Noninvasive Characterization of Intra-Atrial Reentrant Tachyarrhythmias After Surgical Repair of Congenital Heart Diseases

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Background: Intra-atrial reentrant tachyarrhythmia (IART) after surgical repair for congenital heart diseases (CHD) has not been noninvasively characterized.

Methods and Results: The 28 patients after surgery for CHD and 14 patients without surgery were investigated by 87-lead body surface mapping (BSM), 12-lead electrocardiogram (ECG), 20-lead signal averaged ECG (SAECG) and endocardial electroanatomical mapping (CARTO) during clockwise (CW: n=9) or counterclockwise (CCW: n=5) incisional atrial tachycardia (Incision-AT), CCW (n=23) or CW (n=4) cavotricuspid isthmus-dependent atrial flutter (CTI-AFL), and double-loop reentry (n=4). On the BSM, the isopotential map pattern and its locus of the minimum potential could differentiate the reentrant circuits, and the activation map revealed the reentrant circuits, which were highly coincident with those obtained from CARTO. On the 12-lead ECG, negative-positive polarity in the inferior leads or a discordant pattern in the precordial leads was observed in all cases of CTI-AFL, but 3/14 Incision-AT, positive polarity in lead V₁ was observed in all cases of CCW, but none of CW CTI-AFL, positive polarity in lead I was observed in all cases of CW, but none of CCW Incision-AT.

Conclusions: Flutter-wave isopotential map and its activation sequence from the BSM predict reentrant circuits of IART after surgery for CHD. Flutter-wave polarity on the 12-lead ECG could differentiate these reentrant patterns. (Circ J 2009; 73: 451–460)

Key Words: Atrial flutter; Atrial tachycardia; Cardiac surgery; Electrocardiography; Mapping

Intra-atrial reentrant tachyarrhythmia (IART), such as incisional atrial tachycardia (Incision-AT) or cavotricuspid isthmus (CTI)-dependent atrial flutter (AFL), has emerged as a major long-term complication for patients after surgery for congenital heart diseases (CHD),^{1,2} and antiarrhythmic drugs are often ineffective. IART is amenable to treatment with radiofrequency (RF) catheter ablation,^{3,4} but successful ablation represents a considerable challenge because of the complex structural abnormalities. Recent electroanatomical endocardial mapping, which facilitates understanding of the complex endocardial contour, can demonstrate the reentrant circuits of IART^{5–10} and thus may improve the success rate of catheter ablation of IART. Noninvasive demonstration of the reentrant circuit of IART may assist in the selection of patients and the approach to RF catheter ablation of this tachycardia.

trocardiogram (ECG) during the common type of CTI-AFL has been described as having a “sawtooth” pattern with predominantly negative deflections in the inferior leads (II, III and aVF),¹¹ whereas that during the reverse common CTI-AFL is described as positive inferiorly.¹² However, the surface ECG characteristics of IART are still poorly described, in part because of the difficulty in defining the

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Flutter wave (Fl-wave) morphology on the 12-lead elec-

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Table 1. Patients Characteristics

Total (n)	42
Age (years)	51±16
Sex (M/F)	28/14
IART CL (ms)	257±49
Surgical lateral RA incision (–)	14
Surgical lateral RA incision (+)	28
ASD	13
VSD	2
TOF	4
Ebstein’s anomaly	1
TGA	1
TAPVR	2
MVP	3
Aortic stenosis	1
Sealy	1
12-lead ECG	
Common	25
Uncommon	20

IART, intra-atrial reentrant tachycardia; CL, cycle length; RA, right atrium; ASD, atrial septal defect; VSD, ventricular septal defect; TOF, tetralogy of Fallot; TGA, transposition of the great arteries; TAPVR, total anomalous pulmonary venous return; MVP, mitral valve prolapse; ECG, electrocardiogram.

Figure 1. Comparison of the signal-averaged electrocardiogram (SAECG) and lead II of the standard 12-lead electrocardiogram (ECG) during atrial flutter. The QRS complex was used as a fiducial marker for the SAEKG. Flutter-wave onset was defined as the onset of high-frequency and low-amplitude potentials (f wave) recorded by SAEKG (A). The baseline (=0 mV) of each ECG lead was defined as potential level of the onset during tachycardia (B).

onset of FI-wave during IART from the 12-lead ECG.

In this study, we noninvasively determined the onset of FI-wave by signal averaged ECG (SAECG), and evaluated whether or not the reentrant patterns could be distinguished on the surface ECG.

Methods

Patients

The study population consisted of 42 consecutive adult patients (28 men, 14 women, mean age 51 ± 16 years) who had a history of recurrent IART for 3.9 ± 4.5 years. All patients were referred for catheter ablation of IART at the National Cardiovascular Center, Suita, Japan, between 1999 and 2005. Retrospective analysis of atrial activity on the 12-lead ECG and 87-lead body surface mapping (BSM) were performed after characterization of the reentrant circuits by endocardial electroanatomical mapping. Of the total, 28 patients had a single right atrial (RA) incision after corrective surgery for CHD (Table 1) and the remaining 14 did not. All antiarrhythmic drugs were discontinued at least 5 drug half-lives before the study, but β -blockers, digitalis, angiotensin-converting enzyme inhibitors and other cardio-active drugs were continued in all patients.

BSM and Signal-Averaged ECG

All subjects were breathing quietly while supine during the recording. BSM and SAEKG were recorded during IART with a VCM-3000 (Fukuda Denshi Co, Tokyo, Japan) before the electrophysiological study and catheter ablation. BSM recording techniques have been described in detail previously.^{13–16} In brief, 87 leads are arranged in a lattice (13×7 matrix) covering the entire thorax, with 59 leads located on the anterior chest (rows A–I) and 28 leads on the back (rows J–M). The 87 unipolar electrograms with the Wilson's central terminal as a reference, a standard 12-lead ECG, and Frank X, Y, and Z scalar leads are recorded simul-

taneously during IART. The SAEKG is recorded from 16-unipolar leads on the anterior chest and modified bipolar Frank X, Y, and Z leads during IART, which is similar to that recently reported for P-wave SAEKG.^{17,18} In brief, the QRS complex was used as a trigger for SAEKG, and each signal-averaged lead was amplified, digitalized at 1.0 kHz, and filtered forward with a band pass of 40–300 Hz; 200 beats were averaged with a noise level of less than $0.3 \mu\text{V}$. The filtered signals for the X, Y and Z leads were combined into a special magnitude $(X^2 + Y^2 + Z^2)^{1/2}$ that allowed the detection of high-frequency voltage in any lead.¹⁶

Measurement of FI-Wave

The FI-wave onset was defined as the deflection of high-frequency and low-amplitude potentials (persistent level $>0.3 \mu\text{V}$) recorded by the SAEKG, and we defined the onset potential level as the isopotential line (=0 mV) in each ECG lead (Figure 1A). After revision of the baseline potential, FI-wave polarity (positive or negative, the absolute value ≥ 0.05 mV) during IART were examined in the 12-lead ECG.

FI-wave isopotential maps from 87-lead BSM recordings during IART were obtained at 10 ms intervals, and the minimum and maximum potentials (the absolute value ≥ 0.05 mV) of the isopotential map were computed in each period. Activation time during IART was defined as the interval between the onset and the minimum first derivative (dV/dt) point of FI-wave (Figure 1B). Thus, we computed the FI-wave activation map from 87-lead BSM during tachycardia, and compared it with the endocardial activation patterns.

Electroanatomical Mapping and Catheter Ablation

After written informed consent was given, all patients underwent electrophysiological testing while in a fasting, unsedated state. Endocardial activation mapping was performed using CARTO® (Biosense, Tirat, HaCarmel, Israel) as described previously.^{5–7,10} The 12-lead ECG and endocar-

Table 2. Reentrant Patterns of IART

Reentry type	CTI-AFL		I-AT		Double-loop	
	CCW	CW	CW	CCW	CCW CTI-AFL +CW I-AT	CW CTI-AFL +CCW I-AT
Surgery (+)	11	2	9	5	2	2
Surgery (–)	12	2	–	–	–	–
Total	23	4	9	5	2	2

CTI-AFL, cavotricuspid isthmus-dependent atrial flutter; I-AT, incisional atrial tachycardia; CCW, counterclockwise; CW, clockwise. Other abbreviation see in Table 1.

Figure 2. Representative 12-lead electrocardiograms (ECGs) and magnified flutter-waves (I, II, III, V₁, V₃ and V₅ leads) during counterclockwise (CCW) cavotricuspid isthmus-dependent atrial flutter (CTI-AFL) (A), clockwise (CW) CTI-AFL (B), CW incisional atrial tachycardia (Incision-AT) (C), CCW Incision-AT (D), double-loop reentry consisting of CCW CTI-AFL with CW Incision-AT (E), and double-loop reentry consisting of CW CTI-AFL with CCW Incision-AT (F). Dashed line in the magnified ECGs shows the baseline.

dial electrograms were simultaneously displayed on a computer monitor using a Bard Electrophysiology recording system (C. R. Bard Inc, Billerica, MA, USA). All bipolar endocardial electrograms were filtered between a band pass of 30 and 500 Hz and recorded with the 12-lead ECG. Data were stored on a computer disk recorder for off-line analysis.

The RF application was delivered after the electroana-

tomical mapping, and the procedural endpoint for CTI-AFL was complete bi-directional CTI block,¹⁹ whereas that for Incision-AT was conduction block across the channel verified by pacing close to the ablation line and by demonstration of marked delay and reversal in the direction of activation on the opposite side of the ablation line. Programmed stimulation was repeated to induce the same or another IART.

Figure 3. Representative flutter-wave isopotential maps during counterclockwise (CCW) cavotricuspid isthmus-dependent atrial flutter (CTI-AFL) (**A**), clockwise (CW) CTI-AFL (**B**), CW incisional atrial tachycardia (Incision-AT) (**C**), CCW Incision-AT (**D**), double-loop reentry consisting of CCW CTI-AFL with CW Incision-AT (**E**), and double-loop reentry consisting of CW CTI-AFL with CCW Incision-AT (**F**). Isopotential contours of positive and negative voltages are indicated by white and gray areas, respectively, on the map. Isopotential lines are drawn at intervals of 0.05 mV.

Figure 4. Superimposed minimum potentials during counterclockwise (CCW: closed circle) and clockwise (CW: open circle) cavotricuspid isthmus-dependent atrial flutter (CTI-AFL) (A), and CCW (closed triangle) and CW (open triangle) incisional atrial tachycardia (Incision-AT) (B). The minimum potentials for the first 60 ms in CCW CTI-AFL appeared mostly at the left lower chest area (E–K, 1–3; dashed box at 10–60 ms) and rotated CCW in the whole chest area in CCW CTI-AFL, which could differentiate CCW CTI-AFL from the other reentrant patterns. The minimum potentials in CW CTI-AFL were observed primarily in the central anterior chest and remained there (C–E, 4–6; dashed box at 70–120 ms), which could differentiate CW CTI-AFL from the other reentrant patterns. The minimum potentials for the first 60 ms appeared mostly at the right chest (L, M, A–D) in CW Incision-AT, but at the left anterior chest (E–I) in CCW CTI-AFL, and rotated CW or CCW exclusively in the right chest, which could differentiate between CW and CCW Incision-AT.

Statistical Analysis

Parametric data are expressed as mean $\pm$ SD. The ECG parameters in different groups were compared by Student's unpaired t-test. Percentages were compared by Pearson χ^2 test or Fisher's exact test, depending on the frequencies. A value of $P < 0.05$ was considered significant.

Results

Classification of Reentrant Pattern of AT/AFL

In total, 46 IART were recorded in 42 patients. We defined clockwise (CW) and counterclockwise (CCW) Incision-AT as viewing the RA free wall from the right anterior oblique view, and CCW and CW CTI-AFL as viewing the tricuspid annulus from the left anterior oblique view. We excluded IART of left atrial origin ($n=1$), so endocardial electroanatomical mapping could classify the activation pattern during IART into 4 macro-reentrant patterns as follows: CCW CTI-AFL ($n=23$), CW CTI-AFL ($n=4$), CW Incision-AT ($n=9$) and CCW Incision-AT ($n=5$). Moreover, 4 patients had double-loop reentry consisting of CCW CTI-AFL + CW Incision-AT ($n=2$) and CW CTI-AFL + CCW Incision-AT ($n=2$) (Table 2). The representative 12-lead ECG and enlarged FI-wave during these reentrant patterns are shown in Figure 2.

Characteristics of BSM During IART

CCW and CW CTI-AFL The representative FI-wave isopotential map during CCW CTI-AFL (Figure 3A) shows that the minimum potentials appeared at the lower left anterior chest (F–I, 1–3), remained there during the first 40 ms and moved upward to the middle anterior chest (E and F, 7) via the left lateral chest (H–K) after 40–100 ms. The minimum potential returned to the lower site via the right anterior chest (A–E) at 100–220 ms. In the terminal 220–280 ms, the distribution of the isopotential map did not show the maximum and minimum sites because of the low amplitude of the signal (electrically silent). In contrast, during CW CTI-AFL (Figure 3B), the minimum potentials initiated at the central anterior chest (D4), moved slightly upward (D5, D6) and remained there until 170 ms. The minimum potential further moved downward via the left lateral chest (F–J) at 170–210 ms. The terminal 210–240 ms was electrically silent. Moreover, the initial polarities of D5 ($\approx V_1$ lead) and H4 ($\approx V_5$ lead) in the CCW CTI-AFL were positive and negative, respectively, whereas those in the CW CTI-AFL were negative and positive, respectively; thus the polarity between V_1 and V_5 leads was discordant during CTI-AFL (Figures 2A, B).

CW and CCW Incision-AT The representative FI-wave isopotential map during CW Incision-AT (Figure 3C) shows

Figure 5. Representative flutter wave activation maps from body surface mapping (Upper panels) and right atrial endocardial activation maps (Lower panels) during counterclockwise (CCW) cavotricuspid isthmus-dependent atrial flutter (CTI-AFL) (A), clockwise (CW) CTI-AFL (B), CW incisional atrial tachycardia (Incision-AT) (C), CCW Incision-AT (D), double-loop reentry consisting of CCW CTI-AFL with CW Incision-AT (E), and double-loop reentry consisting of CW CTI-AFL with CCW Incision-AT (F). The activation map from BSM during each pattern of these intra-atrial reentrant tachycardias was similar to the endocardial map. TA, tricuspid annulus; SVC, superior vena cava; IVC, inferior vena cava; AP, antero-posterior view; PA, postero-anterior view; RAO, right anterior oblique view; LAO, left anterior oblique view.

that the minimum potentials appeared on the right lower anterior or posterior chest area (B3 or M3, respectively) and remained there during the first 80 ms and moved to the middle upper anterior chest area (D7 or D6) via the right posterior chest (80–160 ms). The potential remained on the middle upper chest at 160–240 ms. In contrast, during CCW Incision-AT (**Figure 3D**), the minimum potentials initiated at the central anterior chest (E 4–6) and remained during the first 90 ms and moved to the middle upper anterior chest (E7 or F7) (90–210 ms). The potential then moved to the right upper anterior chest (B6) (210–280 ms). Moreover, the initial polarities of D5 ($\approx V_1$ lead) and H4 ($\approx V_5$ lead) in the CW Incision-AT were both positive, whereas those in the CCW Incision-AT were both negative, indicating concordant polarity in V_1 and V_5 leads during Incision-AT (**Figures 2C,D**).

Double-Loop Reentry The representative FI-wave iso-

potential map during CW Incision-AT combined with CCW CTI-AFL (**Figure 3E**) shows that the minimum potential appeared on both right and left lower anterior chest during the first 70 ms and moved separately from the lower to the upper anterior chest area via the right posterior chest and left anterior chest. In contrast, that of CCW Incision-AT combined with CW CTI-AFL (**Figure 3F**) shows that the minimum potential initially at the central anterior chest (E5), moving to the upper anterior chest and then splitting right and left. The right division moved with CCW rotation on the right anterior chest, whereas the left moved with CW rotation on the left anterior or posterior chest. The other FI-wave isopotential map patterns during the double-loop reentries also showed the similar patterns as in **Figures 3E** or **F**, combining CTI-AFL with Incision-AT.

Differentiation Between IART Superimposed minimum potentials in CCW and CW CTI-AFL, and CCW and CW

Table 3. The 12-Lead ECG Characteristics and Type of Reentry Circuit

			Sns (%)	Spc (%)	PPV (%)	NPV (%)	Acc (%)
CTI-AFL vs Incision-AT							
A: negative-to-positive in II and III	Yes	No					
CTI-AFL (n=27)	26	1	96	86	93	92	93
I-AT (n=14)	2	12					
B: discordant between V ₁ and V ₅							
CTI-AFL (n=27)	25	2	93	86	93	86	90
I-AT (n=14)	2	12					
A or B							
CTI-AFL (n=27)	27	0	100	79	90	100	93
I-AT (n=14)	3	11					
CTI-AFL (n=27)							
I lead potential	(+)	Flat or (–)					
CW (n=4)	4	0	100	87	57	100	89
CCW (n=23)	3	20					
V ₁ lead initial potential							
CCW (n=23)	23	0	100	100	100	100	100
CW (n=4)	0	4					
Incision-AT (n=14)							
I lead potential	(+)	Flat or (–)					
CW (n=9)	9	0	100	100	100	100	100
CCW (n=5)	0	5					

Sns, sensitivity; Spc, specificity; PPV, positive predictive value; NPV, negative predictive value; Acc, diagnostic accuracy; (+), positive polarity; (–), negative polarity. Other abbreviations see in Tables 1, 2.

Incisional-AT are shown in **Figures 4A** and **B**, respectively. The minimum potentials for the first 60 ms in CCW CTI-AFL appeared mostly in the left lower chest area (E–K, 1–3; dashed box at 10–60 ms in **Figure 4A**) and can differentiate CCW CTI-AFL from CW CTI-AFL, CW Incision-AT and CCW Incision-AT (78/106 vs 2/15, 0/42 and 4/20; $P < 0.01$, respectively). Moreover, the minimum potentials rotated CCW in the whole chest area in CCW CTI-AFL, whereas those in CW CTI-AFL were observed primarily in the central anterior chest. Thus, the minimum potential in the central chest (C–E, 4–6; dashed box at 70–120 ms in **Figure 4A**) can differentiate CW CTI-AFL from CCW CTI-AFL, CCW Incision-AT, and CW Incision-AT (10/10 vs 4/94, 7/28, 7/27; $P < 0.01$, respectively). Finally, the minimum potentials for the first 60 ms appeared mostly in the right chest area (L, M, A–D at 10–60 ms in **Figure 4B**) in CW Incision-AT, but rarely in CCW incisional-AT (37/42 vs 4/20; $P < 0.05$), and the minimum potentials rotated CW or CCW exclusively in the right chest. Thus, their initial site and locus are useful for differentiating between CW and CCW Incision-AT.

Body Surface and Endocardial Activation Maps

During CCW CTI-AFL (**Figure 5A**), the FI-wave began at the left lower chest, propagated CCW around the left anterior chest (E2–G6), indicating the region of the tricuspid annulus, and terminated at the right lower anterior chest. In contrast, during CW CTI-AFL (**Figure 5B**), the FI-wave began at the middle of the right anterior chest, propagated CW around the left anterior chest and terminated at the left lower anterior chest. During CW Incision-AT (**Figure 5C**), the FI-wave at the lower right axilla propagated CW around the right axillary line, consistent with a RA incision, and terminated at the right lower anterior chest. In contrast, during CCW Incision-AT (**Figure 5D**), the FI-wave was initiated at the middle of the right anterior chest, and propagated CCW within the right chest area, and terminated at the right axillary line. Therefore, similar to the representative activation maps shown in **Figures 5A–D**, all of the body

surface activation maps in CTI-AFL or Incision-AT coincided with the endocardial electroanatomical maps generated by CARTO®.

In the case of double-loop (CW Incision-AT + CCW CTI-AFL) reentry (**Figure 5E**), the earliest activation was observed in the lower anterior chest, propagated as a figure-of-eight, resembling a combination of **Figures 5A** and **C**, and the latest activation was observed in the upper anterior chest. In contrast, during another double reentry (**Figure 5F**; reverse type for **Figure 5E**), the earliest activation was observed in the upper anterior chest, propagated in a figure-of-eight pattern, resembling a combination of the maps in **Figures 5B** and **D** with the latest activation in the lower anterior chest. Both FI-wave activation patterns were consistent with the endocardial activation patterns by CARTO®. Therefore, the activation map from BSM could noninvasively reveal the complex reentrant circuits during Incision-AT, CTI-AFL and double-loop reentry.

Characteristics of 12-Lead ECG During IART

The following relationships between the reentrant patterns and the 12-lead ECG morphology were deduced from the results of body surface isopotential mapping of IART. **Table 3** summarizes the estimation indexes with which the 12-lead ECG differentiates the type of reentry circuits of CTI-AFL and Incision-AT, and between CCW and CW rotation of each atrial tachyarrhythmia.

Differentiation Between CTI-AFL and Incision-AT As shown in **Figures 2A, B**, FI-waves with negative-to-positive polarity in the inferior leads were commonly observed in CTI-AFL, whereas this polarity was rarely observed in Incision-AT (26/27 CTI-AFL vs 2/14 Incision-AT, $P < 0.05$; **Figures 2C, D**). FI-waves with both positive and negative (discordant) polarities in the precordial leads were commonly observed in CTI-AFL (**Figures 2A, B**), whereas a discordant polarity was rarely observed in Incision-AT (**Figures 2C, D**) (25/27 CTI-AFL vs 2/14 Incision-AT, $P < 0.05$). Moreover, the combination of negative-to-positive polarity in the inferior leads and a discordant pattern in the

precordial leads accurately differentiates CTI-AFL and Incision-AT (27/27 CTI-AFL vs 3/14 Incision-AT; $P < 0.05$). Therefore, FI-wave polarities in the inferior leads and in the precordial leads are informative for differentiating between CTI-AFL and Incision-AT.

Differentiation Between CCW and CW CTI-AFL FI-wave with positive polarity in lead I was observed in all cases of CW CTI-AFL (**Figure 2B**), but was rare in CCW CTI-AFL (**Figure 2A**) (4/4 CW vs 3/23 CCW CTI-AFL; $P < 0.05$). Moreover, FI-wave with initial positive polarity in lead V₁ was observed in all cases of CCW CTI-AFL (**Figure 2A**), but not in any of CW CTI-AFL (**Figure 2B**) (24/24 CCW vs 0/4 CW CTI-AFL; $P < 0.05$). Therefore, FI-waves polarity in lead I and initial polarity in lead V₁ differentiate between CCW and CW rotation of CTI-AFL.

Differentiation Between CCW and CW Incision-AT FI-wave with positive polarity in I lead was observed in all cases of CW Incision-AT (**Figure 2C**), but not in CCW Incision-AT (**Figure 2D**) (9/9 CW vs 0/5 CCW Incision-AT; $P < 0.05$). Therefore, FI-waves polarity in lead I differentiates between CW and CCW rotation of Incision-AT.

Double-Loop Reentry As shown in **Figure 2E**, FI-waves with negative-to-positive polarity in the inferior leads were observed in most (3 of 4) of the cases of double-loop reentry. However; discordant polarity in the precordial leads, which characterizes CTI-AFL, was not observed in these cases. On the other hand, as shown in **Figure 2F**, the latter double-loop has a positive polarity in the inferior leads, but discordant polarity in the precordial leads. Therefore, double-loops have ECG characteristics of both CTI-AFL and Incision-AT.

RF Catheter Ablation

RF ablation procedure was successful in 24 (92%) of 26 cases of CTI-AFL at the tricuspid annulus (TA)-inferior vena cava (IVC) isthmus, in 13 (93%) of 14 cases of incisional-AT at the channel between the RA incision and IVC ($n=9$), between the RA incision scars ($n=3$) or between the RA incision and TA ($n=1$). Moreover, during double-loop reentry, 3 of 4 cases of IART were successfully ablated at both the RA incision-IVC channel and the TA-IVC isthmus.

Discussion

FI-Wave Onset During IART

IART have an isthmus of the reentrant circuit⁵ and the onset of these arrhythmias is defined as the time just after the excitation wave exits the isthmus, but is difficult to detect on the surface ECG. Similar to previous studies,^{17,18} we noninvasively detected the onset of the FI-wave by the beginning of the high-frequency and low-amplitude potentials on the SAECG (**Figure 1**). As we compared the body surface activation map with the endocardial activation map, the onset of CCW or CW CTI-AFL coincided with the propagation of the excitation wave front from the CTI into the RA septum (**Figure 5A**) or free wall (**Figure 5B**), respectively. On the other hand, the onset of Incision-AT coincided with the propagation of the excitation wave front through the isthmus between the inferior margin of the incision and IVC (**Figures 5C,D**). Therefore, the onset of FI-wave as defined by the SAECG coincided with that of the endocardial activation map.

BSM Characteristics During IART

BSM has been useful for localizing the origin of focal

AT²⁰ and ventricular tachycardia.¹⁵ Moreover, BSM activation patterns during CTI-AFL correlate with endocardial mapping.²¹ In the present study, the isopotential map from BSM during CCW (**Figure 3A**) and CW (**Figure 3B**) CTI-AFL were similar to those previously reported²¹ except for the selection of the onset and baseline potential of the FI-wave. The minimum potentials for the first 60 ms in CCW CTI-AFL appeared mainly at the left lower anterior chest, whereas those in CW CTI-AFL appeared at the center of the anterior chest (**Figure 4A**), corresponding to the area of the coronary sinus ostium and lower RA free wall, respectively.²⁰ Thereafter, the BSM pattern of CTI-AFL was completely reversed with CCW or CW rotation for the first half of the flutter cycle length, consistent with biphasic polarity in the inferior leads of ECG and discordant polarity of leads V₁ and V₅ in CTI-AFL.

On the other hand, the BSM characteristics of Incision-AT have not been well characterized. In this study, the minimum potentials for the first 60 ms in CW Incision-AT appeared at the right lateral chest area, whereas those in CCW Incision-AT appeared at the central anterior chest (**Figure 4B**), and both were largely confined to the right chest area (L, M, A-E), corresponding to the RA free wall.²⁰ Thereafter, the minimum potentials were shifted upward with CW or CCW rotation, and the isopotential map pattern was also rotated CW or CCW, but the polarity in the area of precordial ECG leads remained exclusively positive or negative during CW or CCW Incision-AT, respectively. The concordant polarity of the V₁ and V₅ leads of the ECG suggests activation of the atria along the V₁₋₅ axis during Incision-AT.

Moreover, the activation maps obtained from BSM during IART were similar to those from endocardial mapping by CARTO (**Figures 5A-D**). Therefore, the isopotential map or activation map from BSM specifically localized the reentrant circuit of Incision-AT or CTI-AFL in patients after surgery for CHD.

ECG Characteristics During IART

The 12-lead ECG of common or CCW CTI-AFL is well known as having a "sawtooth" pattern of the FI-wave with predominantly negative deflection in the inferior leads,¹¹ whereas that of CW CTI-AFL is predominantly positive. Although variable FI-wave morphologies have been reported in CCW and CW CTI-AFL,²² those after surgery for CHD have never been systematically described. Moreover, previous studies did not adjust the onset and baseline potential of the FI-wave, thus there are few data that correlate IART circuits with the surface ECG pattern.

In this study, after revision of the baseline potential of the FI-wave, (1) negative-to-positive bipolarity in the inferior leads of the ECG and (2) discordant polarity between the V₁ and V₅ leads distinguished CTI-AFL from Incision-AT. These ECG characteristics of CTI-AFL are the result of macro-reentry around the tricuspid annulus preceding passive left atrial conduction. On the other hand, during Incision-AT, the reentrant circuit is small and limited to the RA free wall that the wave front collides with at the RA septum (**Figures 5C,D**), resulting in no negative-to-positive bipolarity in the inferior leads of the ECG. Therefore, the most significant difference between CTI-AFL and Incision-AT in the surface ECG is determined by whether the reentry circuit includes the atrial septum or the left atrium. These findings are consistent with previous clinical²³⁻²⁵ and experimental²⁶ studies showing that septal and/or left atrial

activation produces the characteristic FI-wave morphology in the inferior and precordial leads.

Moreover, polarity in lead I of the ECG is informative for differentiating between CW and CCW CTI-AFL, and CW and CCW Incision-AT, because positive polarity in lead I is the result of propagation from the right to left atrium. Therefore, the 12-lead ECG localization algorithm should differentiate not only the reentrant pattern (Incision-AT and CTI-AFL), but also the rotational (CW vs CCW) pattern.

Characteristics During Double-Loop Reentry

Akar et al reported atrial tachyarrhythmias in a cohort of post-atriotomy patients, which demonstrated that 37% of patients had Incision-AT alone and 19% had CTI-AFL alone, but 44% of the patients actually had coexistence of both atrial tachyarrhythmias.² Verma et al also reported 31% of patients who had a single RA incisional scar had both Incision-AT and CTI-AFL.⁷ Another study showed that double-loop atrial reentry was present in only 8% of patients with surgical repair for CHD.²⁷ In the present study, 14 of 31 cases of (45%) IART after surgical repair for CHD were Incision-AT alone, 42% were CTI-AFL, and 13% were double-loop reentry. Moreover, some cases of Incision-AT demonstrated CTI-AFL activation patterns in the inferior and precordial leads of the ECG because of the passive CTI-AFL-like conduction of the septum and/or left atrium or the double-loop reentry. Thus, Incision-AT activation patterns masked by the CTI-AFL patterns make it difficult to differentiate double-loop reentry from CTI-AFL on the 12-lead ECG. However, the 87-lead BSM patterns clearly differentiate these complex reentrant patterns.

Clinical Implications

Atrial tachyarrhythmias commonly occur late after surgical correction of CHD, and most of them are considered to be reentry in the RA around the surgical incision and/or tricuspid annulus.^{1-7,27} RF catheter ablation has been used successfully to treat IART^{3,4} and the use of electroanatomical mapping (CARTO®) has improved our understanding and definition of AT circuits.⁵⁻⁷ However, it has been difficult to noninvasively predict these complex reentrant circuits from the surface ECG. Using the ECG characteristics based on BSM during IART, we could accurately differentiate Incision-AT and CTI-AFL and the pattern of rotation in each circuit. This study was a retrospective analysis of 12-lead and BSM electrocardiograms after characterization of the reentrant circuits by endocardial mapping, so it is difficult to quantitatively estimate how this non-invasive characterization can help in invasive mapping and/or RF ablation procedure. However, the use of BSM and standard ECG analysis of these tachycardias may shorten the procedure time and help define the optimal ablation sites.

Study Limitations

First, BSM reflects both right and left atrial electrical activity; however, our endocardial map by CARTO® showed only RA activation during IART. Therefore, our isopotential and isochronal maps from BSM did not directly correlate with the endocardial maps. Moreover, this study did not include lower-loop or upper-loop reentry AFL, reentry around an atrial septal patch, or left AFL. Thus, we cannot differentiate these reentrant arrhythmias from IART. Second, some of the cases of IART after surgery for CHD had double-loop reentry, in which FI-wave morphology is masked by the CTI-AFL pattern; therefore, the reentrant

patterns are difficult to infer from the 12-lead ECG. Third, we used SAECG to examine the onset of the IART, but this method cannot be used in subjects in whom the P-R interval is obviously irregular during IART or obvious slow conduction exists outside the reentrant circuit. Thus, we excluded cases in which persistent noise still remained more than 0.3 μ V after 200-beat averaging of ECG. Moreover, this noninvasive approach is limited in IART with 1:1 or 2:1 atrial-ventricular conduction.

Conclusion

This study revealed characteristics of the standard 12-lead ECG and 87-lead BSM during IART in patients after surgery for CHD. The onset during IART was determined from the SAECG, and after revision of the baseline potential, the FI-wave isopotential map and its activation map from the 87-lead BSM noninvasively localized the reentrant circuits of Incision-AT and/or CTI-AFL. Moreover, the FI-wave polarity during CTI-AFL was not simply negative or positive, but negative-to-positive in the inferior leads of ECG. Therefore, the 12-lead ECG characteristics could differentiate the reentrant patterns of Incision-AT and CTI-AFL, together with their rotation patterns.

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