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Mapping of Atrial Tachycardia by Remote Magnetic Navigation in Postoperative Patients with Congenital Heart Disease

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Abbreviations

3D = three dimensional

AF= atrial fibrillation

AFL= atrial flutter

ASD = atrial septal defect

AT = atrial tachycardia

CHD = congenital heart diseases

CL=cycle length

CS = coronary sinus

CT= computed tomography

DILV=double inlet left ventricle

DORV=double outlet right ventricle

EAM= electroanatomic mapping

EP= electrophysiological

IART = intraatrial reentrant tachycardia

IVC= inferior vena cava

LAA=left atrial appendage

LRT= localized reentry tachycardia

LV=left ventricle

MV= mitral valve

PA = pulmonary artery

PVA = pulmonary venous atrium

RA = right atrium

RAA= right atrial appendage

RAO =right anterior oblique

RF= radiofrequency

RMN = remote magnetic navigation

RV = right ventricle

SA=sinoatrial

SV= single ventricle

SVA = systemic venous atrium

SVC=superior vena cava

TA=tricuspid atresia

TCPC = total cavopulmonary connection

TGA = transposition of the great arteries

TOF=tetralogy of Fallot

TV= tricuspid valve

"The treatment of congenital heart disease is unsatisfactory. As a rule, nothing can be done to improve patients symptomatically; in some instances digitalis may be of help."

— — L. Emmett Holt, MD, 1933

1. Introduction

With the development of advanced surgical techniques over the past 30 years, a growing number of patients with complex congenital heart disease (CHD) such as tricuspid atresia (TA), single ventricle (SV) or transposition of great arteries (TGA) have reached their adolescence and even their adulthood.

Whereas Fontan operations or modifications are still used to treat patients with TA, double outlet right ventricle (DORV), double inlet left ventricle (DILV) or SV[17], Mustard[46] and Senning[58] operations were performed in patients with d- TGA to construct an “atrial switch” operation.

Arrhythmias significantly contribute to morbidity and mortalityin this adult CHD population[19, 64]. Among those, atrial tachycardia (AT), especially intraatrial reeentry tachycardia (IART) is the most common early and late complication after surgical procedures[19, 23]. As successful drug treatment is hard to achieve, catheter ablation came into focus for treating these arrhythmias[3].

The initial experience of mapping and catheter ablation of IART in patients with CHD was reported in the middle of 1990s[67, 68]. Over the last 15 years, the technique of catheter ablation for IART was improved and facilitated by the use of non-contact mapping[36], electroanatomic mapping systems[71] and irrigated tip catheters for ablation[65].

Remote magnetic navigation (RMN) is a new technique for steering a soft and flexible catheter by the use of an external magnetic field[14]. RMN has been used for mapping and ablation of supraventricular reentrant tachycardia[7, 53, 63], atrial fibrillation[47] and ventricular tachycardia[6]. As the RMN catheter offers stable contact with the myocardial wall without the risk of perforation, it might be especially suited for accessing difficult anatomy as in post-surgical congenital heart disease.

The purpose of our studies was to investigate the possibility to use RMN in patients with complex CHD and to see if RMN offers a reduction of fluoroscopy time when used for atrial tachycardia mapping in a spectrum of patients with CHD after “simple” or “complex” cardiac surgery.

1.1. Cardiac operations for the correction of different forms of congenital heart disease

1.1.1. “Simple” atrial surgical procedures

A lateral atriotomy is part of almost all surgical cardiac procedures, from the most “simple” cardiac operations (septal defect closure) (Figure 1.1) to more complex procedures (e.g. Fontan and Mustard/Senning operation) and also part of complex ventricular or/and great arteries procedures (e.g. Repair of Tetralogy of Fallot).

The atrial septal defect (ASD) is one of the most common CHD. Lewis reported the first ASD closure using open heart surgery in 1953[39]. With the assistance of an extracorporeal pump-oxygenator circuit[44], the surgical techniques have been improved, achieving nowadays a mortality rate of zero. With the development of interventional techniques, non-surgical ASD closure is increasingly perfomed and avoids the atriotomy scar [35].

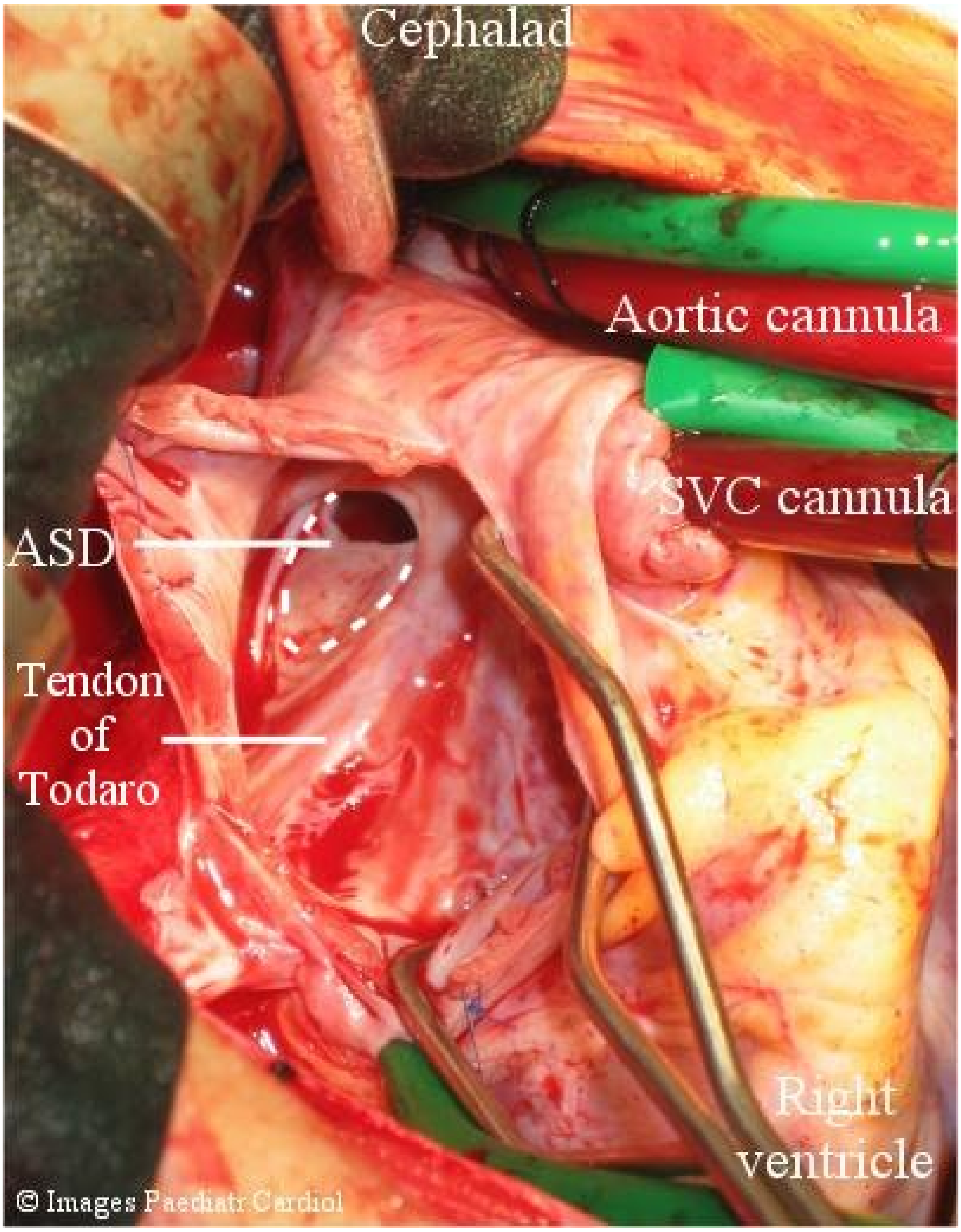


Figure 1.1. *Right atriotomy showing atrial septal defect (ASD) and margins of enlarged ASD (dotted lines).*

1.1.2. Fontan operation and modifications

The first Fontan procedure was performed for tricuspid atresia in 1973[17] (Figure 1.2), and was consecutively used for also for patients with DORV, DILV or hypoplastic left heart syndrome [43]. The operation was introduced to provide blood flow from the systemic venous system directly to the pulmonary circulation without the requirement of a pumping chamber [22].

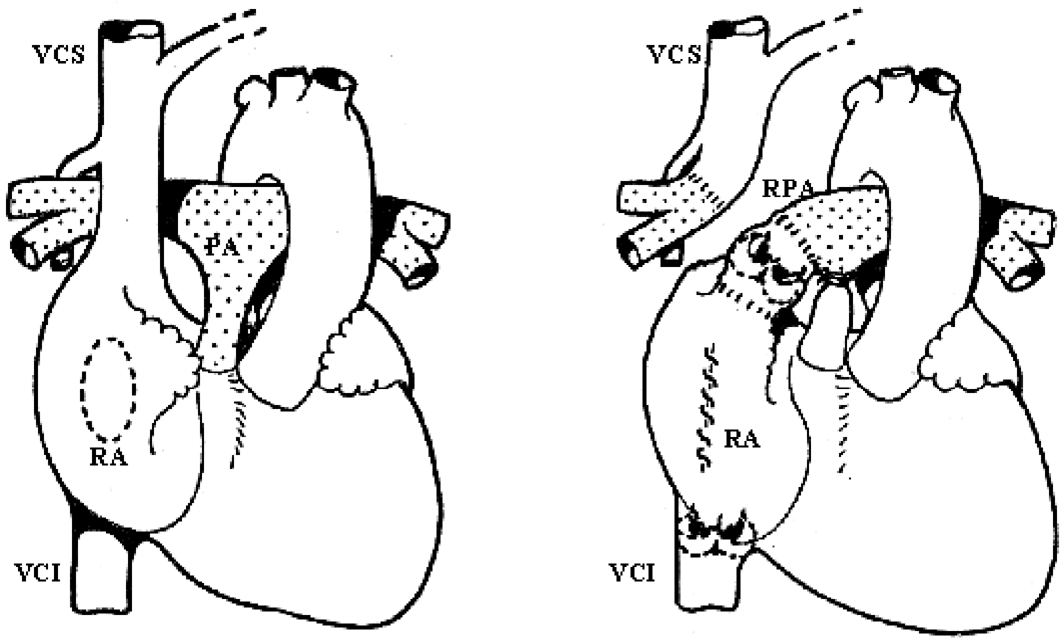


Figure 1.2: Fontan-Operation (1971): Left: Tricuspid atresia Typ 2b; Right: Fontan – Operation.

PA= pulmonary artery; RA=right atrium; VCI=vena cava inferior; VCS= vena cava superior.

Over the past 30 years, the Fontan operation has undergone numerous modifications and improvements. The “classical” Fontan operation underwent several modifications: Fontan-Lins with classical RA-PA connection[17, 57], Fontan-Kreutzer directly connecting RA appendage to PA connection without the step of a Glenn operation[37], or Fontan-Björk connecting RA and PA via a conduit[5]. With newer techniques such as total cavopulmonary connection (TCPC) [9, 55, 61], including lateral tunnel[49] (Figure 1.3) and extracardiac tunnel[38] (Figure 1.4), venous blood drains directly from the caval veins to the PA.

During the last decade, a three-step approach was designed for patients requiring a modified Fontan procedure. The first procedure is often an aorto-pulmonary shunt performed within the first few weeks of life which is followed by a second procedure during the first year of life called a “Glenn” operation or “partial cavo-pulmonary connection“ (PCPC) which directs venous blood from vena cava superior (SVC) to the pulmonary artery (PA) [25]. In the 3rd step the IVC is connected (via an intra- or extracardiac conduit) to the pulmonary artery (TCPC) and thereby the circuits are separated. This operation is nowadays performed as the final step at an age of about 2 years.

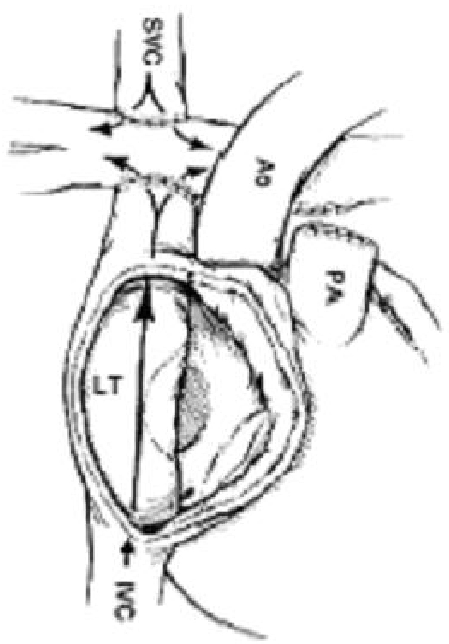


Figure 1.3: The intra-atrial lateral tunnel of total cavopulmonary connection. Ao=aorta; IVC=inferior vena cava; LT=lateral tunnel; PA=pulmonary artery; SVC= superior vena cava.

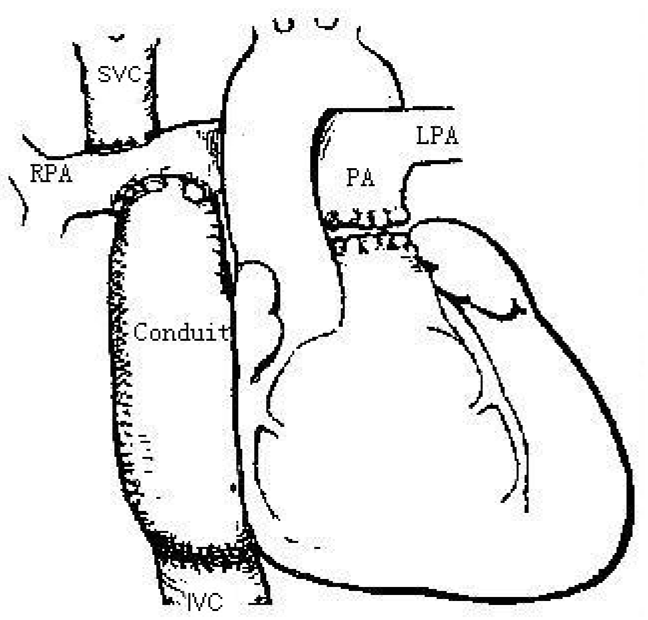


Figure 1.4: The extracardiac total cavopulmonary connection.

LPA=left pulmonary artery; PA=pulmonary artery; RPA=right pulmonary artery; IVC= inferior vena cava; SVC= superior vena cava.

As a result of improving surgical procedures, the perioperative and early mortality after Fontan operation has decreased significantly over the past 30 years. The main causes of death during long-term follow-up[22] were thromboembolism[45], heart failure[20, 27, 73] and sudden death[32]. Arrhythmia is a very common early and late postoperative complication. A reason for sinus node dysfunction in adults is surgical operative injury to SA node or its artery[70]. The Fontan operation is associated with a higher early risk of altered SA node function[42]. Pacemaker implantation is an advised therapy for symptomatic sinus bradycardia [70], whereas tachycardia is often difficult to treat.

1.1.3. Mustard/Senning operations

Mustard[46] and Senning[58] were the first in 1959 to use an atrial baffle construction in patients with d-TGA that directs venous blood from the SVC and IVC to the mitral valve and the left ventricle and pulmonary venous blood to the tricuspid valve (TV) and right ventricle (RV) ("atrial switch procedure") (Figure1.5 and Figure 1.6).

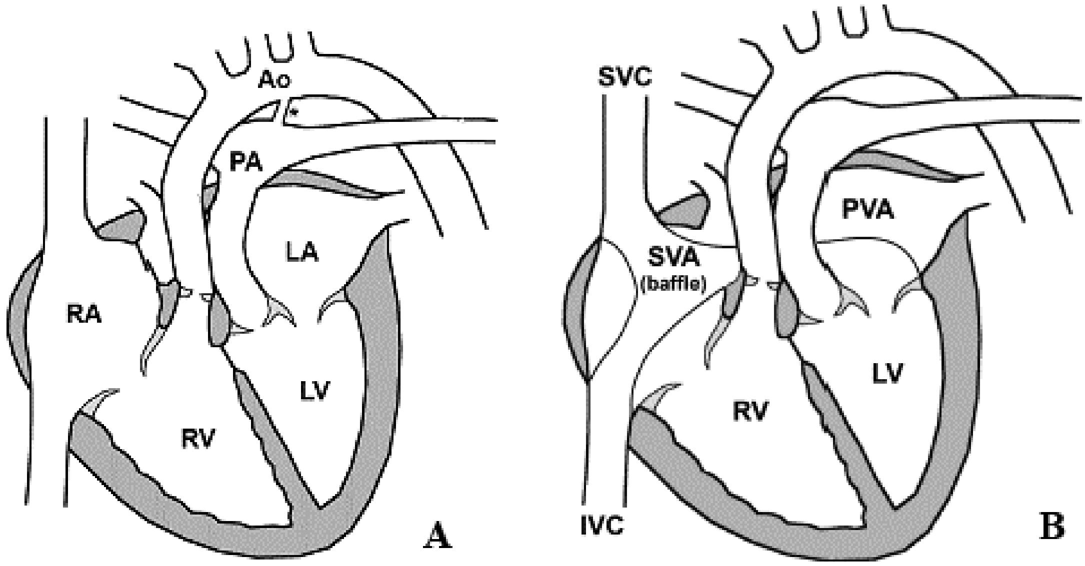


Figure 1.5: A: The anatomy in d-transposition of the great arteries: the aorta arises from the right ventricle and the pulmonary artery from the left ventricle. B: Anatomy after the "atrial switch" procedure (Mustard or Senning operation): the creation of a synthetic (Mustard operation) or a pericardial patch (Senning operation) directs the blood from systemic caval veins to the mitral valve and left ventricle, and the blood from the pulmonary veins to tricuspid valve and right ventricle.
Ao=aorta; IVC=inferior vena cava; LA=left atrium; LV=left ventricle; PA=pulmonary artery; PVA=pulmonary venous atrium; RA=right atrium; RV=right ventricle; SVA=systemic venous atrium; SVC=superior vena cava.

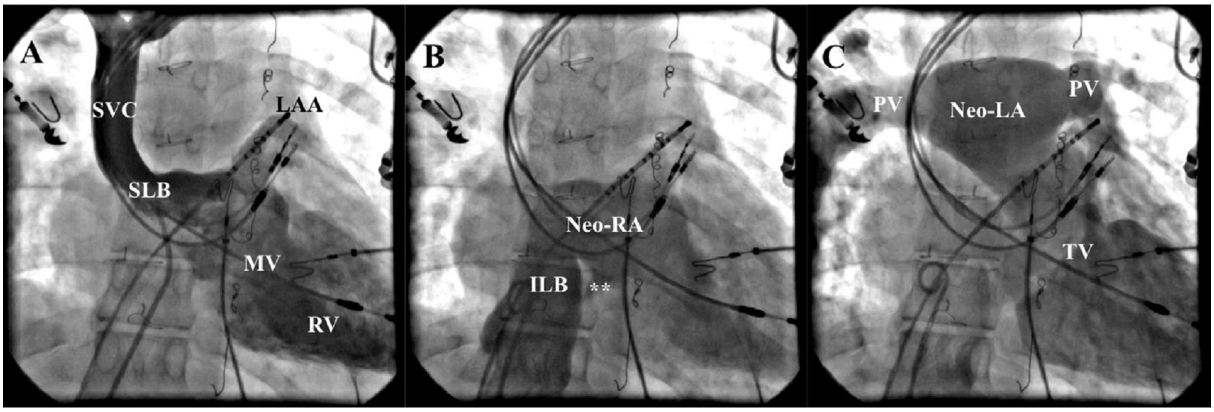


Figure 1.6: Angiography of a Senning baffle. A: Power contrast injection in the superior limb of the Senning baffle (SLB.) B: Power contrast injection of the inferior limb of the baffle (ILB), accessing the neo-left atrium (neo-LA). Flow into the neo-right atrium (neo-RA) is unimpeded. C: Delayed imaging: contrast flow from pulmonary venous (PV) return into the neo-LA and toward TV.
MV=mitral valve; RV=right ventricle.

Sequels of this type of operation include systemic ventricular dysfunction[72], AV-valve regurgitation[54] and arrhythmias. Like the Fontan operation, the Mustard and Senning operation also can result in trauma to SA node or/and SA artery[24] leading to snus node dysfunction. In the survivors after Mustard operation, a progressive loss of normal sinus rhythm was found[12, 16]. A symptomatic sinus node dysfunction is observed in 64% and 82% on 5 and 16 years of follow-up. Tachycardia, especially peritricuspid atrial flutter are also common[33].

1.2. Atrial Tachycardia in postoperative patients with congenital heart disease: mechanism and electrophysiological studies

IART is the most common and difficult arrhythmia encountered in patients with CHD after atrial surgery[69]. Usually tachycardia is due to a macroreentry within abnormal atrial muscle. The term “IART” was introduced to distinguish these tachycardias forms from “simple” typical cavo-tricuspid dependent atrial flutter (AFL) in normal hearts. Compared to the typical AFL with cycle length (CL) around 250 msec, IART can be slower with CL of 250 to 400 msec. Usually there is 2:1 or 3:1 AV-conduction but with a high conductive ability of the AV-node. IART can result in rapid ventricular reaction due to 1:1 AV-conduction, causing hemodynamic instability or sudden death. Since the initial experience with mapping and catheter ablation of IART[67], catheter ablation is currently considered as an important or even the first-line therapy for AT in postoperative patients with CHD[1, 34].

1.2.1. IART after ASD closure/atriotomy

Surgical closure can result in the scar tissue at the free lateral wall (atriotomy) and the atrial septum. In post-atriotomy patients, up to 92% typical macroreentry tachycardia was cavotricuspid isthmus dependent[5]. Additionally, the flutter circuit is sometimes found around the atriotomy scar, named by Kalman et al as “incisional IART”[28]. Figure1.7 shows the activation map of reentry tachycardia around tricuspid ring (Figure 1.7 A) and around the lateral atriotomy scar (Figure 1.7 B). Therefore, during catheter ablation, a lateral line between the IVC and atriotomy is deployed in that case.

It is still under discussion whether device ASD closure can help to avoid the incidence of AT[60, 71]. Although avoiding the atriotomy, the incidence of AT was reported similar before and after percutaneous closure in 264 patients with atrial septal defects aged 40 years and over[61].

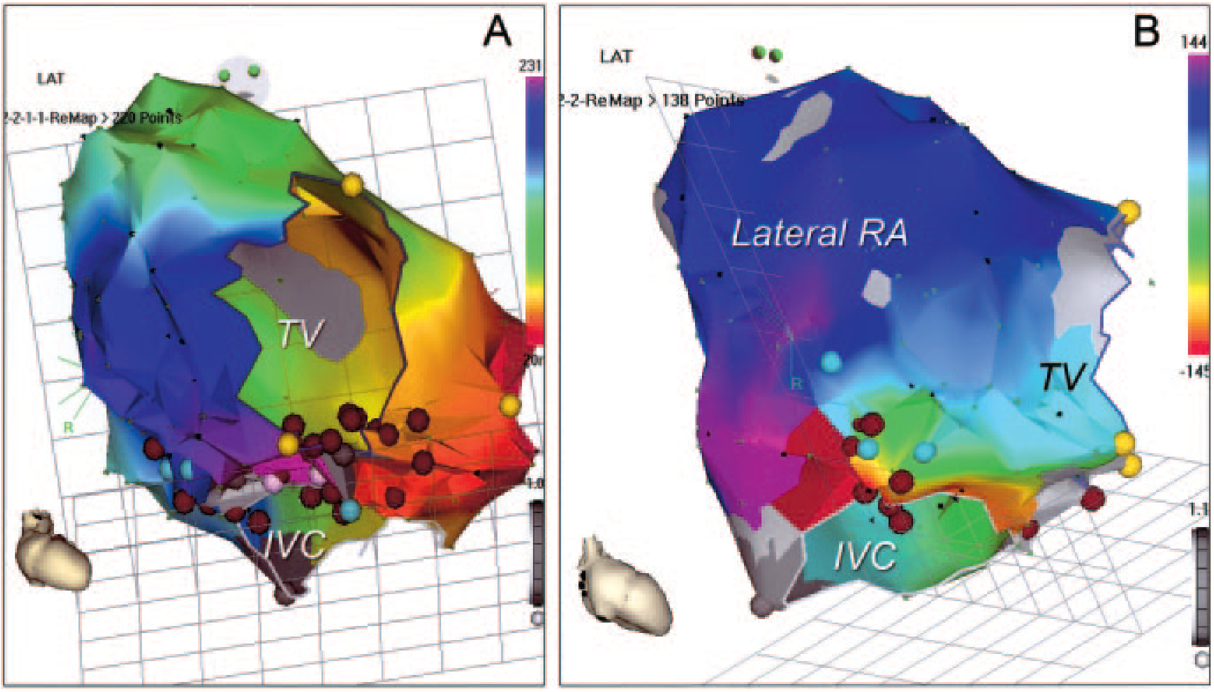


Figure 1.7: Electroanatomic maps of 2 IART circuits in a young adult who had closure of a large atrial septal defect. A: The initial circuit in a counterclockwise fashion around the TV. RF applications (red dots) of the isthmus between the TV and IVC eliminated this form of IART. B: Despite effective isthmus block, a second form of IART was induced. It appeared to propagate around a small area of split potentials (blue dots) along the low-lateral RA, which probably represented the atriotomy scar or caval cannulation site. The second form was terminated by Radiofrequency (RF) applications from the lower edge of the scar down to the IVC.

1.2.2. IART after Fontan operation

AT, especially IART occurs in up to 50% of patients after Fontan type operations[10, 15]. There are three key anatomical structures contributing to the variable and complex intraatrial reentry in post-Fontan patients: (1) “the cavotricuspid isthmus”; (2) the atriotomy site: lateral right atrial wall; and (3) RA-PA connection region (Fontan connection region). Relating to the different positions, there are different reentry circuits or mechanisms: (1) pericaval and periannular IART[26, 41]; (2) incisional IART[28]; and (3) IART around the RA/PA connection region[69] (Figure 1.8)· Focal atrial tachycardia or microreentrant tachycardia, often located in the lateral RA is relatively uncommon but also has a high acute successful ablation[48, 59].

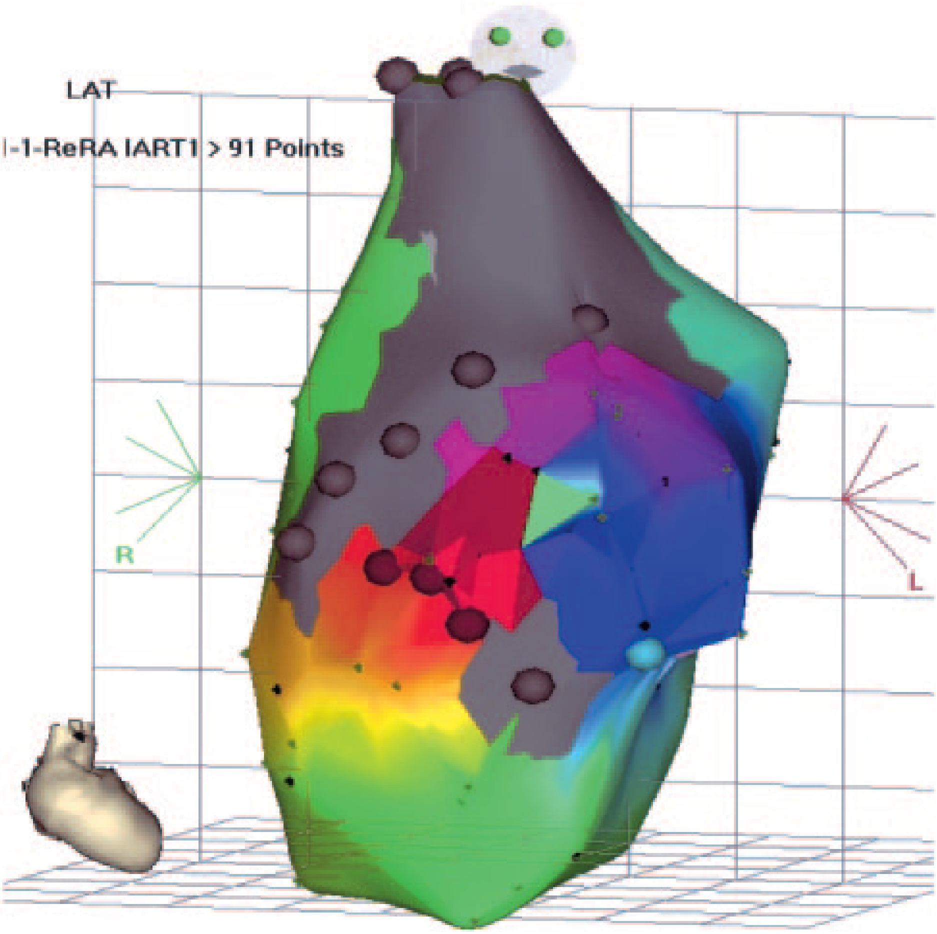


Figure 1.8: Electroanatomic map of an IART circuit in a child with a single ventricle who underwent a Fontan operation. The anterolateral aspect of the right atrium in shown and is notable for the 2 large areas of scar (gray surfaces). The IART propagation pattern proceeds between the edges of these scars. This channel was closed with RF applications (red dots), and IART was eliminated.

Risk factors for the development of IART are giant atria and pressure overload[8]. Sinus node dysfunction is also a risk factor of occurrence of AT[15]. IART is often hemodynamically poorly tolerated and difficult to control[8]. Besides management with antiarrhythmic drugs and antitachycardia pacing, which is successful in less than 50% of patients[3], catheter ablation can be of value in this population. However, the early recurrences after catheter ablation were apparent because of new reentrant circuits[32].

TCPC is nowadays considered as a preferred option for Fontan surgery[64]. The incidence of early arrhythmia was reported less in patients after TCPC compared to patients with a RA-PA connection[65]. The proportion of patients free of new arrhythmia was 93% after 2 years of follow-up and 78% after 5 years of follow-up[18].

1.2.3. IART after Mustard/Senning operation

Late cardiac arrhythmias, especially IART occur in up to 30% of this patient population during long-term follow-up and seem to represent a significant factor for long-term morbidity and mortality[29, 72].

IART is the most common arrhythmia substrate in patients with Senning or Mustard baffles. Peritricuspid reentry tachycardia which includes mainly structures in the pulmonary venous atrium (PVA) is the most frequent type of IART in these cases (Table 1). Another typical circuit of IART was along the lateral SVA, relevant to the atriotomy[40].

The peritricuspid IART in post-Senning or Mustard patients is different from typical cavo-tricuspidal isthmus dependent atrial flutter in several ways: Firstly, its atrial rate is often slower than typical flutter, leading to 1:1 AV-conduction, which results in hemodynamic instability or even sudden death[39]. Secondly, the tricuspid ring is not reachable from the systemic vein but retrograde through aorta[67, 68, 74] (Figure 1.9) or trans-baffle puncture[13, 51] (Figure 1.10). What's more distinguishing is that the former cavotricuspid isthmus is divided into two atria (systemic venous and pulmonary venous) and the usual boundaries for isthmus-dependent flutter are surgically changed. This indicates the necessity of biatrial ablation to reach the “isthmus-block”[11]. The biatrial ablation (Figure 1.11) is performed in most centers[11, 31, 40, 68, 74], including the lesions in IVC and the lesions in the PVA, from tricuspid annulus to right inferior pulmonary vein. Acute successful rate of AT in these cases ranged from 70% to 90%[11, 31, 40, 74].

Type of tachyarrhythmia	Relative prevalence	Comments
IART	****	Most common atrial tachyarrhythmia
Rotating around tricuspid valve	****	Circuit typically includes portion in pulmonary venous atrium
Other	**	Circuit involving superior baffle lines is next most common
Focal atrial tachycardia	***	May coexist with IART
Nonautomatic	***	Predominantly around suture lines
Automatic	**	Typically junctional in nature
AV nodal re-entrant tachycardia	**	Slow pathway most ofter in pulmonary venous atrium
Atrial fibrillation	*	Some forms of IART may resemble atrial fibrillation
Accessory-pathway-mediated tachycardia	*	Rare, unlike congenitally corrected transposition
Ventricular tachycardia/fibrillation	**	May be primary or secondary to atrial tachyarrhythmias

Table 1.1: Tachyarrhythmias in Transposition of the Great Arteries after the Mustard or Senning operation

Asterisks represent a relative ordinal scale ranging from uncommon (*) to high prevalent (****). AV=atrioventricular; IART=intra-atrial re-entrant tachycardia.

Modified from Khairy, P., Landzberg, M.J., Lambert, J., O'Donnell, C.P. Long-term outcomes after the atrial switch for surgical correction of transposition: a meta-analysis comparing the Mustard and Senning procedures. Cardiol Young. 14 (2004) 284 –292

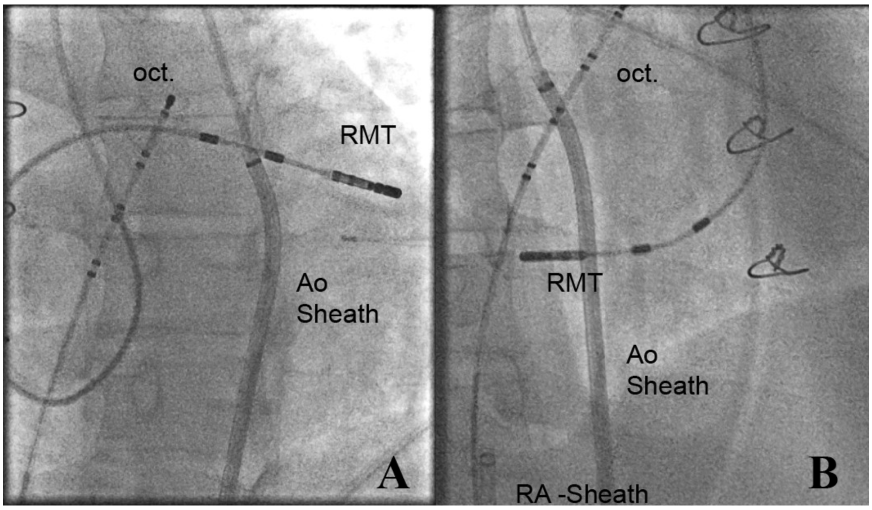


Figure 1.9: Fluoroscopy image of the retrograde approach to reach PVA in a patient with d-TGA after Senning operation. A (left anterior oblique): The RMT catheter is positioned in the left PV after two large curves (through the aortic valve and the tricuspid valve) over a long sheath placed in the descending aorta. The octapolar catheter is placed in the left atrial appendage as reference. B (right anterior oblique, RAO): The RMT catheter is positioned at the tricuspid ring.

Ao= aorta; oct=octapolar reference catheter.

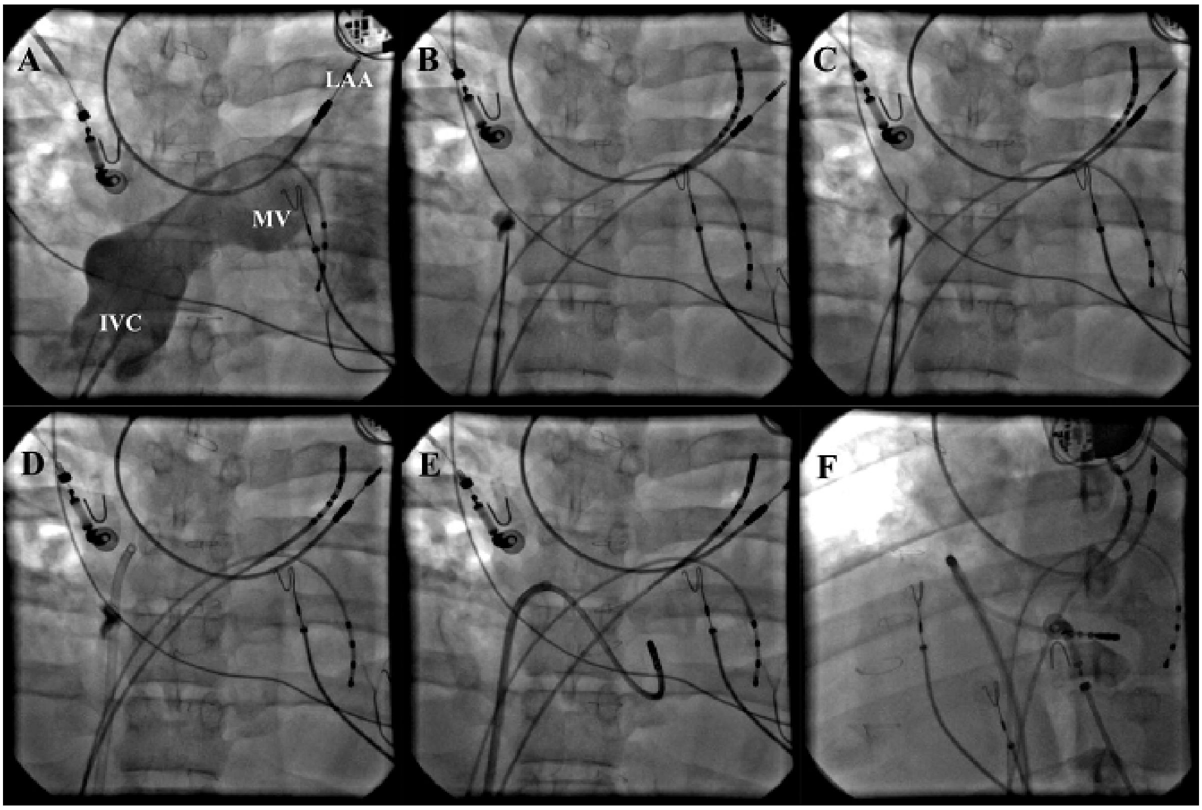


Figure 1.10: Transbaffle puncture in a patient with a Mustard baffle. A: Angiography of the inferior limb of the baffle shows unobstructed flow and no intra-atrial shunting. B and C: A transseptal needle traverses from the SVA into PVA. D: An 8.5F sheath is advanced in PVA. Position of ablation catheter at the successful IART ablation site in right (E) and left (F) anterior oblique.

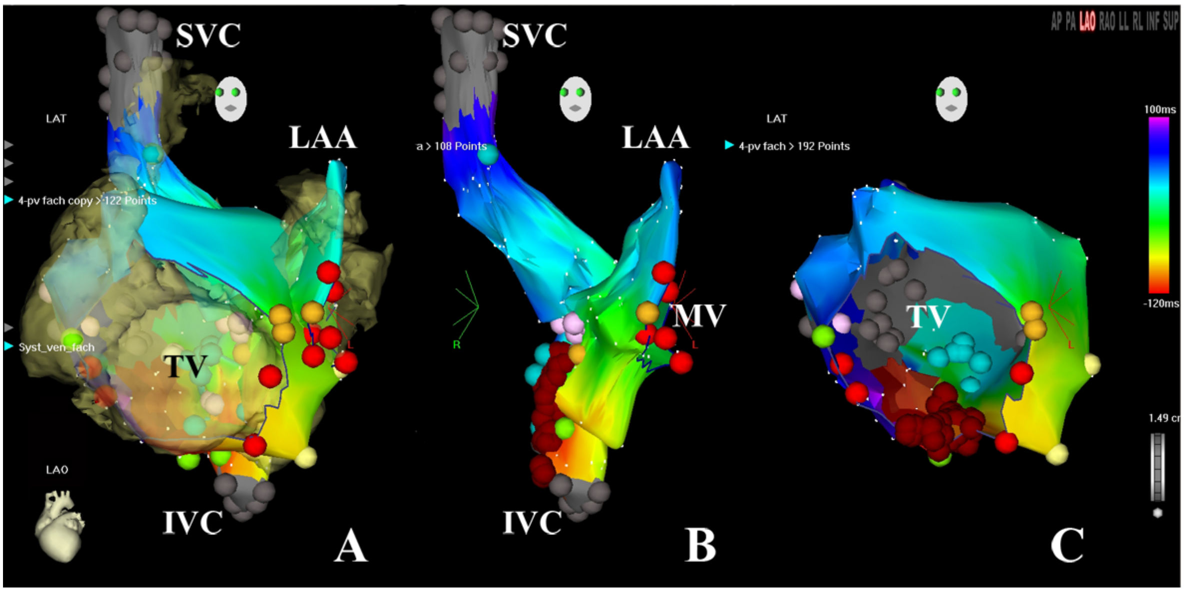


Figure 1.11: A: Fusion of electroanatomic map and CT-based anatomy after registration using the “merge” function of the CartoMerge® System.

B (SVA) and C (PVA): Local activation maps during tachycardia of the SVA and PVA. The bipolar threshold for scar area (grey colour) was set to 0.05mV.

IVC= inferior vena cava; LAA=left atrial appendage; MV=mitral valves; SVC=superior vena cava; TV=tricuspid valves.

1.3. Mapping and catheter ablation of atrial tachycardia in postoperative congenital heart disease patients

1.3.1. Three-dimensional mapping systems

The technique of catheter ablation for IART was improved and facilitated by the use of electroanatomic mapping and non-contact mapping systems.

In the late 1990s, three-dimensional (3D) mapping systems began to be used widely in the clinical electrophysiological (EP) examination. One of the most important 3D mapping system is electroanatomical mapping (EAM) system (Carto®, Biosense-Webster, Diamond Bar, CA, USA). The system has a roving mapping catheter (Navistar, Biosense-Webster) with small magnetic sensors in the tip in a low magnetic field generating pad[21]. When the roving catheter moves, its location is monitored by the system. By gating the acquisition of points, points that represent both location and electrical activity at that location will be displayed on a screen[21]. After acquiring enough points, a three-dimensional representation is constructed. Finally the Carto System displays the anatomical structure with the electrophysiological information. With the renovated Carto system, named as CartoMerge, the electrophysiological anatomic can merge with the segmented 3D computed tomography (CT) based anatomy. This system enabled us to display the “true” complex anatomy, whereas the conventional 3D EAM showed inconsistencies (Figure 1.12) [52].

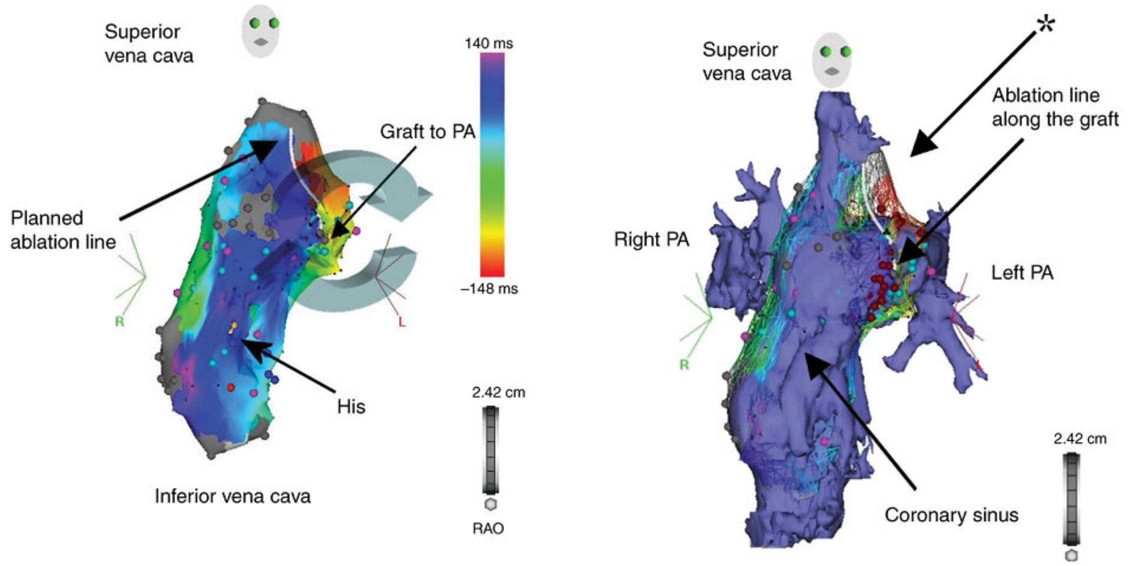


Figure 1.12: Conventional electro-anatomic map in a patient after Fontan operation in right anterior oblique (RAO) view (left). A clockwise re-entry is around the RA-PA connection. A small scar is part of the central obstacle. The planned ablation line is marked with white dots. CT based anatomy (blue) and underlying map (mesh) show the detailed anatomy of the right atrium with coronary sinus, the graft, and the PA (right). The importance of the exact anatomical reconstruction can be demonstrated in the area of planned ablation. The conventional anatomic 3D reconstruction is incorrect because of the special anatomical appearance (*) of the anastomosis between the atrium and the PA. With the correct information from the CT, the ablation line (red dots) was placed more lateral and directed to the border of the left PA.

Another widely used 3D-ampping system, Ensite 3000™ (St. Jude Medical, Deveau Place, MN, USA) is a noncontact mapping system. The location and electrophysiological information are acquired by measurement of impedance between the catheters and several patches attached to the patient.

With the anatomical and electrophysiological activation information, the activation maps help to visualize the activation route, define the arrhythmias mechanisms, design ablation strategies, guide ablations, and improve the safety of mapping and ablation. These advantages are especially important for patients with CHD[8, 48], in which the anatomy is complex and abnormal and the tachycardia substrates are variable and confusing. Figure 1.13 and 1.14 demonstrate the examples that how the activation map helps visualize and understand the complex tachycardia mechanisms in patients after Fontan or Senning operations, who have complex and abnormal heart anatomies. The use of EAM to guide ablation is one of the positive predictors of chronic success of IART ablation[37]. Figure 1.15 shows atrial scar in the voltage map *of the RA* with the different 3D mapping system.

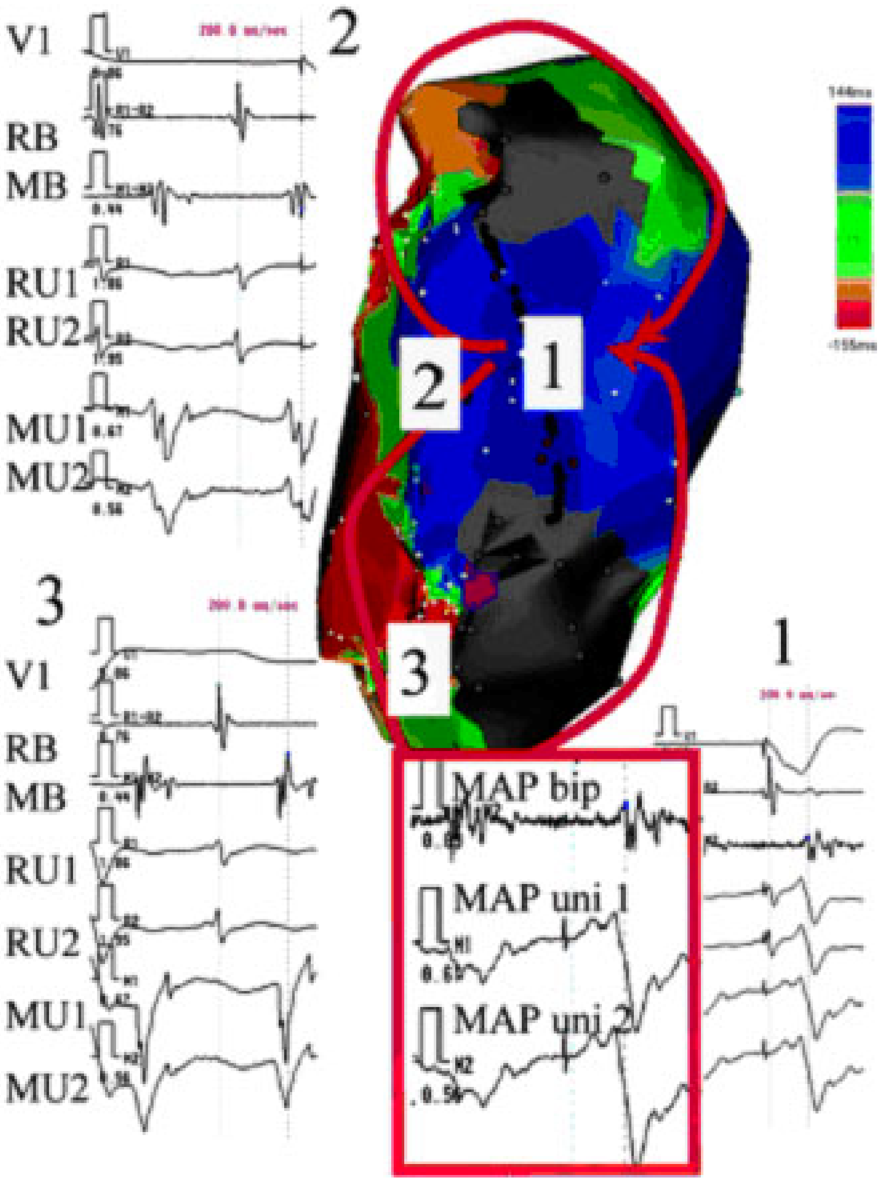


Figure 1.13: Color-coded (bipolar) activation map during IART (CL 290ms) in patients after Fontan procedure. The scar tissue (grey zones) was defined on 0.1 mV bipolar cutoff value. The local activation map shows the "figure 8" type tachycardia, with the activation circling around 2 scars as indicated by red arrows. Panels 1, 2 and 3 show the local activation recorded in different location.

RB=bipolar reference; MB=bipolar mapping catheter; RU1=unipolar reference tip; RU2=unipolar reference electrode 2; MU1=unipolar mapping tip; MU2=unipolar mapping electrode 2; bip=bipolar; uni=unipolar.

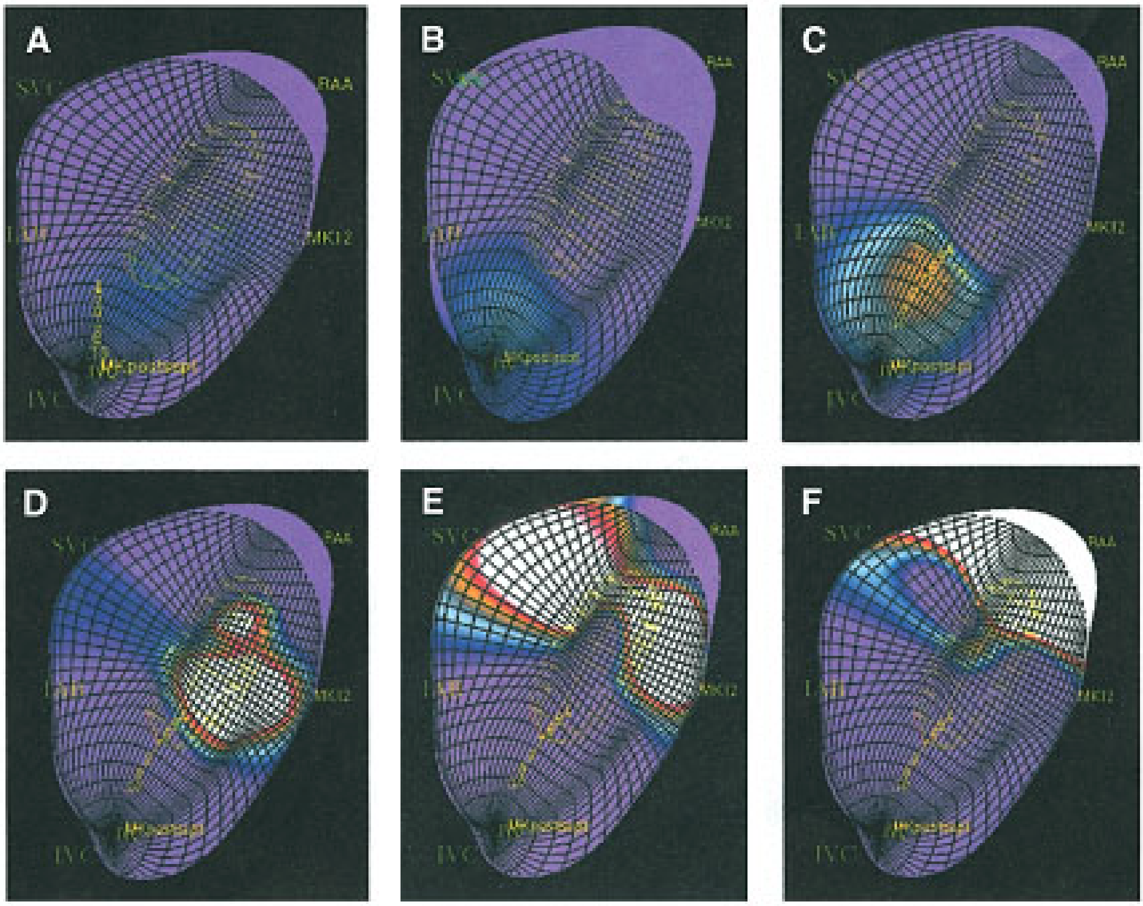


Figure 1.14: Atrial activation sequence atrial reentry tachycardia, as displayed by color-coded isopotential map (30-degree right anterior oblique view) in patient with d-TGA after Senning operation. The systemic venous atrium (SVA) is opened virtually. Depolarization is depicted as colors on the isoelectric (purple) endocardium. Before the breakthrough of activation into the SVC, activation of the pulmonary venous atrium (PVA) was visualized as low-amplitude, far-field activity (A). Endocardial breakthrough was firstly noticed at the junction of the intraatrial baffle to the posterior wall of the SVA (B), and then the activation spreads further radially in SVA (C and D), separates (E) and finally collides at the left atrial appendage (F).

IAB= intraatrial baffle; IVC= orifice of inferior caval vein; MK 12= mitral valve annulus at 12 o'clock position; RAA=functional right atrial appendage; postsept= posterior wall of systemic venous atrium; SVC=orifice of the superior caval vein. Numbers indicate *sites of virtual electrograms obtained.*

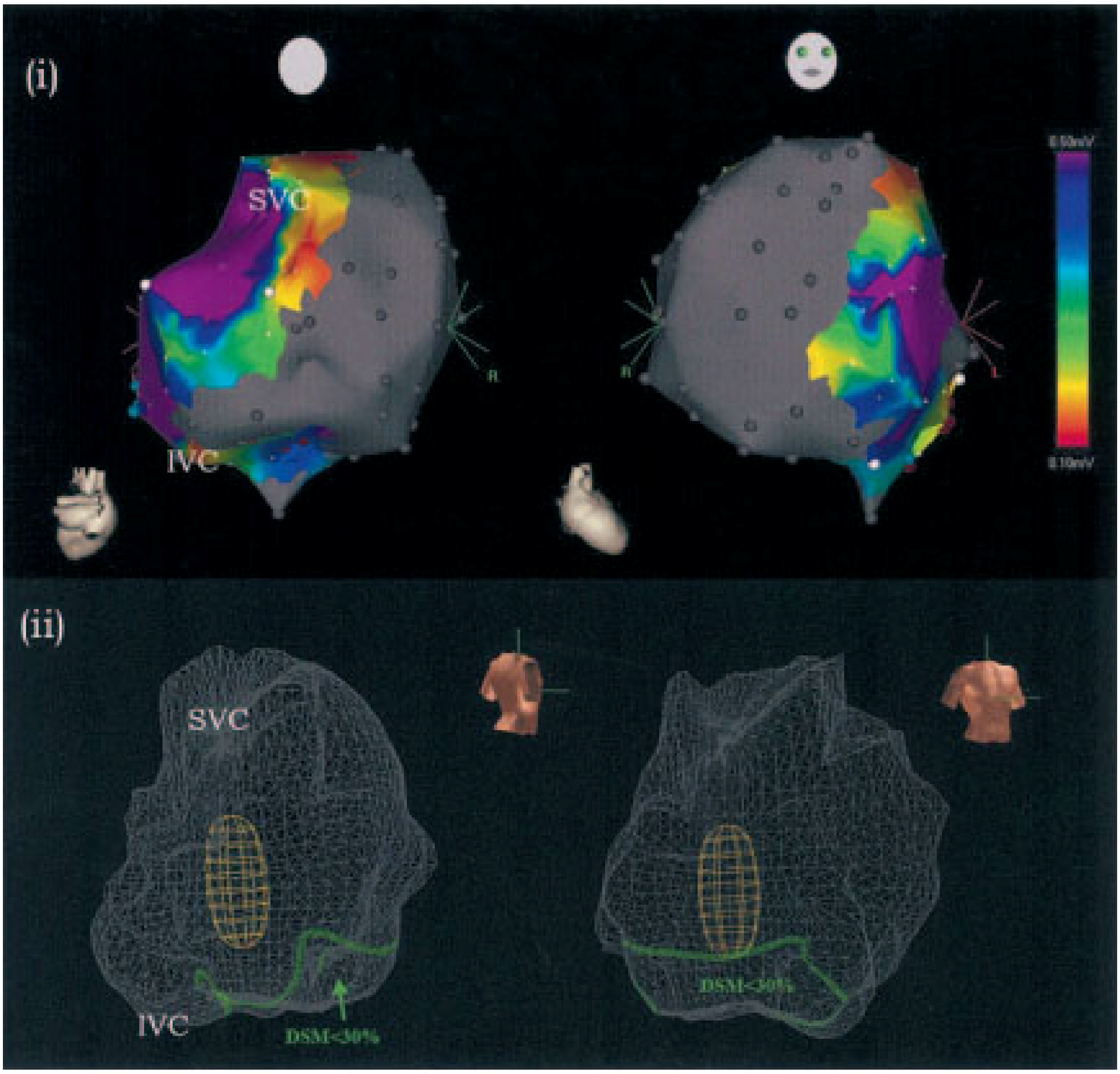


Figure 1.15: Voltage mapping of the RA with electroanatomic and noncontact mapping in a patient after Fontan operation. i. In electrophysiological system, areas of scar shown in gray and areas of normal endocardium (>0.5 mV) depicted in purple. All colors in between denote low-voltage endocardium (<0.5 mV), as seen in the color bar. The maps demonstrate a large area of dense scar (gray) in the lateral RA wall. ii, In noncontact map, the scar area is defined by DSM <30%PN on the inferior aspect of the lateral wall, demarcated by the green line.

1.3.2. Irrigated tip ablation catheter

Compared to catheter ablation of atrial flutter or supraventricular tachycardias in patients with normal heart structures, IART ablation in patients with CHD remains to show quite low successful rates[52]. One reason might be that myocardial substrate is thickened by hypertrophy and fibrosis[8]. Ablation with irrigated tip catheters has been shown to be more effective by creating deeper lesions in these thick-walled atria[8, 66], and the use of irrigated tip catheters is a positive factor for acute success in IART ablation[8].

1.3.3. Remote magnetic navigation system

Remote magnetic navigation (RMN, Niobe®, Stereotaxis Inc, St Louis, MO, USA. Figure 1.16) is a new technique for steering a soft and flexible catheter (Figure 1.17) by the use of an external magnetic field. The movements of a catheter inside the heart include orientation (which is provided by the magnetic field), advance and retraction, which require a catheter advancer system (Cardiodrive™, Stereotaxis, St. Louis, MO, USA), which is fixed on the patient's leg. The cardiodrive is a small system that is stuck to the operating field and connected to a computer-controlled rotating wire, resulting in the advance and retraction of the catheter location. RMN can be combined to 3D mapping system. The system CartoRMT (Biosense-Webster) is specially designed for RMN, which is especially useful for the complex anatomy. The function of „contact bar"on the CartoRMT-System indicates catheter to heart wall contact estimated by RMN (based on the difference between current magnetic direction and real-time catheter orientation).

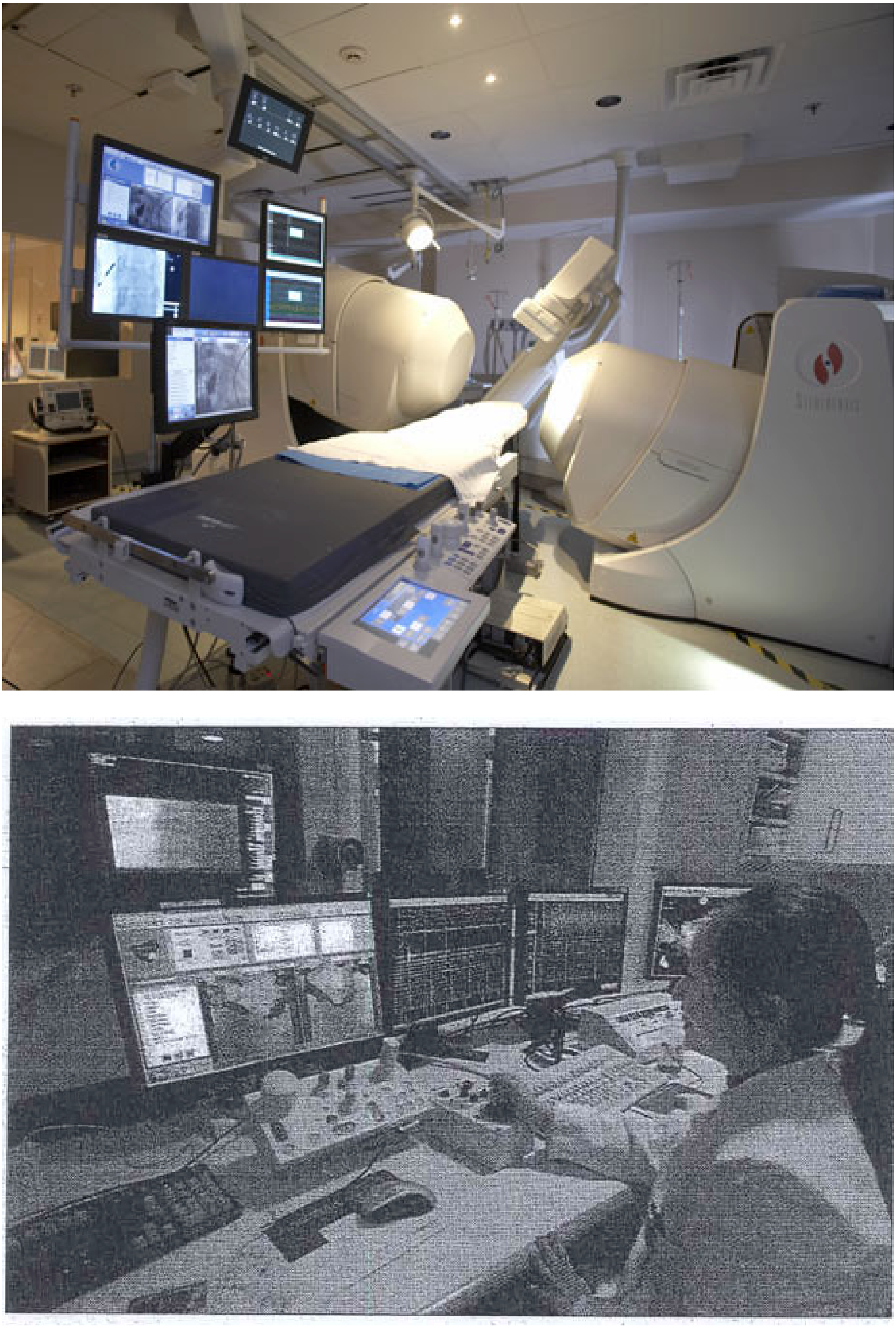


Figure 1.16: Procedure room (upper) and control room (lower) of catheter labor with

remote magnetic navigation system (Stereotaxis). The catheter was remotely navigated by joystick in the control room.

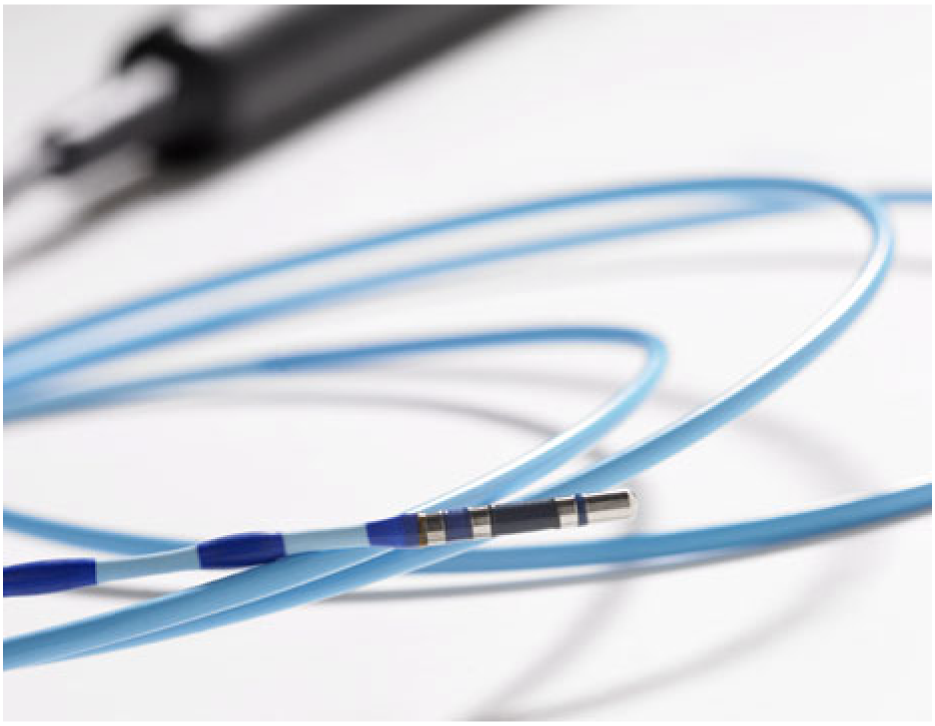


Figure 1.17: The soft and flexible catheter (Navistar RMT™, Biosense-Webster). The distal tip of the mapping/ablation catheter is loaded with four small, permanent magnets.

RMN was firstly used for mapping and ablation of supraventricular reentrant tachycardia in adults [7, 14] and in children[53], which shows the feasibility of using RMN in clinical EP study (Figure1.18). Pappone et al. reported acute success using RMN in atrial fibrillation (AF) ablation[47], which combined the RMN to CartoRMT (Figure 1.19).

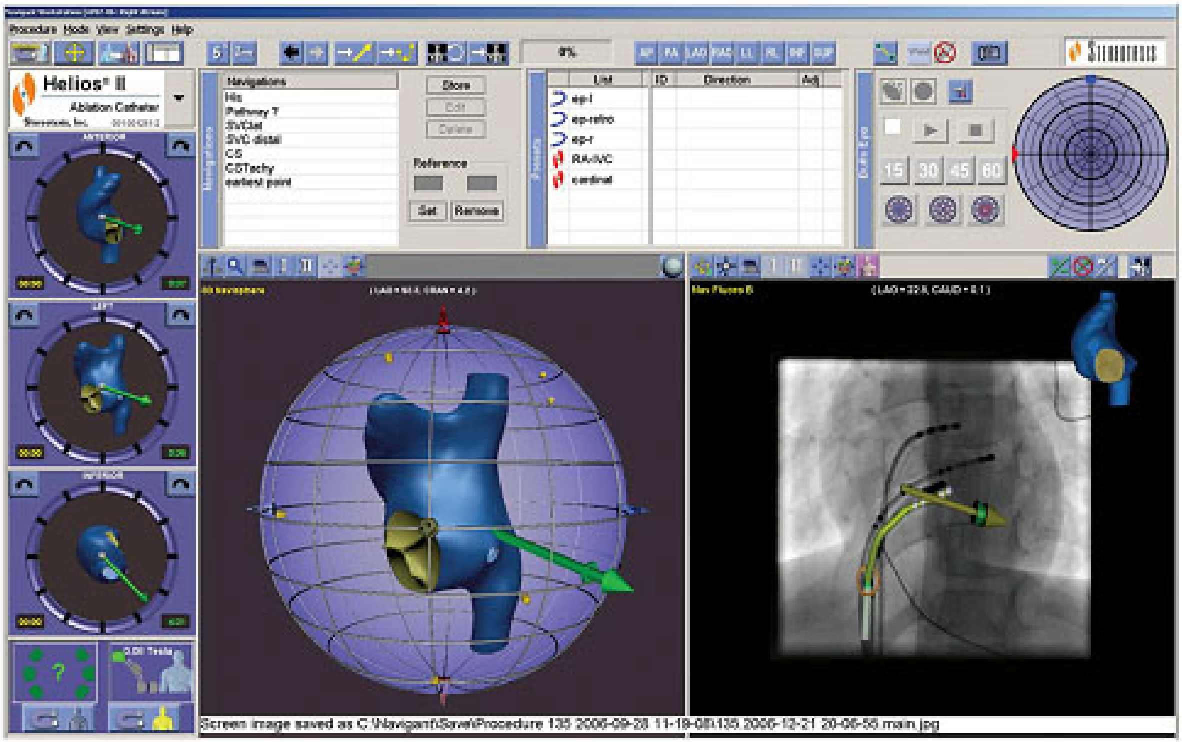


Figure 1.18: Navigation window of the Sterotaxis System. Left: different views of a standard RA; a magnetic vector (green arrow) directed remotely by mouse movement of the operator. Right: virtual catheter (yellow) projected on a fluoroscopic view of the heart, showing the mapping catheter position (CS ostium).

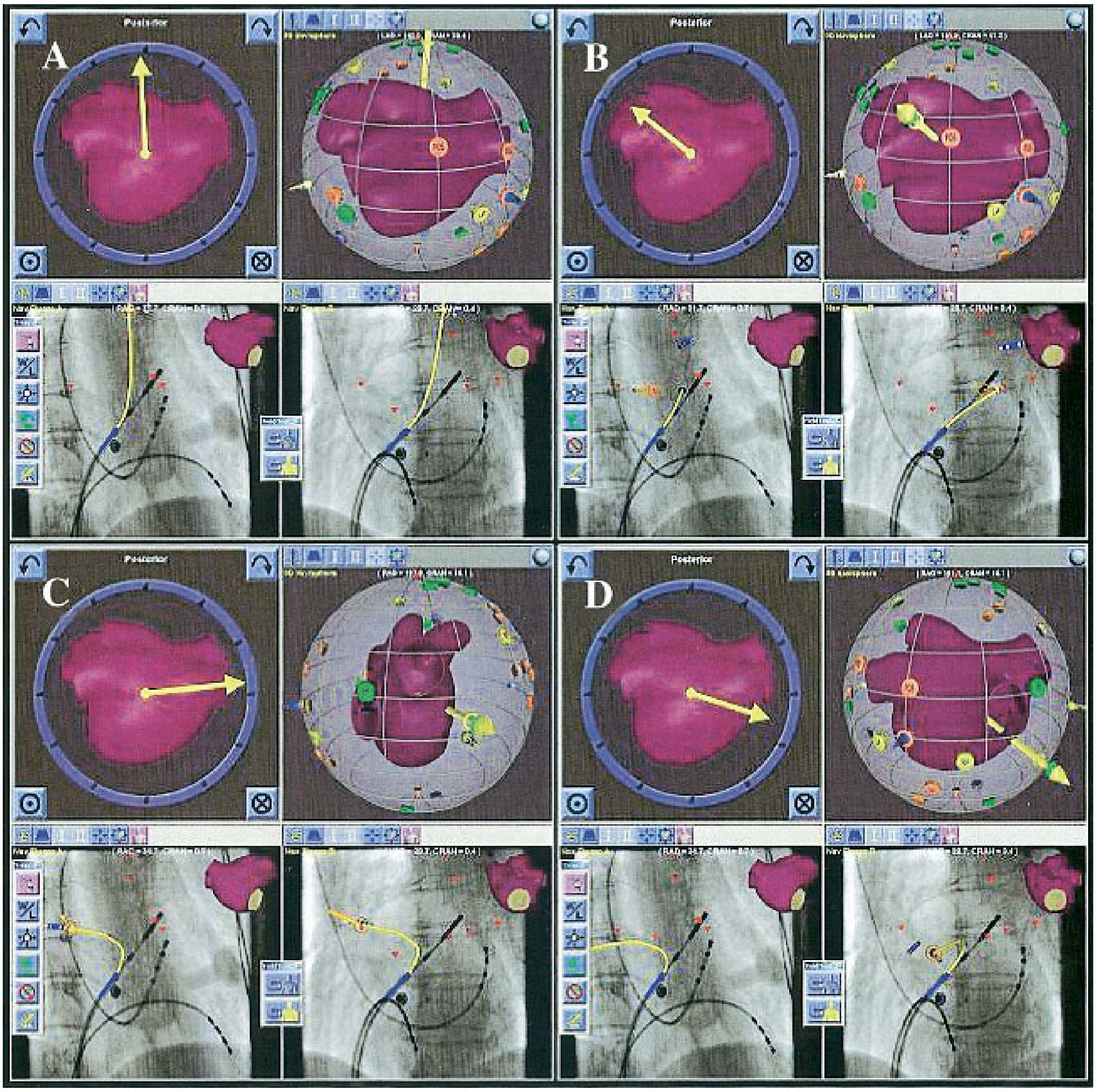


Figure 1.19: RMN system combined to CartoRMT system in AF ablation.

There are several advantages of RMN that could be beneficial for CHD patients: (1) the retrograde approach using RMN in left sided accessory pathway ablation[63] and left ventricular tachycardia ablation[6] shows that RMN might be especially suited for accessing the PVA retrogradely in a safe way in post Senning or Mustard patients, without hurting the aortic or tricuspid valve. Additionally, the soft RMN catheter offers stable contact with the myocardial wall without the risk of perforation. (2) Looking at the complex anatomy and complex tachycardia mechanism in this population, RMN might offer a possible reduction of fluoroscopy time and procedure duration and (3) guided by magnetic power, a more precise and stable catheter placement and avoidance of tachycardia interruption is anticipated.

These benefits might be crucial for AT mapping and ablation, especially in the special CHD population with complex anatomy.

1.4 Objectives

The goal of this thesis was to explore the possibility to use remote magnetic navigation (RMN) for AT mapping and then to investigate if RMN can help to reduce fluoroscopy time in a spectrum of patients with CHD after minor atrial surgery, Fontan operation and Senning/Mustard operation.

2. Methods

2.1 Patient characteristics

From October 2006 until September 2008, 22 consecutive patients (mean age 33±15 years, 8 females) with postoperative CHD underwent RMN guided atrial tachycardia (AT) mapping (n= 22) and ablation (n=7).

According to the extent of previous cardiac surgery, patients were classified into 3 groups: Group1 (n=7) included patients with “simple” atrial surgery (ASD or atriotomy as part of surgery). Group 2 (n=9) included patients after complex right atrial surgery (Fontan procedure or TCPC). Patients in Group 3 (n=6) had complex biatrial surgery (Mustard or Senning procedures). Table I shows patient characteristics.

2.2 Pre-ablation workup and EP study

The details of pre-ablation work-up and EP study were shown in the chapter of Appendix, Publication 1. Details of RMN system have been described previously[7, 47]. Discontinuous fluoroscopy was used to monitor the catheter location and movement.

A quadripolar 7F RMN catheter (non-irrigated) with a 4 mm tip (Navistar RMT™, Biosense-Webster) was used in first 16 patients, an 8mm tip RMN catheter ((Navistar RMT DS™, 7F, quadripolar, non-irrigated) in the last 6 patients.

2.3 Atrial mapping using RMN

Mapping was performed by remote navigation of the joystick during ongoing clinical tachycardia. In the patients who came to the lab in sinus rhythm, an atrial anatomy of the directly accessible atrium was created firstly and tachycardia was then induced by atrial programmed or burst stimulation. Entrainment manoeuvers were performed as described before[65]. The mechanism of AT was defined as macro-reentry[74], focal activation[11], or a "localized" reentry (definition in the chapter of Appendix, Pubication2). The mapping procedure was considered complete if sufficient points had been taken for understanding the atrial anatomy and mechanism of the tachycardia. The completed maps were fused with the segmented CT-anatomy using the CartoMerge® software.

Details of atrial mapping using RMN in 3 groups were shown in the chapter of Appendix, Publication 2.

2.4 Catheter ablation

Ablation was performed in 3 patients using the 4mm solid tip RMN catheter (65°C, 30W), and in 4 patients using the 8mm tip RMN catheter (65°C, 50W). If tachycardia did not terminate, a conventional irrigated tip catheter (Navistar Thermocool™, Biosense-Webster) (43°C, 30W) or an 8mm solid tip catheter (Blazer II XP, Boston Scientific, San Jose, CA, USA) (60°C, 50W) was used.

The endpoint of the first group ("simple" atrial surgery) was to assess bidirectional isthmus block. In the Fontan group, the endpoint was no inducible sustained tachycardia. In the Mustard/Senning group, the endpoint was tachycardia termination and split double potentials indicating a line of block.

2.5 Procedure and fluoroscopy times

The recorded procedure duration and fluoroscopy time was separated into mapping and ablation (period definition in the chapter of Appendix, Publication 2). In Group 3, fluoroscopy time for retrograde access was recorded separately (period definition in the Appendix, Publication 1).

The fluoroscopy time for catheter placement in Group 2 and Group 3 was recorded as the mapping fluoroscopy exposure time for physicians.

2.6 Fluoroscopy time using conventional mapping

To analyse if the RMN system reduces fluoroscopy time in patients with complex CHD, we compared our results to 27 patients from our database (see the chapter of Appendix, publication 2).

2.7 Follow-up

Patients were discharged 2 days after ablation and followed in our outpatient department usually 3, 6, 12 months and then once a year after the procedure. Echocardiography and Holter-electrocardiograms were performed regularly during follow-up (see the chapter of Appendix, publication 1).

2.8 Statistical analysis

Data are presented as counts and mean±SD or appropriate range. A 2-tailed unpaired t-test was used. Statistical difference was considered significant at the level of P value<0.05.

3. Results

3.1 In the first 4 patients after the Mustard /Senning operation: feasibility of RMN mapping

In the first 4 patients in Group 3 with d-TGA after Mustard/Senning operation, the SVA and PVA were successfully mapped during IART.

Mapping of the SVA by RMN was obtained in all patients without major problems. For the PVA, the retrograde approach was chosen (see the chapter of Appendix, publication1). The mean distance between EAM maps and the CT was 2.53mm, showing a good correlation between EAM and CT anatomy (see the chapter of Appendix, publication1).

3.2 In a spectrum of patients with CHD after “simple” or “complex” atrial surgery: reduction of fluoroscopy time in AT mapping procedure

The detailed results of atrial mapping are seen in Table II.

3.2.1 Atrial mapping using RMN

Mapping was performed during 14 forms of ongoing clinical tachycardia in 14 patients and 12 forms of induced tachycardia in 8 patients (see the chapter of Appendix, publication2). The electroanatomic map (EAM) was completed successfully in all 22 patients.

3.2.2 Mechanism of tachycardia

Group 1: Cavotricuspid (n=6) or cavomitral (n=1, patient with cc-TGA) isthmus dependent IART (mean CL 306±36 ms) was found.

Group 2: A total of 13 AT (mean cycle length 336.2±85.7ms) were mapped in the 9 patients. Tachycardia mechanism was IART (n=10), localized reentry (n=1) or focal activity (n=2).

Group 3: Peritricuspidal IART was found in 5 patients. In one patient a localized reentry in the region below the right inferior pulmonary vein was detected.

3.2.3 Procedure and fluoroscopy times and learning curve for mapping

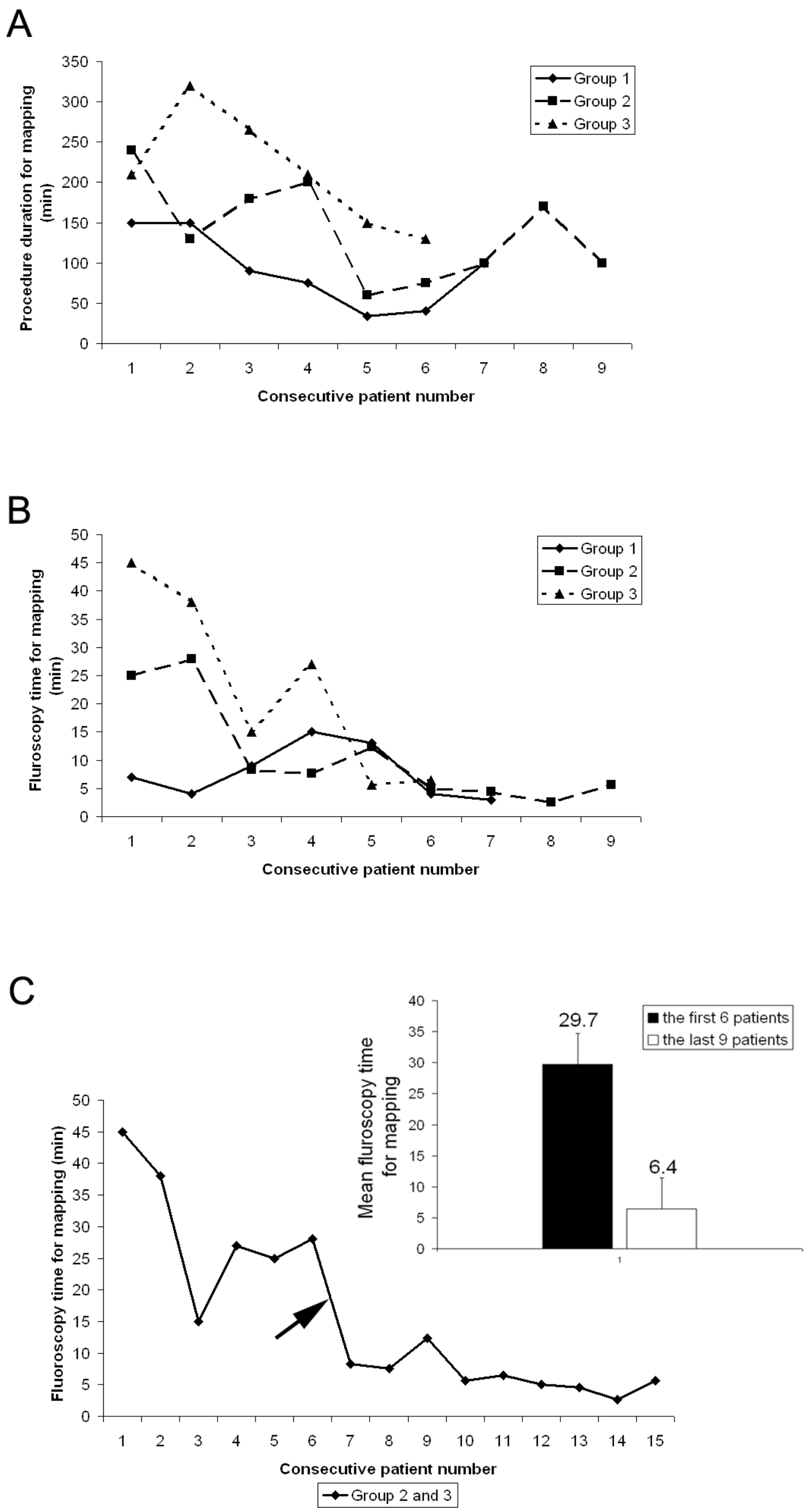
The procedure and fluoroscopy times was recorded in Table III. See the details in the chapter of Appendix, Publication2.

Group 1: No clear learning curve was found regarding procedure time (Figure 3A) and fluoroscopy time (Figure 3B) for AT mapping.

Group 2: The mean fluoroscopy time was reduced significantly in the last 4 patients (4.4±1.3 min) compared to it in the first 5 patients (14.8±7.4 min, $P<0.05$) (Figure 3B).

Group 3: A significant decrease of mapping fluoroscopy time appeared after 4 patients (Figure 3B). A decrease of fluoroscopy time for the retrograde access was noted from 12.0±5.0 min to 1.5±0.7 min between the first 4 patients and the last two patients.

Group 2 and 3: Combining the 15 patients of Group 2 and Group 3 with complex CHD, the mean mapping fluoroscopy time was 15.7±13.5 min. A distinctive decrease of mapping fluoroscopy time was between 6th and 7th patient. In the last 9 patients; it was significantly shorter than it in the first 6 patients (6.4±2.8 min vs. 29.7±10.5 min, $P<0.0001$, Figure 3C). The mean exposure time for physicians was 7.7±7.9 min.



A
Procedure duration for mapping (min)
Consecutive patient number
Group 1
Group 2
Group 3
B
Fluroscopy time for mapping (min)
Consecutive patient number
Group 1
Group 2
Group 3
C
Fluoroscopy time for mapping (min)
Consecutive patient number
Group 2 and 3
Mean fluroscopy time for mapping
29.7
6.4
the first 6 patients
the last 9 patients

Figure 3: Procedure duration for mapping and fluoroscopy time for mapping. A. Procedure duration for mapping is shown for the consecutive patients of the 3 groups. B: Fluoroscopy time for mapping in the consecutive patients of all 3 groups. C: Fluoroscopy time for mapping in the 15 consecutive patients of Group 2 and 3 with complex congenital heart disease. Arrow shows a significant reduction of fluoroscopy time for mapping between the first 6 and the last 9 patients (P<0.0001).

3.2.4 Fluoroscopy times: Comparison of RMN with conventional tachycardia mapping

Overall, no significant reduction of fluoroscopy time (including mapping und ablation) was found in the RMN patients compared to 27 postoperative patients with complex CHD with a conventional approach (21.8±17.9 min vs 24.8±11.6 min, P=0.52). However, in the last 9 patients after reaching the learning curve, the fluoroscopy time for RMN patients was significantly shorter (14.9±10.2 min vs 24.8±11.6 min, P=0.02).

3.3 Ablation results

Ablation of AT was successfully performed in 21/22 (97%) patients without complications. No ablation was performed in the patient from Group 2 who had atrial fibrillation not amenable to electrical cardioversion. Ablation results and the catheter for ablation were shown in Table II. Procedural and fluoroscopy times for ablation are shown in Table III.

3.4 Follow-up

During follow-up (1-25 months; mean 8.1±7.8 months; Table II), 2 patients had AT recurrence and all the other patients were free of tachycardia after ablation. There were no procedure related complications. (See the chapter of Appendix, publication2).

4. Discussion

4.1 Main Findings

There are two main findings. First, mapping of AT in the abnormal atrial anatomical structures after surgical procedures was feasible and safe using RMN. The second finding was that RMN for AT mapping in patients with complex atrial anatomy after the Fontan or Senning/Mustard operation led to a significant reduction of fluoroscopy time.

4.2 RMN in patients after minor atrial surgery

In patients after "minor" atrial surgery no real learning curve or significant reduction of fluoroscopy time was achieved compared to a conventional approach[66]. This is probably due to "simple" cavotricuspid dependent reentry with a clearly defined substrate.

4.3 RMN in patients with complex congenital heart disease

In the 15 patients after complex atrial surgery (Fontan type operations/TCPC or Mustard/Senning procedures), a significant reduction of fluoroscopy time was noted, corresponding to a rather fast learning curve despite complex anatomy. Our fluoroscopy time for the whole procedure (mapping and ablation) of 21.8±17.9 min is comparable to the data reported by Peichl et al.[50], and shorter than the fluoroscopy time by Schwagten et al.[57] (see the chapter of Appendix, publication2).

4.3.1 RMN in patients after Mustard/Senning operation

Atrial tachycardia in patients after the Mustard or Senning procedure is often cavotricuspid dependent. The main problem is that the cavotricuspid isthmus is anatomically located in both surgically “created” new atria[11] and that especially the pulmonary venous atrium is difficult to access and explore due to complex shape. As described by Thornton et al.[63], reaching the PVA retrograde firstly turned out to be a challenge, especially passing the aortic valve with the RMT catheter was difficult (see chapter of Appendix, Publication1). The main reduction of fluoroscopy time was accomplished by learning how to rapidly cross the aortic and tricuspid valve. By using the retrograde approach, transseptal puncture of the atrial baffle is not necessary and possible complications of this technique are avoided[13, 51]. Compared to a previous study[74], the mean fluoroscopy time for mapping and ablation was reduced significantly by RMN after the initial learning curve.

4.3.2 RMN in patients after Fontan/TCPC operation

In patients after the Fontan procedure the most important improvement compared to the conventional approach is the better wall contact in all segments of those often extremely enlarged atria (see chapter of Appendix, Publication2). In the RMN system once familiar with the “contact bar” good wall contact is relatively easy to achieve. There are very few reports showing fluoroscopy times in the Fontan group. Compared to the data of Betts[4], our mean fluoroscopy time (for mapping and ablation) of 14.6±11.4 min was shorter.

4.4 Catheter ablation with the RMN catheter

Catheter ablation with the 4 mm solid tip RMN catheter in complex anatomy did not turn out satisfactory (see chapter of Appendix, publication1 and 2). Schwagten et al[57] used the 8mm solid tip RMN catheter for successful ablation in 11 of 12 patients. In our study the 8mm solid tip RMN was successful in 3 of 4 ablations. Looking at previous studies using the conventional approach, the use of an irrigated tip catheter was the greatest predictor of ablation success[65], and more effective than solid tip catheters by creating deeper lesions in these thick-walled atria[62, 66]. We used a conventional 4 mm irrigated tip catheter successfully in 16 patients.

4.5 Limitation

As patient numbers in this population are limited, we did not perform a randomized study to compare magnetic and manual mapping/ablation. We did not routinely use the non-irrigated RMN catheters for ablation. Our data show that fluoroscopy time for mapping in these cases play the major part in the whole procedure. Further studies are needed evaluating this catheter and its potential for a further reduction of fluoroscopy times. (See the chapter of Appendix, publication2)

5. Summary

Mapping of atrial tachycardia (AT) still presents a challenge in complex congenital heart disease (CHD). The goal of this thesis was to explore the possibility to use remote magnetic navigation (RMN) for AT mapping in patients with complex CHD and to investigate if RMN can help to reduce fluoroscopy time in a spectrum of patients with CHD after minor atrial surgery, Fontan operation and Senning/Mustard operation.

In the first 4 patients (all after the Senning/Mustard operation for d-Transposition of the great arteries), mapping of cavo-tricuspid isthmus dependent IART in the SVA and PVA (PVA retrogradely by passing the aortic and tricuspid valve) was feasible and safe. In the following series of 15 patients with complex CHD (Group 2 and Group 3), the fluoroscopy time for mapping in the last 9 patients (6.4±2.8 min) was significantly shorter than in the first 6 patients (29.7±10.5 min, $P<0.0001$). Acutely successful ablation was achieved in 21/22 patients (97%) using the RMN catheter (n=3) or a conventional catheter (n=18) without procedural complications.

As the first main finding of thesis, mapping of AT in the abnormal atrial anatomical structures after surgical procedures was feasible and safe using RMN. The second finding was that RMN for AT mapping in patients with complex atrial anatomy after the Fontan or Senning/Mustard operation led to a significant reduction of fluoroscopy time.

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Table I. Patient Characteristics

	Pat No.	Age (Y)	Gender	Anatomic Diagnosis	Surgical/interventional Procedures	Age at OP (Y)	AT History	AAD	Pre-EPS (n)
Group1	1	66	M	ASD	ASD repair	18	6Y	-	0
	2	52	M	TOF	Complete TOF repair	27	25Y	-	0
	3	55	M	ASD	ASD- closure	24	18Mo	-	0
	4	50	F	cc-TGA	Commissurotomy of PA	5	5Y	-	IART ablation (1) FAT ablation (1)
	5	31	M	Ebstein, ASD	TV plastic repair, ASD- closure	24	7Y	-	IART ablation (1)
	6	16	M	CAVSD	MV plastic repair	15	1 Y	-	0
	7	40	M	TOF, LPSVC	Complete TOF repair ASD closure (patch)	2	9D	Sotalol, Amiodarone	0

Group2	1kw	40	M	DILV, L-MGA, ASD	Fontan-Lins	24	26Y	-	0
	2rg	46	F	TA	Fontan-Kreutzer	27	2Mo	-	0
	3pa	9	M	DORV	TCPC	5	1Y	-	0
	4lm	25	M	DORV, MGA, VSD, MA	Fontan-Lins	1	1Y	Amiodarone	0
	5pa	9	F	DILV	TCPC	2	1Y	-	0
	6wt	37	F	DORV, SI, AVD	Fontan-Kreutzer	9	10Y	-	0
	7cg	21	F	TA	Fontan-Björk	1	20Y	-	FAT ablation (2)
	8wj	37	M	DILV	Fontan-Lins	18	8Y	-	IART ablation (2)
	9ua	24	F	SV, PA	Fontan-Lins	3	7Mo	Amiodarone	0
Group3	1	40	M	d-TGA	Mustard	1	5Mo	-	0

2	32	F	d-TGA	Senning	2	4Y	-	IART and FAT ablation (1)
3	23	M	d-TGA	Senning	2	7D	-	0
4	30	F	d-TGA	Senning	4	5Y	-	IART ablation (2)
5	17	M	d-TGA	Senning	1	1Y	-	0
6	30	M	d-TGA	Mustard	2	5Y	-	0

AAD=antiarrhythmic drug; ASD=atrial septal defect; AT=atrial tachycardia(s); AVD= atrioventricle discordance; CAVSD=complete atrio-ventricular septal defect; ccTGA= congenitally corrected transposition of great arteries; D=days; DILV=double inlet left ventricle; DORV=double outlet right ventricle; Ebstein= Ebstein´s anomaly of the tricuspid valve; EPS=electrophysiological study; F=female; FAT=focal atrial tachycardia(s); IART=intraatrial reentry tachycardia(s); MGA= malposition of the great arteries; LPSVC=left permanent superior vena cava; M=male; MA=mitral atresia; Mo=month(s); MV=mitral valve; OP= operation; PA=pulmonary artresia; Pat=patient; SI=situs inversus; SV=single ventricle; TGA=transposition of great arteries; TA=tricuspid atresia; TCPC=total cavopulmonary connection; TOF=tetralogy of Fallot; TV=tricuspid valve; VSD=ventricular septal defect; Y=year(s).

Table II. Procedural data

Group No.	Pat. No	EAM done by RMN	EAP	Type of AT	CL of AT (ms)	Ablation Catheter	Ablation Location	Follow-up (Month)
Group 1	1gg	RA;LA	200;100	IART	330	4mm RMT, EPT	CTI	3
	2rm	RA	260	IART	260	4mm RMT, EPT	CTI	11
	3hg	RA	140	IART	290	4mm IR	CTI	3
	4ke	RA	270	IART	270	4mm IR	CMI	22
	5aj	RA	100	IART	330	4mm IR	CTI	3
	6wp	RA	100	IART	300	8mm RMT	CTI	3
	7h	RA;LA	200;110	IART	360	8mm RMT, IR	CTI	1
mean±SD			181.4±70.3; 105		305.7±36.0			6.6±7.5
Group 2	1	RA;LA	250;30asd	IART; AF	450	-	-	-

2	RA	200	IART	310	4mm IR	TR to atriotomy	25
3	RA;LA	120;200	IART	390/290	4mm IR	CTI	3
4	RA	204	IART/FAT	240/260/390	4mm IR	Between scar	8
5	RA;LA	144†	LRT	220	4mm IR	TR to PA entrance	3
6	RA	310	IART	500/370	4mm IR	CMI	3
7	RA;CS	130;120	FAT	300	8mm RMT	CS ostium	3
8	RA	280	IART	390	4mm IR	MR	3
9	RA	310	IART	260	4mm IR	TR, TR to atriotomy	3
mean±SD		216.4±75.1		336.2±85.7			6.4±7.7

Group 3	1	SVA; PVA	130;60	IART	250	4mm RMT, 4mm IR	TR to RPV; septal IVC	14
	2	SVA; PVA	150;230	IART	390	4mm IR	TR to RPV; septal IVC	19
	3	SVA;PVA	370;130	IART	290	4mm IR	TR to RPV	20
	4	SVA; PVA	200;70	IART	280	4mm IR	TR to RPV; septal IVC	16
	5	SVA; PVA	170;100	IART	250	4mm IR	TR to RPV; septal IVC	3
	6	SVA;PVA	120;80	LRT	370	8mm RMT	TR to RPV	1
mean±SD			190.0±93; 111±63		305.0±60.6			12.2±8.2

AF=atrial fibrillation; Ant.=anterior; AT=atrial tachycardia(s); CMI=cavomitral isthmus; CL=cycle length; CS= coronary sinus;

CTI=cavotricuspid isthmus; EAM=electroanatomic map; EAP=eletroanatomic points; Etr.=entrainment; FAT=focal atrial tachycardia; FI=fluoroscopy; IART=intraatrial reentry tachycardias; IR=irrigated tip; IVC=inferior vena cava; LA=left atrium; Lat.=lateral; LRT =localized reentry tachycardia; MR=mitral ring; ms=millisecond(s); PA=pulmonary artery; RA=right atrium; RMN=remote magnetic navigation; RPV=right pulmonary vein; SD=standard deviation; Sep.=septal; SVA=systemic venous atrium; Pat=Patient; PVA=pulmonary venous atrium; TR=tricuspid ring.

AF was induced by the entrainment. †LA was reached retrograde through the single left ventricle. LA and RA were performed as one map.

Table III: Procedure time and fluoroscopy exposure time (for patients and for physicians).

	Pat. No.	Mapping Procedure			Ablation Procedure		Total Procedure	
		Duration (min)	Fl. Time for Pat (min)	Fl. Time for physicians (min)	Duration (min)	Fl Time (min)	Duration (min)	Fl Time (min)
Group 1	1	150	7	nr	100	8.4	250	15.4
	2	150	4	nr	400	7.3	550	11,3
	3	90	9	nr	300	44	390	53
	4	75	15	nr	180	16.2	255	31.2
	5	34	13	nr	160	5	194	18
	6	40	4	nr	140	4.6	180	8.6
	7	100	3	nr	184	24	284	37

Mean±SD		91.3±46.8	7.9±4.7	-	209.1±104.3	15.6±14.3	300.4±129.8	24.9±16.1
Group 2	1	240	25	2.9	-	-	-	-
	2	130	28	2.7	245	13.5	375	41.5
	3	180	8.3	3.6	285	0.5	465	8.8
	4	200	7.6	2.3	45	4.9	245	12.5
	5	60	12.3	2.7	207	3.2	267	15.5
	6	75	5	3.5	276	4.3	351	9.3
	7	100	4.5	4.5	116	0.5	216	5
	8	170	2.6	2.6	211	12.4	381	15
	9	100	5.6	1.3	86	3.4	186	9
Mean±SD		145.5±60.8	10.7±8.8	2.9±1.0	168.4±96.4	5.3±4.7	303±92.9	14.6±11.4
Group 3	1	210	45(16)*	24.3	312	26	522	71
	2	320	38(15)	12.3	53	1.2	373	39.2

	3	265	15(5)	22	290	4.3	555	19.3
	4	210	27(12)	19.5	225	0.5	435	27.5
	5	150	5.6(2)	5	111	13.4	265	19
	6	130	6.5(1)	6	89	6.5	219	13
Mean±SD		214.2±70.4	22.9±16.5 (8.5±6.7)	14.9±8.3	180±110.2	8.7±9.7	394.8±135.4	31.5±21.4
Group 2+3	15	169.3±73.2	15.7±13.5	7.7±7.9	173.1±98.4	6.6±7.0	340±116.8	21.8±17.9
Total	21	144.5±74.8	13.2±11.9	8.0±8.0	191.2±96.6	9.7±10.7	327.4±119.4	22.9±17.0

Pat=Patient; Fl=fluoroscopy; min=minutes; nr=no record; SD=standard deviation.

*In Group3, the value in brackets means the fluoroscopy time for retrograde access to pulmonary venous atrium.

9. Appendix

9.1 Publication 1

Mapping of Intraatrial Reentrant Tachycardias by Remote Magnetic Navigation in Patients with d-Transposition of the Great Arteries After Mustard or Senning Procedure

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Remote Magnetic Mapping After Mustard/Senning Procedure. ***Introduction:*** **Mapping of intraatrial reentrant tachycardia (IART) still presents a challenge in complex congenital heart disease. The goal of this work was to present our initial experience with remote magnetic navigation (RMN) for mapping of IART in four patients after the atrial switch procedure (Mustard n = 1, Senning n = 3) for d-transposition of the great arteries.**

Methods: **Three-dimensional (3D) mapping of the systemic venous atrium and the pulmonary venous atrium (PVA) was performed using RMN (Niobe) in conjunction with 3D mapping (CartoRMT). The maps were fused with a CT-based 3D anatomy.**

Results: **All patients had cavotricuspid isthmus-dependent IART with a mean atrial cycle length of 305 ms. Mapping of both atria (PVA retrogradely by passing the aortic and tricuspid valve) was feasible and safe. The procedure time for IART mapping ranged from 210 to 320 minutes with a mean of 251 minutes. The fluoroscopy time for IART mapping ranged from 15.8 to 45.0 minutes (mean 31.6 minutes) for patients, and ranged from 12.3 to 24.3 minutes with a mean of 19.5 minutes for physicians. No procedural complications occurred.**

Conclusion: **Precise mapping of IART in the complex anatomical structures after an atrial switch procedure was feasible and safe using RMN. The maneuverability of the catheter was possible even with a retrograde access crossing two valves. Further reduction of procedural and fluoroscopy times for both patients and physicians seems possible** *(J Cardiovasc Electrophysiol, Vol. 19, pp. 1153-1159, November 2008)*

transposition of great vessels, intraatrial reentrant tachycardias, remote magnetic navigation, mapping, catheter ablation

Introduction

Mustard[1] and Senning[2] were the first to use an atrial baffle construction in patients with d-transposition of the great arteries (d-TGA) that directs venous blood from the superior (SVC) and inferior vena cava (IVC) to the mitral valve and the left ventricle and pulmonary venous blood to the tricuspid valve and the right ventricle (RV) ("atrial switch procedure") (Fig. 1A, B). Many patients who underwent these operations have now survived into adulthood. Late cardiac arrhythmias, especially intraatrial reentrant tachycardias (IART), occur in up to 30% of this population during long-term follow-up and seem to represent a significant factor for long-term morbidity and mortality.[3,4]

Since the initial experience with mapping and catheter ablation of IART,[5,6] different mapping techniques, such as noncontact mapping[7] and electroanatomic mapping,[8] have been introduced to facilitate the procedure and to improve ablation success.

Remote magnetic navigation (RMN) is a new technique for steering a soft and flexible catheter by the use of an external magnetic field.[9] RMN has been used for mapping and ablation of supraventricular reentrant tachycardia,[10–12] atrial fibrillation,[13] and ventricular tachycardia.[14] As the RMN catheter offers stable contact with the myocardial wall without the risk of perforation, it might be especially suited for accessing difficult anatomy as in postsurgical congenital heart disease. This is the first report using the RMN system for IART mapping in patients following the Mustard or Senning procedure.

Methods

Patients

Four patients (2 males, 2 females; age 23–40 years) had undergone an atrial switch procedure at the age of 1–4 years. The Mustard procedure had been performed in one patient, the Senning procedure in two patients, and in one patient the original Mustard operation had been converted to a Senning procedure because of pulmonary venous obstruction. All patients were admitted with a 12-lead

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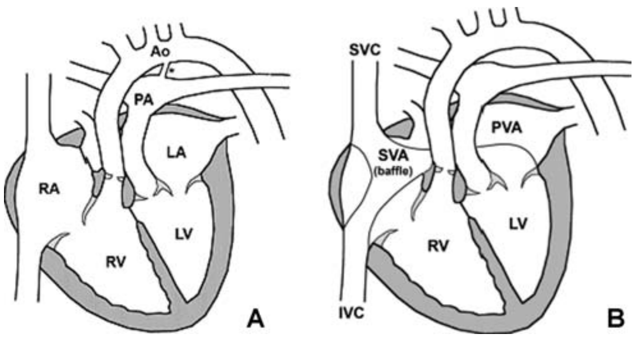

Figure 1. *(A) The anatomy in d-transposition of the great arteries: the aorta arises from the right ventricle and the pulmonary artery from the left ventricle. (B) Anatomy after the "atrial switch" procedure (Mustard or Senning operation). The creation of a synthetic (Mustard operation) or a pericardial patch (Senning operation) directs the blood from systemic caval veins to the mitral valve and left ventricle, and the blood from the pulmonary veins to tricuspid valve and right ventricle. Ao = aorta; IVC = inferior vena cava; LA = left atrium; LV = left ventricle; PA = pulmonary artery; PVA = pulmonary venous atrium; RA = right atrium; RV = right ventricle; SVA = systemic venous atrium; SVC = superior vena cava.*

electrocardiogram suggesting IART (Fig. 2A). All patients were put on oral metoprolol to slow atrioventricular conduction; in one patient, tachycardia terminated spontaneously before the electrophysiological (EP) study. Patient characteristics are shown in Table 1.

Preablation Workup and Electrophysiological Study

Patients provided written informed consent for the EP study. Continuous heparin infusion was started at least 48 hours before the procedure. A transesophageal echocardiography was performed to exclude intraatrial thrombus formation. A contrast enhanced 64-slice cardiac computed tomography (CT) was performed and the three-dimensional (3D) CT images were reconstructed, segmented, and prepared for integration with the 3D electroanatomic map using the CartoRMT system (Biosense-Webster, Diamond Bar, CA, USA).

The EP study was performed under conscious sedation. At the beginning of the procedure, three patients had ongoing IART and one patient had sinus rhythm. After femoral venous and arterial access, an octapolar, 6-French (F) diagnostic catheter (EP-XT, C.R. Bard, Lowell, MA, USA) was placed in the left atrial appendage connecting to the systemic venous atrium (SVA) as reference (Fig. 2B). Heparin i.v. was administered continuously and the activated coagulation time maintained at levels of 200–250 seconds. In the patient with sinus rhythm, clinical IART was induced by programmed atrial stimulation.

Mapping of the SVA by RMN

A long 8-F sheath (SL0®, St. Jude Medical, Minnetonka, MN, USA) was placed via femoral vein access at the transition of the IVC to SVA. The quadripolar 7-F RMN catheter with a 4 mm tip (Navistar RMT, Biosense-Webster) was advanced manually until the end of the sheath and connected to the catheter advancer system (Cardiodrive, Stereotaxis), which was fixed on the patient's leg. Details of the magnetic navigation system (Niobe, Stereotaxis Inc) have been described previously.[11,13] The system was used in conjunction with a monoplane fluoroscopy system (Axiom Artis, Siemens, Erlangen, Germany) and the CartoRMT system.

Mapping of the SVA was performed with the "RA" navigation model of the RMN system. By remote navigation of the joystick, an electroanatomic map of the SVA (including SVC and IVC) was created (Fig. 3). Discontinuous fluoroscopy was used to monitor catheter movement. After the SVA map was completed, one "landmark" in the electroanatomic map

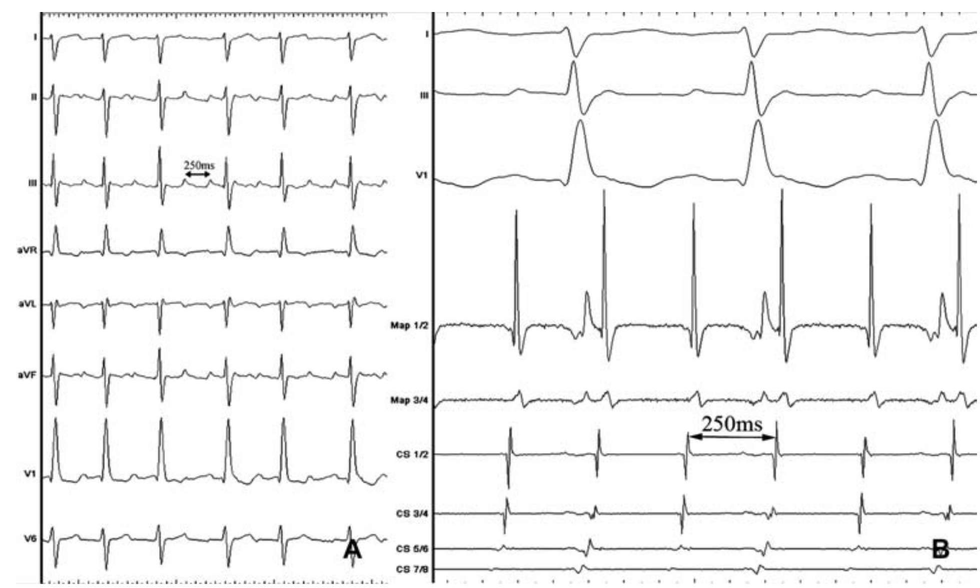

Figure 2. *(A) Surface ECG recordings (recording speed = 25 mm/s) of a patient during tachycardia. The onset and the end of one reentrant cycle are marked. (B) Surface and intracardiac recordings of the intraatrial reentrant tachycardia (same patient; recording speed = 100 mm/s). Channels from top to bottom are: surface electrocardiogram lead I, III, V1, bipolar electrograms of the mapping catheter, which was positioned at the cavotricuspid isthmus, and bipolar electrograms recorded by an octapolar catheter. This catheter was placed in the left atrial appendage as part of the systemic venous atrium. The recordings show an atrial tachycardia with the cycle length of 250 ms and 2:1–3:1 AV-conduction.*

TABLE 1
Patients Characteristics

No. Patient	Age (Y)	Male/ Female	Type of OP	Age for OP	History of IART	Pre-EPS (n)	CL of IART (ms)	SD in SROCM (mm)	Follow-Up (Mo)
1	30	Female	M	2Y	4 Y	1	250	2.80	9
2	23	Male	S	4Y	7 days	0	290	2.40	12
3	31	Female	S	2Y	5 Y	1	390	1.70	10
4	40	Male	S	1Y	5 Mo	0	280	3.20	9
Mean	31	–	–	2.3Y	–	–	305	2.53	10.5

CL = cycle length; EPS = electrophysiological study; IART = intraatrial reentrant tachycardia(s); M = Mustard; Mo = month(s); mm = millimeter; ms = millisecond(s); OP = operation procedure(s); S = Senning; SD = standard deviation; SROCM = surface registration of CartoMerge; Y = years.

of the SVA was attached to the corresponding location on the 3D CT -based anatomy and both maps were merged (CartoMerge).

Mapping of the Pulmonary Venous Atrium (PVA) by RMN

Retrograde access to the PVA via the femoral artery, aorta, aortic valve, right ventricle (RV) and tricuspid valve was employed using the RMN catheter (Fig. 4). The RMN catheter was advanced over another SL0 sheath placed in the descending aorta. The “LA” protocol of the RMN system was chosen for navigation in the PVA. By using the joystick, mapping started in the pulmonary vein compartment and was then completed by navigating the RMN catheter around the anterior part of the PVA with the tricuspid valve.

Biatrial Entrainment Mapping

Entrainment mapping was performed during IART at multiple sites, especially at sites located within the presumed reentrant circuit at the tricupid annulus (in the SVA and PVA). Pacing was performed with a cycle length 20 ms faster then the tachycardia cycle length. Entrainment was considered positive if the postpacing intervals were less than 20 ms different from the tachycardia cycle length.

Catheter Ablation

After mapping of SVA and PVA, ablation was performed in the PVA and/or SVA.[8] The same access to the SVA and PVA was chosen as used for mapping. In the first patient, ablation was started using the RMN catheter with a maximal temperature of 65°C and maximal power of 30–35 W. As a second ablation catheter in this patient and as a first-line ablation catheter in the other three patients, a conventional irrigated tip catheter (Navistar Thermocool, Biosense-Webster) with a maximal temperature 43°C and maximal power of 35 W was used. Radiofrequency energy was delivered using an EP shuttle radiofrequency generator (Stockert, Biosense-Webster).

Procedure and Fluoroscopy Times

Procedure time was defined from the beginning of the venous puncture until catheter removal. The periods for mapping and ablation were recorded separately. The mapping time was defined as the period from the venous puncture until completion of the SVA and PVA maps. Ablation time was defined as the period from the end of the mapping to the time of catheter removal. Fluoroscopy time in minutes was divided into five components: (1) puncture and catheter placement, (2) SVA mapping, (3) retrograde access to PVA, (4) PVA

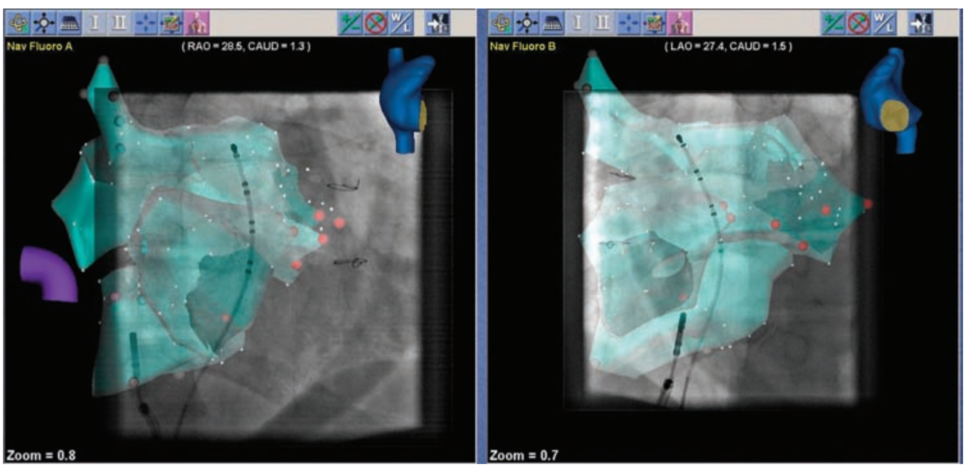

Figure 3. *Navigation fluoroscopy window A and B of Stereotaxis in right anterior oblique 28.5° (left window, A) and left anterior oblique 27.4° (right window, B). Shown is the 3D biatrial anatomy (systemic and pulmonary venous atrium) created by the RMN combined with the CartoRMT® system overlapped with real-time-fluoroscopy image. “RA” was selected as the navigation model. With adjusting the translucency of the 3D anatomy, the catheter location becomes visible in the fluoroscopy image. An octapolar catheter was placed in the left atrial appendage (part of the systemic venous atrium) as the intracardiac reference. The RMT catheter used for mapping (quadripolar, 4 mm tip, 7-French) is advanced over a long sheath positioned at the intersection of the IVC to the systemic venous atrium.*

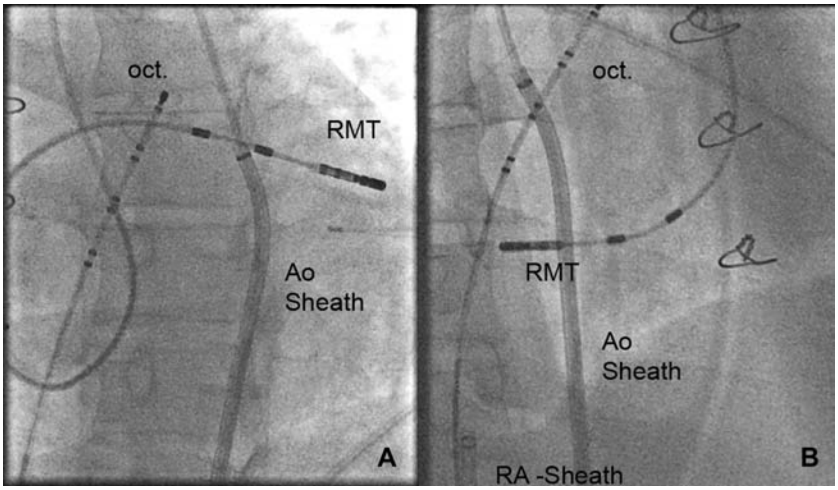

Figure 4. *Fluoroscopy image of the retrograde approach to reach the pulmonary venous atrium (PVA). (A, left anterior oblique 27.4°): The RMT catheter is positioned in the left PV using the magnetic navigation via the retrograde (aortic) access. The catheter course shows two large curves (through the aortic valve and the tricuspid valve). The octapolar catheter is placed in the left atrial appendage as reference. (B, right anterior oblique 28.5°): The RMT catheter is positioned at the cavotricuspid isthmus. Ao = aorta; oct = octapolar reference catheter; RA = right atrium.*

mapping, and (5) ablation. Patients' fluoroscopy time for mapping included first, second, third, and fourth components, whereas physicians' fluoroscopy time for mapping included the first and third component. Data are presented as counts and mean or appropriate range.

Results

The SVA and PVA were mapped during IART with atrial cycle lengths ranging from 250 to 390 milliseconds. Tachycardia did not terminate in any patient during catheter movement and mapping.

Mapping of the SVA by RMN

Mapping of the SVA by RMN was obtained in all patients without major problems. The RMN catheter was driven into the SVA in a straight fashion via the IVC toward the SVC. The SVA was mapped beginning from the SVC by withdrawing continuously the catheter along the atrial and baffle walls toward the IVC. For the electroanatomic maps of the SVA, 133 to 292 points (mean 217 points) were taken by the RMN catheter.

Retrograde Access and Mapping of the PVA by RMN

For the PVA, the retrograde approach was chosen. To cross the aortic valve, the looped RMN catheter was positioned manually in the ascending aorta. Using remote navigation and various vector directions, the aortic valve could not be crossed or, if this was finally achieved, the catheter could not be stabilized in the right ventricle while navigating toward the tricuspid valve. Finally, the looped catheter was advanced manually over the aortic valve. After crossing the aortic valve, a caudally oriented vector was applied to advance the catheter more deeply inside the RV. Then the catheter was continuously advanced with a vector pointing toward the inferior, lateral aspect of the tricuspid valves (TV) (i.e., a strictly right lateral vector). After crossing the TV, the catheter was advanced inside the PVA until it was considered stable.

For the PVA map, first the pulmonary vein compartment was mapped including all easily accessible pulmonary veins. Then the more anterior part was mapped with special focus on exact reconstruction of the TV. In two patients, the RMN catheter dislocated into the RV when taking points at the tricuspid ring and had to be navigated back into the PVA. In our first patient, the PVA was reconstructed combining the separate maps of the pulmonary vein compartment and the anterior tricuspid valve compartment. In the other three patients, the PVA was initially mapped in a single anatomic reconstruction. For the PVA electroanatomic map, 69–197 points (mean 117 points) per patient were acquired.

Merging SVA and PVA Map with CT-Based Anatomy

The completed SVA and PVA maps were fused with the CT-derived, segmented anatomy of the individual patients using the CartoMerge® software implemented in the electroanatomic mapping system. The mean distance between the points acquired in the electroanatomic maps and the corresponding points on the CT-derived anatomy were computed by the Carto system. With distances ranging from 1.7 to 3.2 millimeters (mm; mean = 2.53 mm) a good correlation between CT anatomy and the electroanatomic maps was demonstrated (Fig. 5A).

Tachycardia Mechanism

The biatrial electroanatomic local activation map showed continuous spreading of activation around the TV with an "early-meets-late" zone located at the tricuspid annulus corresponding to peritricuspid reentry (Fig. 5B,C). In all patients, the reentry circled in counterclockwise direction around the tricuspid valve. The reentry localization was confirmed by positive entrainment pacing at the tricuspid annulus in the PVA. In all four patients, positive entrainment pacing from the low septum of the SVA close to the entrance of the IVC demonstrated that the SVA component of the original cavotricuspid isthmus was a part also of the reentry circuit.

Ablation

Ablation was performed in the PVA and/or SVA component of the former cavotricuspid isthmus. In the first patient, ablation in both atria using the nonirrigated RMN catheter did not terminate tachycardia. After removal of the catheter from SVA traces of carbonization were found on the catheter tip. Consequently, a conventional 4 mm irrigated tip catheter was used for ablation in both atria. For the other three patients, the conventional irrigated tip catheter was used for ablation in the first place. Using the irrigated tip catheter, IART terminated

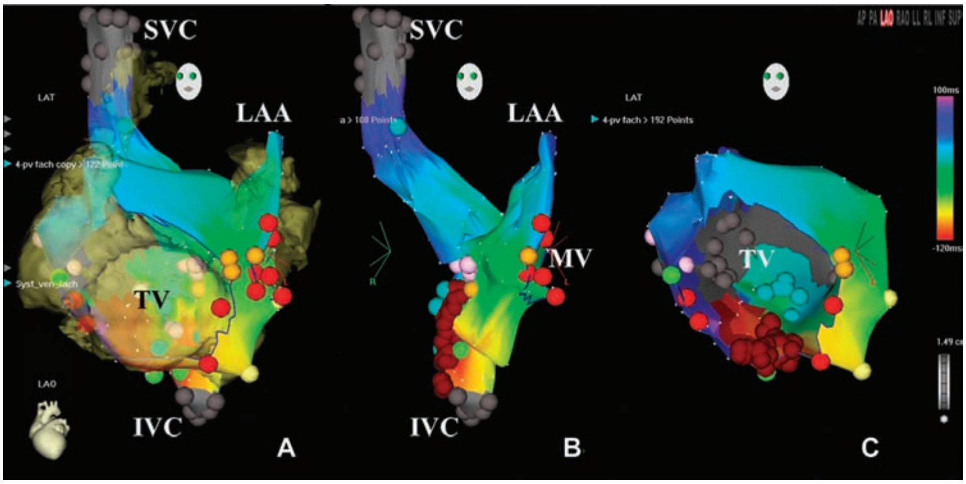

Figure 5. *(A) Fusion of electroanatomic map and CT-based anatomy after registration using the "merge" function of the Carto System. (B) Systemic venous atrium and (C) pulmonary venous atrium: Local activation maps during tachycardia of the SVA and PVA. IART cycle length is 240 ms. The activation maps cover over 90% of tachycardia cycle length. The "early meets late" zone (dark red) is found at the PVA and SVA component of the former cavo-tricuspid-isthmus supporting the concept of isthmus-dependent atrial flutter. Positive entrainment positions at the tricuspid annulus and the caval part of the former cavotricuspid isthmus are labeled with light green points. Radiofrequency lesions are visible in the SVA and PVA (dark red points). The other points show the location of the tricuspid annulus and mitral annulus (red), the His bundle location (orange), the coronary sinus ostium (yellow), an area of double potentials (blue), and an area of fragmented potential (pink). The bipolar threshold for scar area (gray color) was set to 0.05 mV. IVC = inferior vena cava; LAA = left atrial appendage; MV = mitral valves; SVC = superior vena cava; TV = tricuspid valves.*

in all patients during ablation after prolongation of the cycle length. Ablation was continued until split double potentials indicated a complete line of block.

In the third patient, tachycardia stopped during the first RF application at the tricuspid annulus with the irrigated tip catheter. After completing the ablation lesion in the PVA, no significant electrograms were found at the corresponding sites in the SVA. Therefore, no further lesions were applied in the SVA.

Procedural Data and Follow-Up

Table 2 shows the procedural data. Total procedure time ranged from 370 minutes to 490 minutes with a mean of 436 minutes (251 minutes for mapping and 153 minutes for ablation). For mapping, the fluoroscopy time for patients ranged from 15.8 minutes to 45 minutes (mean 31.6 minutes) and for the physician from 12.3 to 24.3 minutes (mean 19.5 minutes).

Transthoracic echocardiography was performed in all patients immediately after the procedure, 24 hours later and 3 months thereafter. No aortic insufficiency was detected. No procedure-related complications occurred.

All four patients are free of tachycardia up to now (from 9 to 13 months, mean 10.5 months).

Discussion

This is the first report using RMN in the setting of intraatrial reentrant tachycardia in postoperative complex congenital heart disease.

Three-dimensional electroanatomic mapping of both atria in four patients after the Mustard or Senning procedure using RMN was feasible and showed a good correlation with the CT-based anatomy. RMN catheter steering for the mapping of the systemic venous and the pulmonary venous atrium (SVA and PVA) was safe without any damage to cardiac or vascular structures. Catheter-to-wall contact was stable, and with the soft, flexible 7-F RMN catheter, no mechanically induced alteration of the tachycardia was observed.

Mapping of the SVA and Retrograde Access to the PVA

Mapping of the SVA was easily achieved by RMN by the venous route and was comparable in time end effort with the conventional approach.

TABLE 2

Procedural Data

No. Patient	Procedure Time (Minutes)			Fluoroscopy Time (Minutes)						
	Mapping	Ablation	Total	T1	T2	T3	T4	T (1 + 2 + 3 + 4)	T (1 + 3)	T5
1	210	222	450	8.3	3.7	16.0	17.0	45.0	24.3	16.0
2	265	200	490	7.3	0.5	5.0	3.0	15.8	12.3	2.5
3	320	30	370	7.2	8.4	14.8	7.8	38.2	22.0	1.0
4	210	160	435	7.2	2.0	12.0	6.3	27.5	19.2	7.2
mean	251	153	436	7.5	3.7	12.0	8.5	31.6	19.5	6.7

T1 = the fluoroscopy time for puncture and catheter placement; T2 = the fluoroscopy time for systemic venous atrium mapping; T3 = the fluoroscopy time for retrograde access to right ventricle, T4 = the fluoroscopy time for pulmonary venous atrium mapping; T (1 + 2 + 3 + 4) = the total fluoroscopy time of mapping for the patient; T (1 + 3) = the total fluoroscopy time of mapping for the physician; T5 = the fluoroscopy time for ablation.

Reaching the PVA turned out to be a challenge. To avoid complications of a transseptal puncture through the atrial baffle (used by some groups),[15,16] we chose the retrograde route via the aortic and tricuspid valve to access the PVA. Passing the aortic valve with the RMN catheter was especially difficult. We encountered the same problem as described by Thornton *et al.*[11] with the catheter tip always jumping back into the aorta arch when trying to pass the aortic valve with a looped catheter. Using the catheter in a straight fashion, it was relatively easy to advance the RMN catheter through the aortic valve by vector navigation, but then the catheter always dislocated back into the aorta when trying to reach the TV and, thus, the PVA. Finally, the looped RMT catheter was maneuvered by manual advancement across the aortic valve. While advancing the catheter continuously, a right lateral pointing vector was used to reach the TV.

Procedure and Fluoroscopy Times

As there are no reports using the RMN system in a similar patient population, a comparison of procedure and fluoroscopy times is limited. The mean procedure time has been reported in the range from 248 minutes to 8.8 hours.[8,17,18]

There is one report describing only the procedure and fluoroscopy times of SVA mapping and ablation using a noncontact mapping system,[7] which is also not comparable to our study. Looking at a previous study from our institution[8] the mean fluoroscopy time was reduced from 64 minutes (16–158 minutes) using conventional electroanatomic mapping to 37.3 minutes (17.3–61 minutes) with RMN. The mean procedure time was slightly higher with 436 minutes (370–490 minutes), compared with 343 minutes (100–630 minutes). This may be due to the new method and a more time-consuming setup. Overall, a further reduction of procedure as well as fluoroscopy times seems possible, especially regarding the learning curve for the time necessary for retrograde access to the right ventricle and PVA.

Ablation

As mentioned before and in line with previous findings from our group,[8] in most patients following the Mustard or Senning operation, biatrial ablation is necessary for successful ablation. In this study, three patients underwent biatrial ablation. The nonirrigated RMN catheter was used for ablation in both atria in our first patient, but it was not effective and we observed carbonization. Carbonization is a known problem with a 4 mm nonirrigated catheter tip, especially when using high power and/or temperature settings.[19] In RMN catheter ablation, this might be an additional point to consider: Since the catheter-to-wall contact is virtually never lost, the effective ablation time at a given point is equal to the time the catheter is not moved on. Thus, the catheter should be probably moved on faster during ablation than in conventional (manual) ablation technique.

As to the effectiveness of ablation, although nonirrigated tip catheters have been used to ablate IART in congenital heart disease,[6,7] ablation with irrigated tip catheters has been shown to be more effective by creating deeper lesions in these thick-walled atria.[17,20] Triedman *et al.* found that the greatest predictor of success was the use of irrigated tip catheters, highlighting the difficulty of this ablation substrate.[21] In line with these findings (conventional), irrigated tip catheter ablation terminated tachycardia in all patients.

Conclusion

This report reflects our initial experience with the RMN system for mapping intraatrial reentrant tachycardia in four patients with complex congenital heart disease. We believe that in complex postoperative congenital heart disease patients remote navigation in combination with a 3D electroanatomic mapping system is precise and safe and might reduce fluoroscopy time for patients and physicians substantially.

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9. Appendix

9.2 Publication 2

Mapping of Atrial Tachycardia by Remote Magnetic Navigation in Postoperative Patients With Congenital Heart Disease

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Remote Magnetic Mapping in Congenital Heart Disease. ***Objectives:*** **The purpose of this study was to investigate if remote magnetic navigation (RMN) offers a reduction of fluoroscopy time when used for atrial tachycardia (AT) mapping in a spectrum of patients with congenital heart disease (CHD) after "simple" or "complex" atrial surgery.**

Background: **Data about AT mapping using RMN in larger populations of patients with CHD are scarce.**

Methods: **RMN in combination with electroanatomic mapping was used for AT mapping in 22 patients. According to anatomic complexity, patients were classified into 3 groups: Group 1: patients after minor atrial surgery (n = 7); Group 2: patients after the Fontan operation (n = 9); and group 3: patients after the Senning/Mustard operation (n = 6).**

Results: **Atrial mapping with a nonirrigated tip RMN catheter was completed successfully in all patients. In Group 1 no significant reduction in fluoroscopy time was noticed over time (mean fluoroscopy time 7.9 minutes). In the 15 patients of group 2 and group 3 with complex CHD, the fluoroscopy time for mapping in the last 9 patients (6.4 ± 2.8 minutes) was significantly shorter than in the first 6 patients (29.7 ± 10.5 minutes, P < 0.0001). Acutely successful ablation was achieved in 21 of 22 patients (97%) using the RMN catheter (n = 3) or a conventional catheter (n = 18) without procedural complications.**

Conclusions: **RMN for AT mapping in patients with complex atrial anatomy leads to a significant reduction of fluoroscopy time.** *(J Cardiovasc Electrophysiol, Vol. 21, pp. 751-759, July 2010)*

congenital heart diseases, remote magnetic navigation, catheter ablation, atrial tachycardia, surgery

Introduction

In adult patients with congenital heart disease (CHD) arrhythmias during long-term follow-up significantly contribute to the morbidity and mortality in this patient population.[1] Atrial tachycardia (AT), especially intraatrial reentrant tachycardia (IART) is the most common arrhythmia after atrial surgical procedures for congenital heart defects and occurs in up to 50% of patients after Fontan-type operations[2,3] and up to 30% of patients after Mustard or Senning procedures during long-term follow-up.[4,5] As successful drug treatment is hard to achieve, catheter ablation has evolved as a potentially curative alternative for the treatment of these arrhythmias.[6]

The technique of catheter ablation for IART[7,8] was improved and facilitated by the use of noncontact mapping,[9] electroanatomic mapping systems,[10] and irrigated tip catheters for ablation.[11] Recently, remote magnetic navigation (RMN) was introduced for IART mapping in patients after the Mustard or Senning procedure,[12,13] showing the feasibility and safety of this technique. The purpose of this study was to investigate if RMN offers a reduction of fluoroscopy time when used for atrial tachycardia mapping in a spectrum of patients with CHD after "simple" or "complex" atrial surgery.

Methods

Patient Characteristics

From October 2006 until September 2008, 22 consecutive patients (mean age 33 ± 15 years, 8 females) with postoperative congenital heart disease underwent RMN-guided AT mapping (n = 22) and ablation (n = 7).

According to the extent of previous cardiac surgery, patients were classified into 3 groups: Group1 (n = 7) included patients with "simple" atrial surgery (atrial septal defect closure or atriotomy as part of surgery). Group 2 (n = 9) included patients after complex right atrial surgery (Fontan procedure or total cavopulmonary connection (TCPC)). Patients in group 3 (n = 6) had complex biatrial surgery (Mustard or Senning procedures).

Preablation Workup and Electrophysiological Study

Preablation workup and electrophysiological study were performed as described before.[10] A 3-dimensional electroanatomic mapping system (CartoRMT, Biosense-Webster, Diamond Bar, CA, USA), was used in combination with RMN system (Niobe, Stereotaxis Inc, St. Louis, MO, USA) in all patients. Details of RMN system have been described previously.[12,14,15] Discontinuous fluoroscopy was used to

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monitor the catheter location and movement especially if (1) there was a rapid increase of real-time impedance displayed on the RF-generator (Stockert, Biosense-Webster) or if (2) the "contact bar" on the Carto-System indicated a very strong catheter-to-heart wall contact.

An octapolar, 6F diagnostic catheter (EP-XT, C.R. Bard, Lowell, MA, USA) was placed inside the coronary sinus (CS) or in the systemic venous atrium (SVA) (Mustard/Senning patients) as reference. A quadripolar 7F RMN catheter (nonirrigated) with a 4-mm tip (Navistar RMT, Biosense-Webster) was used in first 16 patients, an 8-mm tip RMN (7F, quadripolar, nonirrigated) in the last 6 patients.

Atrial Mapping Using RMN

Mapping was performed during ongoing clinical tachycardia. In the patients who came to the lab in sinus rhythm, an atrial anatomy of the directly accessible atrium was created first and tachycardia was then induced by atrial programmed or burst stimulation.

Indicated by activation map, a macroreentrant mechanism was assumed if a continuous activation sequence was found with local activation times covering more than 90% of tachycardia cycle length.[10] Entrainment maneuvers were performed as described before.[16] A "localized" reentry was presumed if (1) a local electrogram covering up to 80% of the reentrant cycle length was present; (2) the putative reentry was confined to 1 segment of the atrium only; and (3) if entrainment was only possible at the site of slow conduction electrogram. Focal activation was defined as (1) a radial spreading in all directions from a single site of earliest activation; (2) coverage of less than 90% of the tachycardia cycle length; and (3) elimination of AT by focal ablation at the earliest site.[17] The mapping procedure was considered complete if sufficient points in 1 or 2 atria had been acquired to understand the mechanism of the tachycardia.

Group 1: Similar to conventional manual mapping in the right atrium (RA),[18] the reference catheter was placed in the CS. RA mapping was performed starting from the superior vena cava, proceeding then to the mapping of the whole RA chamber and finally the inferior vena cava. If the atrial septal defect (ASD) had not been completely closed, additional left atrial mapping was performed.

Group 2: The reference catheter was placed in the CS or in the high RA (if the CS could not be entered). The electroanatomic maps of the superior vena cava and the pulmonary artery or conduit were created separately to achieve a better reconstruction of anatomic details. To highlight the supposed position of the atretic tricuspid ring, points in an anteroseptal, anterolateral, and posteroseptal position with a high ventricular far-field potential, points with a visible His electrogram and points close to the anterior aspect of the CS ostium were tagged as tricuspid ring points. If peritricuspid IART was considered, the RMN catheter was navigated around the tagged tricuspid ring and entrainment maneuvers were performed. In 1 patient an additional CS map was acquired to map a focus originating in CS.

Group 3: Biatrial mapping in patients with d-Transposition of great arteries (d-TGA) after the Mustard or Senning procedure using RMN was described earlier by our group.[12] In brief, SVA and pulmonary venous atrium (PVA) were mapped. The PVA was reached retrograde through aortic and tricuspid valve. Entrainment maneuvers were performed around the tricuspid ring.

Catheter Ablation

Ablation was performed in 3 patients using the 4-mm solid tip RMN catheter (65°C, 30 W) and in 4 patients using the 8-mm tip RMN catheter (65°C, 50 W). If tachycardia did not terminate, a conventional irrigated tip catheter (Navistar Thermocool, Biosense-Webster) (43°C, 30 W) or an 8-mm solid tip catheter (Blazer II XP, Boston Scientific, San Jose, CA, USA) (60°C, 50 W) was used. The endpoint of ablation was tachycardia termination and if feasible the assessment of a complete line of block. In the first group ("simple" atrial surgery), bidirectional isthmus block was assessed. In the Fontan group, the endpoint was not inducible sustained tachycardia. In the Mustard/Senning group, ablation was performed as described before.[12] The endpoint was tachycardia termination and split double potentials indicating a complete line of block.

Procedure and Fluoroscopy Times

The recorded procedure time was separated into the mapping and ablation time. Fluoroscopy time was also recorded separately for mapping and ablation. Mapping time was defined as the period from the venous puncture to the completion of atrial mapping. Ablation time was defined as the period from the end of the mapping to the time of catheter removal.

In group 3, fluoroscopy time for retrograde access was recorded separately, defined as the time interval from the catheter introduced into the aorta until the catheter was placed stably in the PVA. The fluoroscopy time for catheter placement in group 2 and group 3 was recorded as the fluoroscopy exposure time for physicians.

Fluoroscopy Time Using Conventional Mapping

To analyze if the RMN system reduces fluoroscopy time in patients with complex CHD, we compared our results to 27 patients (Fontan operation n = 13; Mustard/Senning operation n = 14) from our database (October 2003 to September 2006) who had conventional atrial tachycardia mapping using a 3D system (Carto) as described in our publication.[10]

Follow-Up

Transthoracic echocardiography and 24-hour Holter electrocardiogram was performed after the procedure. Transthoracic echocardiography was repeated within the next 24 hours. Patients were discharged 2 days after ablation and followed in our outpatient department usually 3, 6, 12 months and then once a year after the procedure. Another 24-hour Holter electrocardiogram was done at least once in the outpatient department.

Statistical Analysis

Data are presented as counts and mean ± SD or appropriate range. A 2-tailed unpaired *t*-test was used. Statistical difference was considered significant at the level of P value < 0.05.

TABLE 1

Patient Characteristics

	Pat No.	Age (Y)	Gender	Anatomic Diagnosis	Surgical/Interventional Procedures	Age at OP (Y)	AT Period	AAD History (class I or III)	Pre-EPS (n)
Group 1	1	66	M	ASD	ASD repair	18	6Y	–	0
	2	52	M	TOF	Complete TOF repair	2718	25Y	–	0
	3	55	M	ASD	ASD- closure	2418	18Mo	–	0
	4	50	F	cc-TGA	Commissurotomy of PA	5	5Y	–	IART ablation (1) FAT ablation (1)
	5	31	M	Ebstein, ASD	TV plastic repair, ASD-closure	24	7Y	–	IART ablation (1)
	6	16	M	CAVSD	MV plastic repair	15	1 Y	–	0
	7	40	M	TOF, LPSVC	Complete TOF repair ASD closure (patch)	2	9D	Sotalol, Amiodarone	0
Group 2	1	40	M	DILV, L-MGA, ASD	Fontan-Lins	24	26Y	–	0
	2	46	F	TA	Fontan-Kreutzer	27	2Mo	–	0
	3	9	M	DORV	TCPC	5	1Y	–	0
	4	25	M	DORV, MGA, VSD, MA	Fontan-Lins	1	1Y	Amiodarone	0
	5	9	F	DILV	TCPC	2	1Y	–	0
	6	37	F	DORV, SI, AVD	Fontan-Kreutzer	9	10Y	–	0
	7	21	F	TA	Fontan-Björk	1	20Y	–	FAT ablation (2)
	8	37	M	DILV	Fontan-Lins	18	8Y	–	IART ablation (2)
	9	24	F	SV, PA	Fontan-Lins	3	7Mo	Amiodarone	0
Group 3	1	40	M	d-TGA	Mustard	1	5Mo	–	0
	2	32	F	d-TGA	Senning	2	4Y	–	IART and FAT ablation (1)
	3	23	M	d-TGA	Senning	2	7D	–	0
	4	30	F	d-TGA	Senning	4	5Y	–	IART ablation (2)
	5	17	M	d-TGA	Senning	1	1Y	–	0
	6	30	M	d-TGA	Mustard	2	5Y	–	0

AAD = antiarrhythmic drug; ASD = atrial septal defect; AT = atrial tachycardia(s); AVD = atrioventricle discordance; CAVSD = complete atrioventricular septal defect; cc-TGA = congenitally corrected transposition of great arteries; D = days; DILV = double inlet left ventricle; DORV = double outlet right ventricle; Ebstein = Ebstein's anomaly of the tricuspid valve; EPS = electrophysiological study; F = female; FAT = focal atrial tachycardia(s); IART = intraatrial reentrant tachycardia(s); MGA = malposition of the great arteries; LPSVC = left permanent superior vena cava; M = male; MA = mitral atresia; Mo = month(s); MV = mitral valve; OP = operation; PA = pulmonary artresia; Pat = patient; SI = situs inversus; SV = single ventricle; d-TGA = d-transposition of the great arteries; TA = tricuspid atresia; TCPC = total cavopulmonary connection; TOF = tetralogy of Fallot; TV = tricuspid valve; VSD = ventricular septal defect; Y = year(s).

Results

Atrial Mapping Using RMN

Mapping was performed during ongoing clinical tachycardia in 14 patients. In 8 patients (group 2 n = 5 and group 3 n = 3) tachycardia was induced by atrial programmed or burst stimulation and compared to the clinical tachycardia. In all patients induced and clinical tachycardias were consistent. In 3 post-Fontan patients, 1–2 forms of tachycardia not corresponding to the clinical form were also induced (Table 1).

The electroanatomic map of at least 1 atrium was completed successfully in all 22 patients (Table 2). In 1 post-Fontan patient (patient 8 in group 2) the RA was mapped by RMN and the LA was reached and mapped manually by a retrograde approach.

Group 1: A right atrial map (184 ± 70 points) was completed in all 7 patients, 2 of 7 patients with residual ASD underwent biatrial mapping. For the left atrial map 100 and 110 points were recorded.

Group 2: An electroanatomic map of the RA including the anastomosis to the pulmonary artery was completed in all 9 patients with a mean of 216 ± 75 points (range 120 to 310). Figure 1 shows an example of a patient of tricuspid atresia after Fontan operation. In 1 patient with dilated CS and tachycardia origin inside the CS, an additional CS map with 120 points was done. Using the RMN system an additional left atrial map (from 30 to 200 points) was done in patients 1, 3, and 5, through the ASD or retrogrades through the single ventricle.

Group 3: Both atria were mapped in all 6 patients. For the SVA 120 to 370 points (mean 190 ± 93 points) were taken, for the PVA 60 to 200 points (mean 111 ± 63 points). Table 2 shows the details of the electroanatomic maps.

Mechanism of Tachycardia

Group 1: Cavotricuspid (n = 6) or cavomitral (n = 1, patient with cc-TGA) isthmus-dependent macroreentrant AT (mean cycle length 306 ± 36 ms) was found (Table 2).

Group 2: A total of 13 AT (mean cycle length 336.2 ± 85.7 ms) were mapped in the 9 patients (Table 2). Tachycardia mechanism was IART (n = 10), localized reentry (n = 1) or focal activity (n = 2). Figure 2 shows 4 different examples of AT in this group. In 1 patient atrial fibrillation refractory to external cardioversion was induced after mapping by entrainment pacing.

Group 3: Peritricuspidal AT around the tricuspid valve was found in 5 patients. In 1 patient a localized reentry in the region below the right inferior pulmonary vein was detected.

TABLE 2

Procedural Data

Group No.	Pat. No	Mapping Catheter	EAM Guided by RMN	EAP	Type of AT	CL of AT (ms)	Ablation Catheter	Ablation Location	Follow-Up (Month)
Group 1	1	4 mm RMN solid	RA;LA	200; 100	IART	330	4 mm RMN solid, 8 mm solid	CTI	3
	2	4 mm RMN solid	RA	260	IART	260	4 mm RMN solid, 8 mm solid	CTI	11
	3	4 mm RMN solid	RA	140	IART	290	4 mm irrigated	CTI	3
	4	4 mm RMN solid	RA	270	IART	270	4 mm irrigated	CMI	22
	5	4 mm RMN solid	RA	100	IART	330	4 mm irrigated	CTI	3
	6	8 mm RMN solid	RA	100	IART	300	8 mm RMN solid	CTI	3
	7	8 mm RMN solid	RA;LA	200;110	IART	360	8 mm RMN solid, 4 mm irrigated	CTI	1
mean ± SD	-	-	-	181.4 ± 70.3; 105	-	305.7 ± 36.0	-	-	6.6 ± 7.5
Group 2	1	4 mm RMN solid	RA;LA	250;30	IART; AF	450	-	-	-
	2	4 mm RMN solid	RA	200	IART	310	4 mm irrigated	TR to atriotomy	25
	3	4 mm RMN solid	RA;LA	120;200	IART (2)	390;290	4 mm irrigated	CTI	3
	4	4 mm RMN solid	RA	204	IART (2); FAT	240;260;390	4mm irrigated	Between atriotomical scar	8
	5	4 mm RMN solid	RA;LA	144†	LRT	220	4 mm irrigated	TR to PA entrance	3
	6	4 mm RMN solid	RA	310	IART (2)	500;370	4 mm irrigated	CMI	3
	7	8 mm RMN solid	RA;CS	130;120	FAT	300	8 mm RMN solid	CS ostium	3
	8	8 mm RMN solid	RA	280	IART	390	4 mm irrigated	MR	3
	9	8 mm RMN solid	RA	310	IART	260	4 mm irrigated	TR, TR to atriotomy	3
mean ± SD	-	-	-	216.4 ± 75.1	-	336.2 ± 85.7	-	-	6.4 ± 7.7
Group 3	1	4 mm RMN solid	SVA; PVA	130;60	IART	250	4 mm RMN solid, 4 mm irrigated	TR to RPV; septal IVC	14
	2	4 mm RMN solid	SVA; PVA	150;230	IART	390	4 mm irrigated	TR to RPV; septal IVC	19
	3	4 mm RMN solid	SVA;PVA	370;130	IART	290	4 mm irrigated	TR to RPV	20
	4	4 mm RMN solid	SVA; PVA	200;70	IART	280	4 mm irrigated	TR to RPV; septal IVC	16
	5	4 mm RMN solid	SVA; PVA	170;100	IART	250	4 mm irrigated	TR to RPV; septal IVC	3
	6	8 mm RMN solid	SVA;PVA	120;80	LRT	370	8 mm RMN solid	TR to RPV	1
mean ± SD	-	-	-	190.0 ± 93; 111 ± 63	-	305.0 ± 60.6	-	-	12.2 ± 8.2

AF = atrial fibrillation; Ant. = anterior; AT = atrial tachycardia(s); CMI = cavomitral isthmus; CL = cycle length; CS = coronary sinus; CTI = cavotricuspid isthmus; EAM = electroanatomic map; EAP = eletroanatomic points; FAT = focal atrial tachycardia; IART = intraatrial reentry tachycardias; IVC = inferior vena cava; LA = left atrium; LRT = localized reentry tachycardia; MR = mitral ring; ms = millisecond(s); PA = pulmonary artery; RA = right atrium; RMN = remote magnetic navigation; RPV = right pulmonary vein; SD = standard deviation; Sep. = septal; SVA = systemic venous atrium; Pat = Patient; PVA = pulmonary venous atrium; TR = tricuspid ring. ∗AF was induced by the entrainment. †LA was reached retrograde through the single left ventricle. LA and RA were performed as 1 map.

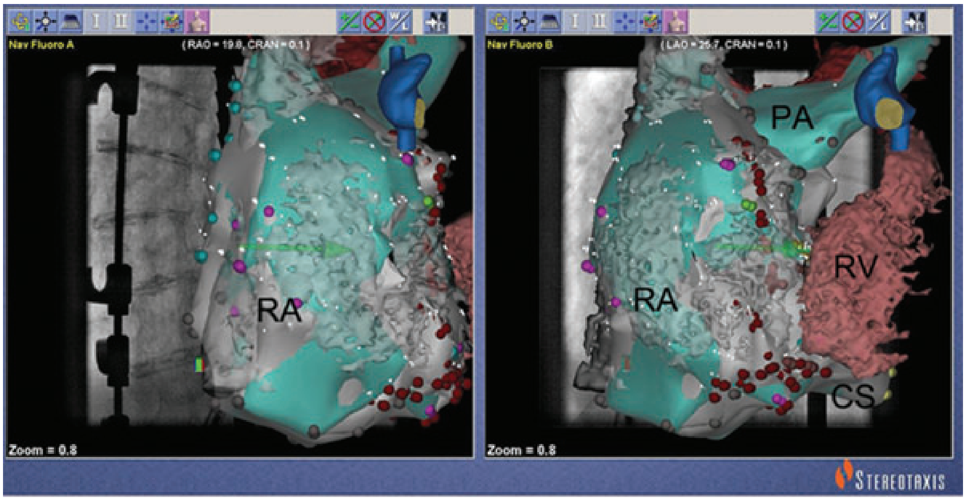

Figure 1. *Navigation fluoroscopy window of Stereotaxis in a right anterior oblique (RAO; left window) and left anterior oblique (LAO; right window) view. An example of a patient with tricuspid atresia after the Fontan operation is shown. Overlapping with a real-time fluoroscopy image, atrial anatomy (green) was created by the CartoRMT system combined with RMN and was merged with a segmented 3D-CT image (gray) of the patient. The two 3D anatomies fit each other in size and in shape. CS = coronary sinus; PA = pulmonary artery; RA = right atrium; RV = hypoplastic right ventricle.*

Procedure and Fluoroscopy Times and Learning Curve

The mapping procedural and mapping fluoroscopy time (mapping exposure time for patients), mapping exposure time for physicians are shown in Table 3.

Group 1: No clear learning curve was found regarding procedure time (Fig. 3A) and fluoroscopy time (Fig. 3B) for AT mapping.

Group 2: The first 2 patients had the longest fluoroscopy time. The mean fluoroscopy time of the group 2 was 10.7 ± 8.8 minutes. A distinct decrease of fluoroscopy time was noted between the patient 5 and 6 (Fig. 3B). The mean fluoroscopy time was reduced significantly in the last 4 patients (4.4 ± 1.3 minutes) compared to it in the first 5 patients (14.8 ± 7.4 minutes, $P < 0.05$). The mean exposure time for physicians was 2.9 ± 1.0 minutes.

Group 3: A trend toward shorter procedure time for mapping was noticed in this group (Fig. 3A). A significant decrease of mapping fluoroscopy time appeared after 4 patients (Fig. 3B). A decrease of fluoroscopy time for the retrograde access was noted from 12.0 ± 5.0 minutes to 1.5 ± 0.7 minutes between the first 4 patients and the last 2 patients. The mean exposure time for physicians was 14.9 ± 8.3 minutes. Mean fluoroscopy time for retrograde mapping of the PVA was 8.5 minutes.

Group 2 and 3: Combining the 15 patients of group 2 and group 3 with complex CHD, the mean mapping fluoroscopy time was 15.7 ± 13.5 minutes. A distinctive decrease of mapping fluoroscopy time was between the sixth and seventh patient. In the last 9 patients it was significantly shorter than it in the first 6 patients (6.4 ± 2.8 minutes vs 29.7 ± 10.5 minutes, $P < 0.0001$, Fig. 3C). The mean exposure time for physicians was 7.7 ± 7.9 minutes.

Fluoroscopy Times: Comparison of RMN with Conventional Tachycardia Mapping

Overall, no significant reduction of fluoroscopy time (including mapping und ablation) was found in the RMN patients compared to 27 postoperative patients with CHD with a conventional approach (21.8 ± 17.9 minutes vs 24.8 ± 11.6 minutes, $P = 0.52$). However, there was a learning curve using the new system, and in the last 9 patients studied the fluoroscopy time for RMN patients was significantly shorter (14.9 ± 10.2 minutes vs 24.8 ± 11.6 minutes, $P = 0.02$).

Ablation Results

Ablation of AT was successfully performed in 21 of 22 (97%) patients without complications. No ablation was performed in the patient from group 2 who had atrial fibrillation not amenable to electrical cardioversion. The solid tip RMN catheter was used as first-line ablation catheter in 7 patients (Table 2). The 4-mm tip catheter was used in 3 patients, the 8-mm tip catheter in 4 patients. Procedural and fluoroscopy times for ablation are shown in Table 3.

Group 1: In the first 2 patients, ablation attempts of the cavotricuspid isthmus using the 4-mm RMN catheter failed. The tachycardia was terminated and bidirectional block of the cavotricuspid isthmus was achieved using a conventional 8-mm tip catheter. In another 2 patients, an 8-mm tip RMN catheter achieved isthmus block in 1 patient and an additional conventional irrigated catheter was required in the other.

Group 2: An 8-mm tip RMN catheter successfully terminated a focal atrial tachycardia originating from a dilated CS. In the other 7 patients a conventional 4-mm irrigated tip catheter was used for IART and localized reentry tachycardia ablation.

Group 3: The 4-mm RMN catheter was used in the first patient. After ablation in both atria tachycardia did not terminate and a conventional 4-mm irrigated tip catheter was used for ablation. The conventional irrigated tip catheter was used for ablation the in first place in 4 patients, which terminated tachycardia in all patients. Split double potentials indicating a complete ablation line of block could be observed in these patients after ablation. An 8-mm tip catheter successfully terminated localized reentry in 1 patient.

Follow-Up

During follow-up (1–25 months; mean 8.1 ± 7.8 months; Table 2) 1 patient from group 2 had an AT recurrence in the

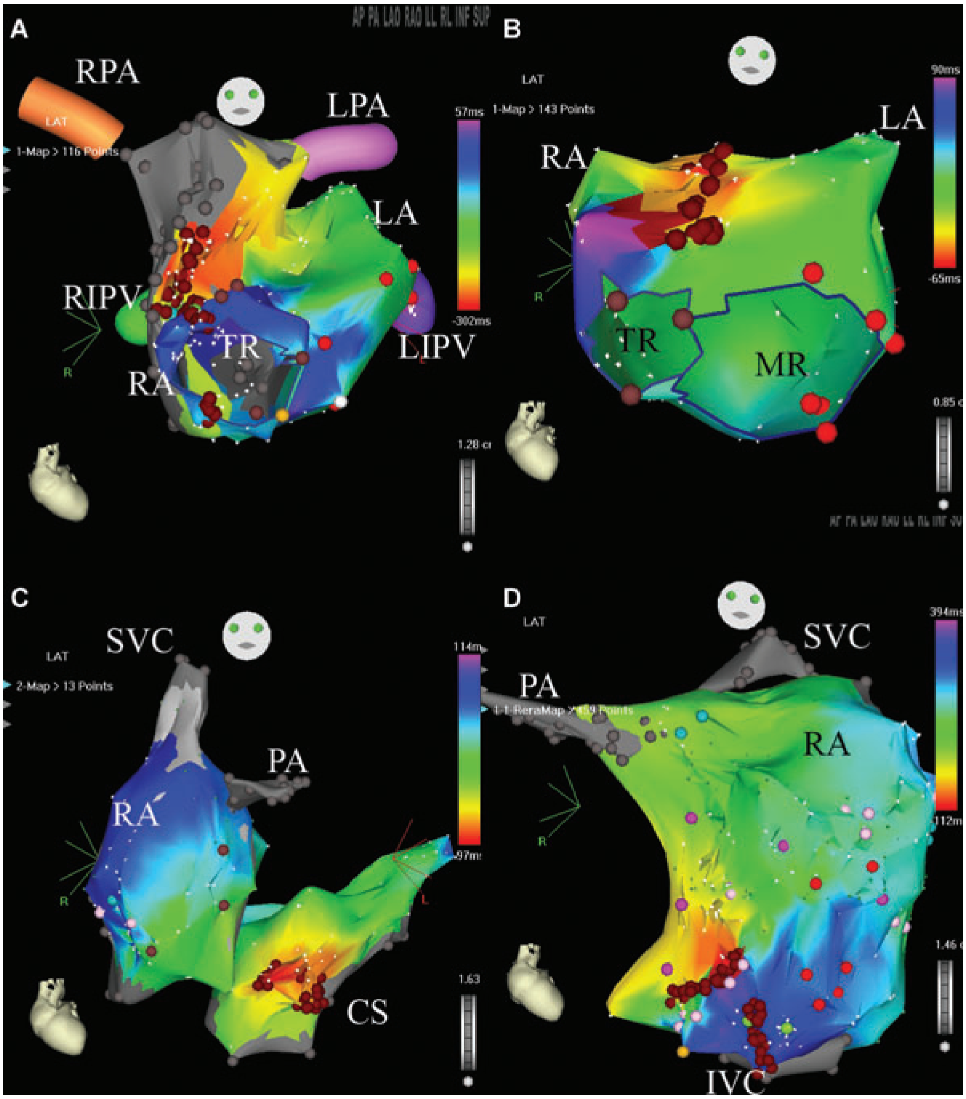

Figure 2. *Different tachycardia mechanisms in patients after the Fontan operation or total cavopulmonary connection (TCPC). A: Suture IART (cycle length (CL) 390 ms) in patient 3 with double inlet left ventricle (DILV). B: Localized reentry tachycardia (CL 220 ms) at the anterior wall of the RA in patient 5 with DILV. C: Focal atrial tachycardia (CL 300 ms) in patient 7 with double outlet right ventricle (DORV). The dilated CS was mapped additionally. D: Perimitral IART (CL 500 ms) in patient 6 with DORV, situs inversus and atrioventricular discordance. Radiofrequency lesions are visible as dark red points. Positive entrainment positions are shown as light green points and negative entrainment positions with pink points. The other points show the location of the tricuspid annulus (brown) and mitral annulus (red), the His bundle location (orange), an area of double potentials (blue), and an area of fragmented potential (light pink). Scar area (gray color) was set to 0.05 mV. CS = coronary sinus; IVC = inferior vena cava; LA = left atrium; LIPV = left inferior pulmonary vein; LPA = left pulmonary artery MR = mitral ring; PA = pulmonary artery; RA = right atrium, RIPV = right inferior pulmonary vein; RPA = right pulmonary artery; SVC = superior vena cava; TR = tricuspid ring.*

TABLE 3

Procedure Time and Fluoroscopy Exposure Time (for Patients and for Physicians) for Mapping

	Mapping Procedure			Ablation Procedure		Total Procedure Time	
	Duration (min)	**Fl. Time for Pat (min)**	**Fl. Time for physicians (min)**	**Duration Duration (min)**	**Fl Time (min)**	**Duration (min)**	**Fl Time (min)**
Group 1	91.3 ± 46.8	7.9 ± 4.7	nr	209.1 ± 104.3	15.6 ± 14.3	300.4 ± 129.8	24.9 ± 16.1
Group 2	145.5 ± 60.8	10.7 ± 8.8	2.9 ± 1.0	168.4 ± 96.4	5.3 ± 4.7	303 ± 92.9	14.6 ± 11.4
Group 3	214.2 ± 70.4	22.9 ± 16.5 (8.5 ± 6.7)*	14.9 ± 8.3	180 ± 110.2	8.7 ± 9.7	394.8 ± 135.4	31.5 ± 21.4
Group 2 and 3	169.3 ± 73.2	15.7 ± 13.5	7.7 ± 7.9	173.1 ± 98.4	6.6 ± 7.0	340 ± 116.8	21.8 ± 17.9
Total	144.5 ± 74.8	13.2 ± 11.9	8.0 ± 8.0	191.2 ± 96.6	9.7 ± 10.7	327.4 ± 119.4	22.9 ± 17.0

Pat = patient; Fl = fluoroscopy; min = minutes; nr = no record. *In group 3, the value in brackets means the fluoroscopy time for retrograde access to pulmonary venous atrium.

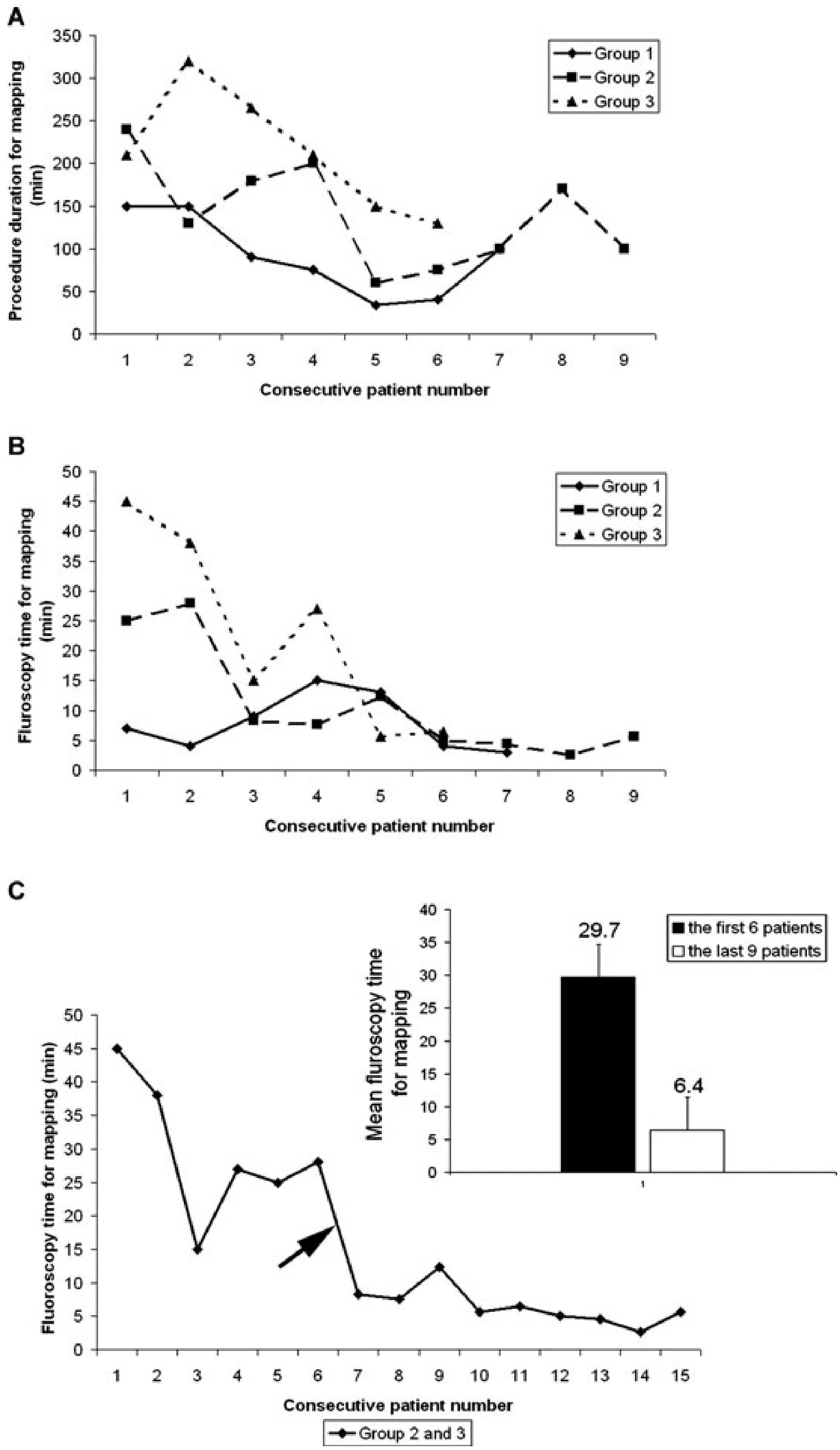

Figure 3. *Procedure duration for mapping and fluoroscopy time for mapping. A. Procedure duration for mapping is shown for the consecutive patients of the 3 groups. B: Fluoroscopy time for mapping in the consecutive patients of all 3 groups. There is a tendency of shortening fluoroscopy time in group 2 and group 3. C: Fluoroscopy time for mapping in the 15 consecutive patients of group 2 and 3 with complex congenital heart disease. Arrow shows a significant reduction of fluoroscopy time for mapping between the first 6 and the last 9 patients.*

first month after ablation and underwent a second ablation procedure. One patient from group 3 had recurrence of IART after 20 months free of tachycardia. A different AT form than during the first procedure was found and ablated. All other 20 patients were free of tachycardia during follow-up. There were no procedure-related complications. The patient with atrial fibrillation from group 2 continued to have atrial fibrillation.

Discussion

Remote magnetic navigation was used in atrial tachycardia mapping in a spectrum of patients with postoperative congenital heart disease ranging from "simple" lesions to complex disease. The main finding of this study is that in patients with complex congenital heart disease (patients after the Fontan/TCPC or Mustard/Senning procedure) a significant reduction of fluoroscopy time for mapping was achieved over time. In our opinion, this makes the technique an excellent alternative to the conventional approach.

RMN in Patients After Minor Atrial Surgery

In patients after "minor" atrial surgery no real learning curve or significant reduction of fluoroscopy time was achieved compared to a conventional approach.[15] This is probably due to the fact that atrial anatomy is almost unchanged and AT in this population is often due to "simple" cavotricuspid-dependent reentry with a clearly defined substrate. Thus, tachycardia diagnosis and treatment also by a conventional approach is relatively straightforward.

RMN in Patients with Complex Congenital Heart Disease

In the 15 patients after complex atrial surgery (Fontan-type operations/TCPC or Mustard/Senning procedures), a significant reduction of fluoroscopy time was noted. This reduction was reached after 6 patients, which corresponds to a rather fast learning curve despite complex anatomy.

Atrial tachycardia in patients after the Mustard or Senning procedure is often cavotricuspid dependent. The main problem is that the cavotricuspid isthmus is anatomically located in both surgically "created" new atria[17] and that especially the pulmonary venous atrium is difficult to access and explore due to complex shape. The main reduction of fluoroscopy time was accomplished by learning how to rapidly cross the aortic and tricuspid valve. Having reached the PVA with the RMN catheter, mapping in this compartment is relatively easy compared to the conventional approach where it is often impossible to reach all parts (especially the posterior of the PVA compartment with the pulmonary veins). In our study it took us 1.5 minutes to cross the aortic valve and tricuspid valve in the last 2 patients, which was much shorter than the first 4 patients (12 minutes). By using the retrograde approach, transseptal puncture of the atrial baffle is not necessary and possible complications of this technique are avoided.[19,20] Compared to a previous study[10] and our database including patients with conventional electroanatomic 3D mapping, the mean fluoroscopy time for mapping and ablation was reduced significantly by RMN after the initial learning curve.

In patients after the Fontan procedure, the most important improvement compared to the conventional approach is the better wall contact in all segments of those often extremely enlarged atria, which facilitates the creation of the electroanatomic map and the understanding of tachycardia mechanism. In these atria with fibrotic remodeled wall tissue good wall contact is crucial for the detection of low-amplitude fractionated potentials representing the slow conduction zone. Using the conventional approach catheter wall contact is controlled by frequent fluoroscopy, which adds to long fluoroscopy times. In the RMN system, once familiar with the "contact bar," good wall contact is relatively easy to achieve. There are very few reports showing fluoroscopy times in the Fontan group. Betts *et al.*[21] used the noncontact mapping system in 6 patients after the Fontan operation, with fluoroscopy times from 46 to 79.5 minutes (mean 58.8 minutes). Compared to that, our mean fluoroscopy time (for mapping and ablation) of 14.6 ± 11.4 minutes time was shorter.

In the study of Peichl *et al.*,[22] in 3 patients after Fontan/TCPC and 4 patients after the Senning/Mustard operation the mean fluoroscopy time for mapping and ablation of atrial tachycardia was 20 ± 15 minutes (under the guidance of intracardiac echocardiography). This is comparable to our fluoroscopy time for the whole procedure in complex CHD (21.8 ± 17.9 minutes). Schwagten *et al.*[13] reported about their experience using the 4-mm tip RMN catheter for mapping and the 8-mm tip catheter for ablation in 12 patients with CHD (including 5 post-Fontan and 1 post-Mustard) with a total fluoroscopy time of 12 to 85 minutes (median 39.4 minutes). This is longer than what we used in the combined RMN/conventional approach (from 5 to 71 minutes, mean 22.9 ± 17.0 minutes).

Catheter Ablation with the RMN Catheter

Catheter ablation with the 4-mm solid tip RMN catheter in complex anatomy did not turn out satisfactory. Using this solid tip RMN catheter, we could not terminate IART in the first 3 patients. In the first case of Mustard/Senning group, charring at the 4-mm tip RMN catheter was found after ablation with usual power settings. The 8-mm solid tip RMN was successful for ablation of focal tachycardia in 1 patient (group 2), isthmus ablation in 1 patient (group 1) and localized reentry ablation in 1 patient (group 3), but failed in another cavotricuspid isthmus ablation. Schwagten *et al.*[13] used the 8-mm solid tip RMN catheter for successful ablation in 11 of 12 patients; however, looking at previous studies using the conventional approach, the use of an irrigated tip catheter was the greatest predictor of ablation success[11] and more effective than solid tip catheters by creating deeper lesions in these thick-walled atria.[23,24] We used a conventional 4-mm irrigated tip catheter successfully in 16 patients.

Limitations

As patient numbers in this population are limited, we did not perform a randomized study to compare magnetic and manual mapping/ablation. This will require a multicenter approach.

We did not routinely use the nonirrigated RMN catheters for ablation as our first experiences were not promising. However, we considered adequate tachycardia mapping using RMN in combination with a 3D mapping system as the main challenge in the cases with complex congenital heart disease.[25] Our data show that fluoroscopy time for mapping in these cases play the major part in the whole procedure (73.3% in Fontan Group, 72.7% in Senning/Mustard Group, and 72.0% in the combined groups). As the irrigated tip catheter is now available, further studies are needed evaluating this catheter and its potential for a further reduction of fluoroscopy times.

Conclusion

Remote magnetic navigation in combination with a 3D mapping system provides a highly useful tool for mapping of atrial tachycardia in patients with complex congenital heart disease and leads to a significant reduction of fluoroscopy time for patients and physicians.

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