients after total cavopulmonary connection, the majority of non-CTI-dependent reentrant circuits were located within the intracardiac baffle. It is important to note that focal AT can also be encountered and are often successfully ablated within the intracardiac tunnel.^{35,51,52}

d-Transposition of the Great Arteries with Atrial Switch

The most important mechanism for AT in D-TGA patients after Mustard or Senning is CTDF, accounting for 64–77 % of all spontaneous and induced AT. This is followed by IART and localised reentry, which may be confined to the PVA or SVA.^{29,30} The tricuspid valve and variable portions of the CTI are located on the pulmonary venous side, dependent on the surgical variant.⁵⁷ In 81 % access to the CTI cannot be achieved via a systemic route but requires either a retrograde transaortic access through the AV-valve or a trans-baffle puncture (see Figure 4).⁵⁴

Trans-baffle Access

An angiogram of the SVA can identify baffle leaks that may be crossed. In the absence of fenestrations or leaks, a trans-baffle puncture can be guided by fluoroscopy, transoesophageal echo or ICE with acute success rates of up to 96 %, if performed in experienced centres.⁵⁸ In selected cases radiofrequency assisted transseptal perforation may be considered.⁵⁹ In the extracardiac conduit Fontan transconduit access to the PVA can be challenging.

Ventricular Arrhythmias

The incidence of sudden cardiac death (SCD) in repaired CHD is 0.9–2.6 per 1,000 patient years, which is 25–100-fold higher than for the general population.^{60,61} Corrected cardiac defects often associated with ventricular arrhythmias and SCD are TGA, repaired tetralogy of Fallot and left sided outflow lesions (see Table 1). Cohort studies reporting on mortality cannot provide the type of ventricular arrhythmia leading to a presumed arrhythmic death.⁶² Ventricular arrhythmias encompass polymorphic VT, ventricular fibrillation in the absence of surgical scar and monomorphic VT; with a higher prevalence in patients who have undergone ventricular incision and patch closure of VSD. VT in repaired tetralogy of Fallot patients can serve as a paradigm for these postoperative monomorphic arrhythmias that are approachable by RFCA.

Indeed, based on ICD interrogation in patients with repaired tetralogy of Fallot and TGA, implanted for primary and secondary prevention, >80 % of all ventricular arrhythmias that prompted ICD therapy in repaired tetralogy of Fallot and around 50 % in TGA patients are fast and monomorphic VT often with heart rates >200 bpm.^{63,64} When rapid and untreated, these monomorphic VT may be fatal even in the presence of preserved cardiac function.

Moderate-to-severe systemic ventricular dysfunction is a dominant predictor for SCD in an unselected population of adults with CHD.⁵⁴ Of interest, in a recent cohort two-thirds of early-to-middle-aged adult tetralogy of Fallot patients who died suddenly or experienced life-threatening VT had a preserved cardiac function before the first event.⁶⁵ In addition, two-thirds of repaired tetralogy of Fallot patients referred for RFCA of fast and potential life-threatening, monomorphic

Table 3: Overview of Recent Literature Concerning Ventricular Tachycardia Ablation in Patients with Repaired Congenital Heart Disease

Author, Year	Location	Year of Inclusion	CHD Type (n)	Method	Patients (n)	Sus-VT (n)	VTCL Mean (ms)	Acute Success	Recurrence
Burton, 1993	Atlanta, US	1992	TOF	PM	2	2	270	2/2	0/2
Biblo, 1994	Cleveland, US	1991	TOF	AM	1	2	430	1/1	0/1
Goldner, 1994	Manhasset, US	1994	TOF	PM	1	1	240	1/1	0/1
Cinushi, 1995	Niigata, Japan	1995	TOF	AM + LL	1	2	420	2/2	0/1
Gonska, 1996†	Karlsruhe, Germany	1996	TOF (7), VSD (1), TGA + VSD (1), PS (2)	AM	11	11	377	9/11	2/11
Horton, 1997	Dallas, US	1997	TOF	AM + LL	2	2	430	2/2	0/2
Baral, 2004	Southampton, UK	2004	ccTGA + Ebstein + TVR	AM (NC) + ENT	1	1	380	1/1	0/1
Rostock, 2004	Hamburg, Germany	2004	TOF	AM + LL	1	1	340	1/1	0/1
Morwood, 2004	Boston, US	1990–2003	TOF (8), VSD (3), Other (3)	–	14 Patients 20 Procedures	–	–	10/20	4/10
Furushima, 2005	Niigata, Japan	2005	TOF/DORV	AM + LL	7	14 Targeted 8	346	4/7	6/7
Kriebel, 2007	Göttingen, Germany, Charleston, US	2007	TOF	SSM + LVA (NC) + LL	10	13	269	8/10	2/8
Zeppenfeld, 2007	Leiden, the Netherlands	1998–2007	TOF (9), AVSD (1), TGA + VSD (1)	SSM + EUS + LL + IMG (1/11, CT)	11	15	276	11/11	1/11
Nair, 2011	Hamilton, Canada	2011	TGA + VSD + sPS	SSM + PM + IMG (CT)	1	1	350	1/1	0/1
Piers, 2012	Leiden, the Netherlands	2012	TGA + sPS	SSM + AM + IMG (CT, CMR)	1	1	340	1/1	0/1
Kapel, 2015	Leiden, the Netherlands, Boston, US	2001–12	TOF (28), TGA + sPS (1), TGA + VSD (1), VSD + sPS (1), PS (1) VSD + bAV (1), AVSD (1)	SSM + EUS + LL + IMG	34	61	295 (242–346)*	25/34‡	0/25‡

* = median (IQR); ‡ = acute success defined as non-inducibility and transection of anatomical isthmus; † = one patient had ICD shock for VF. AVSD = atrioventricular septal defect; AM = activation mapping; (cc)TGA = (congenitally corrected) transposition of the great arteries; CHD = congenital heart disease; CMR = cardiac magnetic resonance imaging; CT = computed tomography; DORV = double outlet right ventricle; ENT = entrainment; EUS = electrically unexcitable scar; IMG = image integration; LL = linear lesions; LVA = low voltage areas; NC = non-contact; PM = pace mapping; (s)PS = (sub)pulmonary stenosis; SSM = substrate mapping; sus-VT = sustained ventricular tachycardia; TOF = Tetralogy of Fallot; TVR = tricuspid valve replacement; VSD = ventricular septal defect; VTCL = ventricular tachycardia cycle length.

VT also had a preserved biventricular function at the time of ablation.⁸ Whether more subtle parameters such as longitudinal LV function may help to identify patients at risk needs further study. Over the last decade progress has been made to determine the anatomical basis of monomorphic VT in repaired tetralogy of Fallot and complex TGA, which is crucial for both risk stratification and treatment.

Anatomical Substrate for Ventricular Tachyarrhythmia and Impact on Catheter Ablation

The feasibility of catheter ablation of VT in patients after repair of CHD has been reported and Table 3 summarises the available data.^{6,8,66–78} The majority of treated patients were repaired tetralogy of Fallot patients. Accordingly, data on the mechanism and substrate of ventricular arrhythmias in other CHD is sparse.

Up to 97 % of all spontaneous and induced monomorphic VT in CHD patients referred for RFCA, or studied for risk stratification, are macro-reentrant VT with a critical reentry circuit isthmus located within electroanatomically defined isthmuses.^{6,8,76} The majority of these VTs are fast and haemodynamically poorly tolerated requiring a substrate-based ablation approach.^{6,8,76}

Mapping and Ablation

A 3D reconstruction of all potential anatomical isthmuses can be obtained during sinus rhythm by identifying the boundaries, facilitated by the use of 3D mapping systems as described for AT. Bipolar electrograms >1.5 mV are considered normal ventricular voltage. At sites with amplitudes <0.5 mV, high-output pacing (10 mA, 2 ms) can be performed to identify unexcitable tissue, which is consistent with

Figure 5: Procedural Workflow for Ablation of a Haemodynamically Nontolerated Ventricular Tachycardia in a Patient After Repair of Tetralogy of Fallot

A. 12-Lead ECG recording of a spontaneous ventricular tachycardia (VT). B. The clinical VT could be induced during programmed stimulation. C. Modified PA-view of electroanatomical bipolar voltage (top) and activation map (bottom) during sinus rhythm. Voltages and activation time are colour-coded according to colour bars, unexcitable tissue is displayed by gray tags. Anatomical isthmus 3 is shown between the ventricular septal defect-patch and the pulmonary valve (PV) in white-dashed brackets. Activation mapping shows continuous conduction through anatomical isthmus 3. D. Pace-mapping at isthmus 3 showed a good pace-match of VT suggesting that the VT isthmus site is located within anatomical isthmus 3. E. Bipolar voltage and activation map during SR after linear RF ablation, connecting the unexcitable boundaries. Red tags indicate ablation sites. White arrows indicate the changed activation sequence through isthmus 3 consistent with unidirectional conduction block. Reprinted with permission from Kapel et al.⁸ TA = tricuspid annulus.

patch material or surgical scars. Depending on the malformation and the type of repair different anatomical isthmuses may be present. Four anatomical isthmuses related to VT in repaired tetralogy of Fallot have been identified (see Figure 1): Isthmus 1 bordered by the tricuspid annulus and the scar or patch in the anterior RVOT; isthmus 2 between the pulmonary annulus and the RV free wall incision or RVOT patch sparing the pulmonary valve annulus; isthmus 3 between the pulmonary annulus and the VSD patch or septal scar; and isthmus 4 between the VSD patch or septal scar and the tricuspid annulus in patients with muscular VSDs.⁶ Additional anatomical isthmuses have been described in complex TGA or after surgery for VSD and pulmonary stenosis.^{8,77,79}

The critical reentry circuit isthmus of an induced VT can be determined by activation and entrainment mapping for haemodynamically tolerated VT or by pace-mapping for unstable arrhythmias.^{6,8} An alternative approach for mapping poorly tolerated VT is noncontact mapping. The system consists of a multielectrode balloon array and allows simultaneous acquisition of virtual unipolar electrograms. The activation sequence of fast VTs in 10 tetralogy of Fallot patients has been reported, the majority being macroreentrant circuits. The anatomical location of the critical isthmus could be identified in all patients.⁷⁶ If the critical isthmus is located within an anatomically defined isthmus the anatomical isthmus can be transected by

Figure 6: Intraoperative View During Pulmonary Valve Replacement Using a Pulmonary Homograft in a Patient with Repaired Tetralogy of Fallot

connecting the adjoining anatomical boundaries by linear radio frequency (RF) lesions during sinus rhythm (SR).

Endpoint of Ablation

Demonstration of conduction block after isthmus transection provides a defined procedural endpoint similar to that for achieving block in the CTI (see Figure 5).⁸ A systematic substrate mapping and ablation approach has been applied in 34 adults with CHD (82 % tetralogy of Fallot). Complete procedural success was defined as noninducibility of any VT and transection of the critical anatomical isthmus, which was achieved in 25 patients. None of these patients had recurrence of a monomorphic VT during 46 ± 29 months of follow-up.⁸ These data suggest that macroreentrant VT based on an anatomical substrate can be treated effectively with catheter ablation. Isthmus ablation with confirmed conduction block should be attempted and, if successful, may be considered curative in patients with preserved cardiac function and no competing arrhythmia mechanism.

Arrhythmogenic Anatomical Isthmuses

Anatomical isthmuses are present in almost all repaired tetralogy of Fallot patients but not all are related to VT. Specific features of the anatomical isthmuses after initial repair, such as isthmus width and

thickness of the myocardium, may be one decisive factor for further remodelling over time thereby forming the substrate for late VT.

In post-mortem series of repaired tetralogy of Fallot, isthmus 3 and 1 were present in almost all specimens, whereas isthmus 2 and 4 were observed in only 25 % and 13 %, respectively.^{6,80} In specimens from patients aged ≥ 5 years at the time of death, isthmus 3 was significantly narrower and thinner with more interstitial and replacement fibrosis than isthmus 1.⁸⁰ In particular, narrow isthmuses with interstitial fibrosis may provide the substrate for slow conduction crucial for re-entrant VT.

To identify the characteristics of anatomical isthmuses that may serve as a substrate for VT, detailed electroanatomical voltage and activation mapping during SR has been performed in a cohort of 74 tetralogy of Fallot patients with at least one risk factor for ventricular arrhythmia, including 13 with prior documented VT. Narrow and slow conducting anatomical isthmuses (calculated conduction velocity <0.5 m/s) were the substrate for all 37 documented and induced ventricular tachycardia in 24 patients with preserved cardiac function (unpublished data). Considering the strong link between slow conducting anatomical isthmuses that can be identified and ablated during stable sinus rhythm and monomorphic VT in repaired tetralogy of Fallot, inducibility of the clinical arrhythmia and haemodynamic tolerance is no longer a prerequisite for successful ablation.

Important reasons for ablation failure are hypertrophied myocardium and protection of portions of anatomical isthmuses by patch material.⁸¹ In particular, in patients who have undergone pulmonary valve replacement (PVR) the implanted pulmonary homograft may cover parts of the infundibular septum preventing transection of anatomical isthmus 3 (see *Figure 6*). If ablation from the RV fails to transect the anatomical isthmuses a left-sided approach may be helpful for those anatomical isthmuses which involve the septum.⁸¹ The strong association between anatomically defined isthmuses, macroreentrant VT and the inability to transect isthmus 3 after PVR may justify pre-operative mapping and preventive ablation in patients with slow conducting anatomical isthmuses who require reoperation for pulmonary valve regurgitation.

With the introduction of a combined transatrial-transpulmonary approach and only limited patch augmentation for pulmonary valve stenosis, anatomical isthmuses 1 and 2 may be prevented in the majority of patients. However, isthmus 3 will remain. Evaluation of its potential arrhythmogeneity by EAM is appealing and could allow personalised risk stratification and tailored treatment for contemporary patients with repaired tetralogy of Fallot. Whether preventive transection of isthmus 3 during initial repair in the very young is feasible, reasonable and safe needs careful, multidisciplinary consideration.

Conclusion

With improved longevity for patients after repair of CHD, management of atrial and ventricular arrhythmias will continue to be of great importance. Patients with repaired CHD represent a highly heterogeneous group, displaying considerable anatomical diversity and complex, variable arrhythmogenic substrates. Enhanced understanding of the underlying substrate as well as technical developments for mapping and RFCA have improved outcomes in patients after CHD repair. However, continued focus on the understanding of the arrhythmogenic substrate in conjunction with technical developments for the accurate delineation of its 3D anatomy and improved ablation techniques to achieve continuous and durable lesions is essential in order to further improve outcomes in this diverse population. ■

Clinical Perspective

- In patients with repaired congenital heart disease (CHD), improved longevity results in a high risk for late tachyarrhythmias leading to significant morbidity and mortality.
- Arrhythmogenic substrates in patients after repair of CHD have changed as a result of evolving surgical techniques.
- Radiofrequency catheter ablation remains challenging in patients with repaired CHD due to variable anatomy, surgically created obstacles and complex arrhythmogenic substrates.
- A substrate-based approach facilitated by 3D-electroanatomical mapping and accurate delineation of the anatomy is desired in catheter ablation procedures in patients with repaired CHD.

- Hoffman J, Kaplan S. The incidence of congenital heart disease. *J Am Coll Cardiol* 2002;**39**:1890–900. PMID: 12084585
- Moons P, Bovijn L, Budts W, et al. Temporal trends in survival to adulthood among patients born with congenital heart disease from 1970 to 1992 in Belgium. *Circulation* 2010;**122**:2264–72. DOI: 10.1161/CIRCULATIONAHA.110.946343; PMID: 21098444.
- Oechslin EN, Harrison DA, Connelly MS, et al. Mode of death in adults with congenital heart disease. *Am J Cardiol* 2000;**86**:1111–6. PMID: 11074209
- Van Hare GF, Lesh MD, Stanger P. Radiofrequency catheter ablation of supraventricular arrhythmias in patients with congenital heart disease: results and technical considerations. *J Am Coll Cardiol* 1993;**22**:883–90. PMID: 8354828
- Nakagawa H, Shah N, Matsudaira K, et al. Characterization of reentrant circuit in macroreentrant right atrial tachycardia after surgical repair of congenital heart disease: isolated channels between scars allow “focal” ablation. *Circulation* 2001;**103**:699–709. PMID: 11156882
- Zeppenfeld K, Schali J, Bartelings MM, et al. Catheter ablation of ventricular tachycardia after repair of congenital heart disease: electroanatomic identification of the critical right ventricular isthmus. *Circulation* 2007;**116**:2241–52. DOI: 10.1161/CIRCULATIONAHA.107.723551; PMID: 17967973
- Chowdhury UK, Sathia S, Ray R, et al. Histopathology of the right ventricular outflow tract and its relationship to clinical outcomes and arrhythmias in patients with tetralogy of Fallot. *J Thorac Cardiovasc Surg* 2006;**132**:270–7. DOI: 10.1016/j.jtcvs.2006.04.001; PMID: 16872949
- Kapel GF, Reichlin T, Wijnmaalen AP, et al. Re-entry using anatomically determined isthmuses: a curable ventricular tachycardia in repaired congenital heart disease. *Circ Arrhythm Electrophysiol* 2015;**8**:102–9. DOI: 10.1161/CIRCEP.114.001929; PMID: 25422392
- Ueda A, Adachi I, McCarthy KP, et al. Substrates of atrial arrhythmias: histological insights from patients with congenital heart disease. *Int J Cardiol* 2013;**168**:2481–6. DOI: 10.1016/j.ijcard.2013.03.004; PMID: 23541611
- 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. DOI: 10.1161/CIRCEP.113.000415; PMID: 23685536
- Yap SC, Harris L, Chauhan VS, et al. Identifying high risk in adults with congenital heart disease and atrial arrhythmias. *Am J Cardiol* 2011;**108**:723–8. DOI: 10.1016/j.amjcard.2011.04.021; PMID: 21684512
- de Groot NM, Atary JZ, Blom NA, Schali J. Long-term outcome after ablative therapy of postoperative atrial tachyarrhythmia in patients with congenital heart disease and characteristics of atrial tachyarrhythmia recurrences. *Circ Arrhythm Electrophysiol* 2010;**3**:148–54. DOI: 10.1161/CIRCEP.109.909838; PMID: 20194797
- Peichl P, Kautzner J, Gebauer R. Ablation of atrial tachycardias after correction of complex congenital heart diseases: utility of intracardiac echocardiography. *Europace* 2009;**11**:48–53. DOI: 10.1093/europace/eun316; PMID: 19029131
- Alexi-Meskishvili VV, Konstantinov IE. Surgery for atrial septal defect: from the first experiments to clinical practice. *Ann Thorac Surg* 2003;**76**:322–7. PMID: 12842577
- Moore J, Hegde S, Committee AIS, et al. Transcatheter device closure of atrial septal defects: a safety review. *JACC Cardiovasc Interv* 2013;**6**:433–42. DOI: 10.1016/j.jcin.2013.02.005; PMID: 23702008
- Gatzoulis MA, Freeman MA, Siu SC, et al. Atrial arrhythmia after surgical closure of atrial septal defects in adults. *N Engl J Med* 1999;**340**:839–46. DOI: 10.1056/NEJM199903183401103; PMID: 10080846
- Giardini A, Dotti A, Sciarra F, et al. Long-term incidence of atrial fibrillation and flutter after transcatheter atrial septal defect closure in adults. *Int J Cardiol* 2009;**134**:47–51. DOI: 10.1016/j.ijcard.2008.02.003; PMID: 18396341
- Silversides CK, Siu SC, McLaughlin PR, et al. Symptomatic atrial arrhythmias and transcatheter closure of atrial septal defects in adult patients. *Heart* 2004;**90**:1194–8. DOI: 10.1136/hrt.2003.022475; PMID: 15367523; PMCID: PMC1768500
- Johnson JN, Marquardt ML, Ackerman MJ, et al. Electrocardiographic changes and arrhythmias following percutaneous atrial septal defect and patent foramen ovale device closure. *Catheter Cardiovasc Interv* 2011;**78**:254–61. DOI: 10.1002/ccd.23028; PMID: 21563292
- Khairy P, Aboulhossn J, Gurvitz MZ, et al. Arrhythmia burden in adults with surgically repaired tetralogy of Fallot: a multi-institutional study. *Circulation* 2010;**122**:868–75. DOI: 10.1161/CIRCULATIONAHA.109.928481; PMID: 20713900
- de Leval MR, Kilner P, Gewillig M, Bull C. Total cavopulmonary connection: a logical alternative to atriopulmonary connection for complex Fontan operations. Experimental

- studies and early clinical experience. *J Thorac Cardiovasc Surg* 1988;**96**:682–95. PMID: 3184963
22. Marcelletti C, Corno A, Giannico S, Marino B. Inferior vena cava-pulmonary artery extracardiac conduit. A new form of right heart bypass. *J Thorac Cardiovasc Surg* 1990;**100**:228–32. PMID: 2143549
23. Stephenson EA, Lu M, Berul CI, et al. Arrhythmias in a contemporary fontan cohort: prevalence and clinical associations in a multicenter cross-sectional study. *J Am Coll Cardiol* 2010;**56**:890–6. DOI: 10.1016/j.jacc.2010.03.079; PMID: 20813285; PMCID: PMC3200364
24. Gerlatti M. Arrhythmia and mortality after the mustard procedure: a 30-year single-center experience. *J Am Coll Cardiol* 1997;**1**:194–201. PMID: 8996314
25. Jatene AD, Fontes VF, Paulista PP, et al. Anatomic correction of transposition of the great vessels. *J Thorac Cardiovasc Surg* 1976;**72**:364–70. PMID: 957754
26. Tobler D, Williams WG, Jegatheeswaran A, et al. Cardiac outcomes in young adult survivors of the arterial switch operation for transposition of the great arteries. *J Am Coll Cardiol* 2010;**1**:58–64. DOI: 10.1016/j.jacc.2010.03.031; PMID: 20620718
27. Bouchardy J, Therrien J, Pilote L, et al. Atrial arrhythmias in adults with congenital heart disease. *Circulation* 2009;**120**: 1679–86. DOI: 10.1161/CIRCULATIONAHA.109.866319; PMID: 19822808
28. van der Velde ET, Vriend JW, Mannens MM, et al. CONCOR, an initiative towards a national registry and DNA-bank of patients with congenital heart disease in the Netherlands: rationale, design, and first results. *Eur J Epidemiol* 2005;**20**: 549–57. PMID: 16121765
29. Lukac P, Pedersen AK, Mortensen PT, et al. Ablation of atrial tachycardia after surgery for congenital and acquired heart disease using an electroanatomic mapping system: Which circuits to expect in which substrate? *Heart Rhythm* 2005;**2**: 64–72. DOI: 10.1016/j.hrthm.2004.10.034; PMID: 15851267
30. Wu J, Deisenhofer I, Ammar S, et al. Acute and long-term outcome after catheter ablation of supraventricular tachycardia in patients after the Mustard or Senning operation for D-transposition of the great arteries. *Europace* 2013;**15**:886–91. DOI: 10.1093/europace/eus402; PMID: 23355133
31. Akar JG, Kok LC, Haines DE, et al. Coexistence of type I atrial flutter and intra-atrial re-entrant tachycardia in patients with surgically corrected congenital heart disease. *J Am Coll Cardiol* 2001;**38**:377–84. PMID: 11499727
32. Verma A, Marrouche NF, Seshadri N, et al. Importance of ablating all potential right atrial flutter circuits in postcardiac surgery patients. *J Am Coll Cardiol* 2004;**44**:409–14. DOI: 10.1016/j.jacc.2004.04.045; PMID: 15261940
33. Mah DY, Alexander ME, Cecchin F, et al. The electroanatomic mechanisms of atrial tachycardia in patients with tetralogy of Fallot and double outlet right ventricle. *J Cardiovasc Electrophysiol* 2011;**22**:1013–7. DOI: 10.1111/j.1540-8167.2011.02062.x; PMID: 21539636
34. de Groot NM, Lukac P, Schali J, et al. Long-term outcome of ablative therapy of post-operative atrial tachyarrhythmias in patients with Tetralogy of Fallot: a European multi-centre study. *Europace* 2012;**14**:522–7. DOI: 10.1093/europace/eur313; PMID: 21971346
35. Seslar SP, Alexander ME, Berul CI, et al. Ablation of nonautomatic focal atrial tachycardia in children and adults with congenital heart disease. *J Cardiovasc Electrophysiol* 2006;**17**:359–365. DOI: 10.1111/j.1540-8167.2006.00354.x; PMID: 16643355
36. 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. PMID: 12039499
37. de Groot NM, Zeppenfeld K, Wijffels MC, et al. Ablation of focal atrial arrhythmia in patients with congenital heart defects after surgery: role of circumscribed areas with heterogeneous conduction. *Heart Rhythm* 2006;**3**:526–35. DOI: 10.1016/j.hrthm.2006.01.011; PMID: 16648056
38. den Uijl DW, Blom NA, Wijnmaalen AP, et al. Real-time integration of intracardiac echocardiography to facilitate atrial tachycardia ablation in a patient with a Senning baffle. *Circ Arrhythm Electrophysiol* 2009;**2**:e28–30. DOI: 10.1161/CIRCEP.109.875534; PMID: 19843911
39. Soejima K, Stevenson WG, Maisel WH, et al. Electrically unexcitable scar mapping based on pacing threshold for identification of the reentry circuit isthmus: feasibility for guiding ventricular tachycardia ablation. *Circulation* 2002;**106**:1678–83. PMID: 12270862
40. Harrison JL, Jensen HK, Peel SA, et al. Cardiac magnetic resonance and electroanatomic mapping of acute and chronic atrial ablation injury: a histological validation study. *Eur Heart J* 2014;**35**:1486–95. DOI: 10.1093/eurheartj/ehs560; PMID: 24419806; PMCID: PMC4048535
41. Triedman JK, DeLucca JM, Alexander ME, et al. Prospective trial of electroanatomically guided, irrigated catheter ablation of atrial tachycardia in patients with congenital heart disease. *Heart Rhythm* 2005;**2**:700–5. DOI: 10.1016/j.hrthm.2005.03.017; PMID: 15992724
42. Broberg C, Meadows AK. Advances in imaging: the impact on the care of the adult with congenital heart disease. *Prog Cardiovasc Dis* 2011;**53**:293–304. DOI: 10.1016/j.pcad.2010.11.004; PMID: 21295671
43. Babu-Narayan SV, Kilner PJ, Li W, et al. Ventricular fibrosis suggested by cardiovascular magnetic resonance in adults with repaired tetralogy of fallot and its relationship to adverse markers of clinical outcome. *Circulation* 2006;**113**:405–13. DOI: 10.1161/CIRCULATIONAHA.105.548727; PMID: 16432072
44. Liew R, Catanchin A, Behr ER, Ward D. Use of non-contact mapping in the treatment of right atrial tachycardias in patients with and without congenital heart disease. *Europace* 2008;**10**:972–81. DOI: 10.1093/europace/eun183; PMID: 18662941
45. Abrams DJ, Earley MJ, Sporton SC, et al. Comparison of noncontact and electroanatomic mapping to identify scar and arrhythmia late after the Fontan procedure. *Circulation* 2007;**115**:1738–46. DOI: 10.1161/CIRCULATIONAHA.106.633982; PMID: 17372177
46. 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. DOI: 10.1016/j.amjcard.2012.03.040; PMID: 22572608
47. Ernst S. Robotic approach to catheter ablation. *Curr Opin Cardiol* 2008;**23**:28–31. DOI: 10.1097/HCO.0b013e3282f2c95c; PMID: 18281824
48. 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. DOI: 10.1161/CIRCEP.111.962993; PMID: 22062797
49. Schwagten B, Jordaens L, Witsenburg M, et al. Initial experience with catheter ablation using remote magnetic navigation in adults with complex congenital heart disease and in small children. *Pacing Clin Electrophysiol* 2009;**32**(Suppl 1):S198–201. DOI: 10.1111/j.1540-8159.2008.02283.x; PMID: 19250093
50. 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. DOI: 10.1111/j.1540-8167.2009.01697.x; PMID: 20132396
51. Correa R, Sherwin ED, Kovach J, et al. Mechanism and ablation of arrhythmia following total cavopulmonary connection. *Circ Arrhythm Electrophysiol* 2015;**8**:318–25. DOI: 10.1161/CIRCEP.114.001758; PMID: 25583982
52. Correa R, Walsh EP, Alexander ME, et al. Transbaffle mapping and ablation for atrial tachycardias after mustard, senning, or Fontan operations. *J Am Heart Assoc* 2013;**2**:e000325. DOI: 10.1161/JAHA.113.000325; PMID: 24052498; PMCID: PMC3835240
53. Yap SC, Harris L, Silversides CK, et al. Outcome of intra-atrial re-entrant tachycardia catheter ablation in adults with congenital heart disease: negative impact of age and complex atrial surgery. *J Am Coll Cardiol* 2010;**56**:1589–96. DOI: 10.1016/j.jacc.2010.04.061; PMID: 21029876; PMID: 21029876
54. El Yaman MM, Asirvatham SJ, Kapa S, et al. Methods to access the surgically excluded cavotricuspid isthmus for complete ablation of typical atrial flutter in patients with congenital heart defects. *Heart Rhythm* 2009;**6**:949–56. DOI: 10.1016/j.hrthm.2009.03.017; PMID: 19482557
55. Yap SC, Harris L, Downar E, et al. Evolving electroanatomic substrate and intra-atrial reentrant tachycardia late after Fontan surgery. *J Cardiovasc Electrophysiol* 2012;**23**:339–45. DOI: 10.1111/j.1540-8167.2011.02202.x; PMID: 22035149
56. Mandapati R, Walsh EP, Triedman JK. Pericaval and periannular intra-atrial reentrant tachycardias in patients with congenital heart disease. *J Cardiovasc Electrophysiol* 2003;**14**:119–25. PMID: 12693488
57. Kanter RJ, Papagiannis J, Carboni MP, et al. Radiofrequency catheter ablation of supraventricular tachycardia substrates after mustard and senning operations for d-transposition of the great arteries. *J Am Coll Cardiol* 2000;**35**:428–41. PMID: 10676691
58. Jones DG, Jarman JW, Lyne JC, et al. The safety and efficacy of trans-baffle puncture to enable catheter ablation of atrial tachycardias following the Mustard procedure: a single centre experience and literature review. *Int J Cardiol* 2013;**168**:1115–20. DOI: 10.1016/j.ijcard.2012.11.047; PMID: 23219079
59. Esch JJ, Triedman JK, Cecchin F, et al. Radiofrequency-assisted transseptal perforation for electrophysiology procedures in children and adults with repaired congenital heart disease. *Pacing Clin Electrophysiol* 2013;**36**:607–11. DOI: 10.1111/pace.12092; PMID: 23380019
60. 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. PMID: 9669277
61. Verheugt CL, Uiterwaal CS, van der Velde ET, et al. Mortality in adult congenital heart disease. *Eur Heart J* 2010;**31**:1220–9. DOI: 10.1093/eurheartj/ehq032; PMID: 20207625
62. Koyak Z, Harris L, de Groot JR, et al. Sudden cardiac death in adult congenital heart disease. *Circulation* 2012;**126**: 1944–54. DOI: 10.1161/CIRCULATIONAHA.112.104786; PMID: 22991410
63. Khairy P, Harris L, Landzberg MJ, et al. Sudden death and defibrillators in transposition of the great arteries with intra-atrial baffles: a multicenter study. *Circ Arrhythm Electrophysiol* 2008;**1**:250–7. DOI: 10.1161/CIRCEP.108.776120; PMID: 19808416
64. Khairy P, Harris L, Landzberg MJ, et al. Implantable cardioverter-defibrillators in tetralogy of Fallot. *Circulation* 2008;**117**:363–70. DOI: 10.1161/CIRCULATIONAHA.107.726372; PMID: 18172030
65. Diller GP, Kempny A, Liodakis E, et al. Left ventricular longitudinal function predicts life-threatening ventricular arrhythmia and death in adults with repaired tetralogy of fallot. *Circulation* 2012;**125**:2440–6. DOI: 10.1161/CIRCULATIONAHA.111.086983; PMID: 22496160
66. Burton ME, Leon AR. Radiofrequency catheter ablation of right ventricular outflow tract tachycardia late after complete repair of tetralogy of Fallot using the pace mapping technique. *Pacing Clin Electrophysiol* 1993;**16**: 2319–25. PMID: 7508611
67. Biblo LA, Carlson MD. Transcatheter radiofrequency ablation of ventricular tachycardia following surgical correction of tetralogy of Fallot. *Pacing Clin Electrophysiol* 1994;**17**:1556–60. PMID: 7991428
68. Goldner BG, Cooper R, Blau W, Cohen TJ. Radiofrequency catheter ablation as a primary therapy for treatment of ventricular tachycardia in a patient after repair of tetralogy of Fallot. *Pacing Clin Electrophysiol* 1994;**17**:1441–6. PMID: 7971406
69. Chinushi M, Aizawa Y, Kitazawa H, et al. Successful radiofrequency catheter ablation for macroreentrant ventricular tachycardias in a patient with tetralogy of Fallot after corrective surgery. *Pacing Clin Electrophysiol* 1995;**18**: 1713–6. PMID: 7491316
70. Gonska BD, Cao K, Raab J, et al. Radiofrequency catheter ablation of right ventricular tachycardia late after repair of congenital heart defects. *Circulation* 1996;**94**:1902–8. PMID: 8873666
71. Horton RP, Canby RC, Kessler DJ, et al. Ablation of ventricular tachycardia associated with tetralogy of Fallot: demonstration of bidirectional block. *J Cardiovasc Electrophysiol* 1997;**8**:432–5. PMID: 9106428
72. Baral VR, Veldtman GR, Yue AM, et al. Successful percutaneous ablation of ventricular tachycardia in congenitally corrected transposition of the great arteries, a case report. *J Interv Card Electrophysiol* 2004;**11**:211–5. DOI: 10.1023/B:JICE.0000048572.37319.fc; PMID: 15548888
73. Rostock T, Willems S, Ventura R, et al. Radiofrequency catheter ablation of a macroreentrant ventricular tachycardia late after surgical repair of tetralogy of Fallot using the electroanatomic mapping (CARTO). *Pacing Clin Electrophysiol* 2004;**27**:801–4. DOI: 10.1111/j.1540-8159.2004.00531.x; PMID: 15189537
74. Morwood JG, Triedman JK, Berul CI, et al. Radiofrequency catheter ablation of ventricular tachycardia in children and young adults with congenital heart disease. *Heart Rhythm* 2004;**1**:301–8. DOI: 10.1016/j.hrthm.2004.05.009; PMID: 15851174
75. Furushima H, Chinushi M, Sugiyama H, et al. Ventricular tachycardia late after repair of congenital heart disease: efficacy of combination therapy with radiofrequency catheter ablation and class III antiarrhythmic agents and long-term outcome. *J Electrocardiol* 2006;**39**:219–24. DOI: 10.1016/j.jelectrocard.2005.08.005; PMID: 16580423; PMID: 16580423
76. Kriebel T, Saul JP, Schneider H, et al. Noncontact mapping and radiofrequency catheter ablation of fast and hemodynamically unstable ventricular tachycardia after surgical repair of tetralogy of Fallot. *J Am Coll Cardiol* 2007;**50**:2162–8. DOI: 10.1016/j.jacc.2007.07.074; PMID: 18036455
77. Nair GM, Healey JS, Gordon E, et al. Catheter ablation of hemodynamically unstable ventricular tachycardia in a patient with dextro-transposition of the great arteries and Mustard's repair. *Indian Pacing Electrophysiol* 2011;**11**:120–5. PMCID: PMC3128818; PMID: 21760683
78. Piers SR, Dyda K, Tao Q, Zeppenfeld K. Bipolar ablation of ventricular tachycardia in a patient after atrial switch operation for dextro-transposition of the great arteries. *Circ Arrhythm Electrophysiol* 2012;**5**:e38–40. DOI: 10.1161/CIRCEP.111.969345; PMID: 22511664
79. Gonska BD, Cao K, Raab J, et al. Radiofrequency catheter ablation of right ventricular tachycardia late after repair of congenital heart defects. *Circulation* 1996;**94**:1902–8. PMID: 8873666
80. Moore JP, Seki A, Shannon KM, et al. Characterization of anatomic ventricular tachycardia isthmus pathology after surgical repair of tetralogy of Fallot. *Circ Arrhythm Electrophysiol* 2013;**6**:905–11. DOI: 10.1161/CIRCEP.113.000450; PMID: 23884199
81. Kapel GF, Reichlin T, Wijnmaalen AP, et al. Left-sided ablation of ventricular tachycardia in adults with repaired tetralogy of Fallot: a case series. *Circ Arrhythm Electrophysiol* 2014;**7**:889–97. DOI: 10.1161/CIRCEP.114.001661; PMID: 25151630