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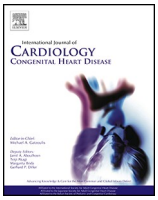

Atrial tachycardia in patients with repaired tetralogy of Fallot; its characteristics and catheter ablation outcome

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ABSTRACT

Background: Patients with repaired tetralogy of Fallot (TOF) now live longer. However, dysrhythmia becomes prevalent in adults with repaired TOF, especially atrial tachyarrhythmia.
Objective: To identify the characteristics of patients who develop atrial tachycardia (AT) and the mechanism of the clinical AT and the induced one.
Method: Seventy-seven patients with repaired TOF were enrolled. The patients were divided into two groups (AT and non-AT). Clinical and electrophysiologic data were studied.
Results: The mean age was 34 years. Twenty-three patients had AT (30 %). In AT group, the left ventricular ejection fraction was lower (58 ± 6 vs 62 ± 5; $P = 0.011$), the right and left atrial area (cm^2) was larger (29 ± 13 vs 15 ± 5; $P < 0.001$, and 19 ± 3 vs 16 ± 4; $P < 0.001$, respectively), and the right ventricular S′ wave (cm/s) was smaller (8 ± 2 vs 10 ± 3; $P = 0.029$).
Patients with AT underwent catheter ablation, and 32 AT were ablated. The mechanism of AT was intra-atrial reentrant tachycardia in 14 AT (44 %), cavotricuspid isthmus-dependent in 12 AT (37 %), and focal activity in the remaining 6 AT (19 %). An important finding was that after the first AT was ablated, another AT was induced in 7 patients. The mechanism was focal in about half of them, in contrast to the first ablated AT, where the focal mechanism was the least common. After a median follow-up of 37 months, four patients had AT recurrence.
Conclusion: The patients with AT had biventricular dysfunction and bi-atrial dilatation. Aggressive induction and ablation of the induced AT may reduce the future AT recurrence.

1. Introduction

The long-term survival after tetralogy of Fallot (TOF) repair is promising, and about 95 % of patients survive 25 years after surgery [1]. However, longevity is often complicated by dysrhythmias. After about 10–15 years post-repair, there is a steady increase in tachyarrhythmia, such as atrial tachycardia (AT), atrial fibrillation, and ventricular tachycardia [2]. Of particular importance is AT, with an estimated prevalence of approximately 20 % [2,3]. The mechanism of AT is usually cavotricuspid isthmus-dependent atrial flutter, intra-atrial reentrant tachycardia, and focal activity which is the least prevalent [4]. The number of surgical procedures, right atrial (RA) enlargement, and severe right-sided regurgitant valves were found to be risk factors for the development of AT [2,4]. Also, AT has been shown to impact the quality of life negatively, increasing morbidity and mortality compared to patients without AT [5]. Consequently, AT was recently included in a risk score system that predicts mortality in repaired TOF patients [6].

In addition to improving the patient's symptoms, maintaining sinus rhythm has been shown to improve ventricular function and delay the need for valve surgery in adult congenital heart disease (ACHD) [7].

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Thus, effective treatment is warranted to suppress AT and decrease the unfavorable consequences. The antiarrhythmic medication is less effective at restoring sinus rhythm in those populations and is often associated with significant adverse effects [8]. Moreover, given the relatively younger age at presentation, prolonged use is anticipated. Therefore, drug therapy becomes less appealing. The alternative is catheter ablation, a more plausible and effective strategy, especially with the recent advances in the 3D mapping systems, which allow better identification of the critical substrate and arrhythmia mechanism [4,8]. However, despite all the improvements in managing arrhythmia in ACHD, AT is still not fully, as some patients experienced AT recurrence after successful suppression of the clinical AT.

In this study, we investigated patients with repaired TOF who developed AT, comparing their characteristics to the patients without AT, and assessing the effectiveness of catheter ablation. We also explored the clinical and echocardiographic associations with AT development, as well as the mechanism underlying the clinical AT, and the induced one after successful ablation, which has not been elucidated well previously.

2. Method

Seventy-seven patients with repaired TOF followed at the University of Tsukuba Hospital were included in the study from 2004 to 2022. Twenty-three patients had a history of sustained AT, and all underwent catheter ablation. Clinical, electrocardiographic, and transthoracic echocardiographic data are obtained and compared between patients who suffered from AT and patients without AT. Echocardiographic parameters were taken while the patients were in sinus rhythm, usually during the first visit after catheter ablation. The assessment of the right heart was performed according to the American Society of Echocardiography [9]. As a part of the right ventricular (RV) evaluation, several parameters were assessed as RV fractional area change percentage (FAC %), tricuspid annular plane systolic excursion (TAPSE) using M-mode, S' wave which is the peak systolic velocity by Pulsed tissue Doppler [10]. Restrictive physiology was also evaluated, defined as end-diastolic antegrade flow in the pulmonary artery as detected by transthoracic echocardiography, which is the reverse of the normal flow pattern and signifies RV diastolic dysfunction [11]. All the visits with a comprehensive data set, including the clinical, laboratory, electrocardiographic, and echocardiographic data, were stored electronically and can be retrieved and reviewed easily. Each patient had multiple follow-up visits. The ethical committee approved the study (R03-312), and all patients gave informed consent by Opt-out method.

2.1. Electrophysiological mapping and ablation procedure

All the procedures were done under conscious sedation. The procedures were guided by 3D electroanatomic mappings such as Carto 3 (Biosense Webster, Diamond Bar, CA), EnSite system (Precision, Abbott, Abbott Park, IL), or Rhythmia system (Boston Scientific, Natick, MA). Standard catheters were placed via transvenous approaches, a quadripolar catheter was placed in the right ventricular apex, a duodecapolar deflectable catheter (BeeAT; Japan Lifeline) was placed within the coronary sinus (CS), and a decapolar deflectable catheter was placed at His Bundle region. Another deflectable decapolar catheter was positioned around the tricuspid valve annulus (TA) when the spontaneous or induced AT was suggestive of atrial flutter (AFL). If the patient had AT at the time of catheter introduction into the heart chambers, then activation mapping was pursued, while voltage mapping was created when the patient was in sinus rhythm. Induction was done after termination of AT by ablation or after completion of substrate mapping by incremental atrial pacing and programmed atrial extra-stimulation (up to three extra-stimuli) from different atrial sites with or without isoproterenol infusion.

The mechanism of AT was determined by high-density 3D electroanatomic mapping and entrainment mapping from different atrial sites and fell into three categories, which were intra-atrial reentrant tachycardia (IART) revolving around RA atriotomy scar from the previous surgery, cavotricuspid isthmus (CTI)-dependent AFL, and focal AT. The ablation strategy was performed according to the AT mechanism. For CTI-dependent AFL, CTI ablation was done, and the bidirectional block line was achieved and confirmed by differential atrial pacing or activation mapping during pacing from proximal CS. For IART, a block line was created from the scar region to the anatomical structure, which was usually to the inferior vena cava after the termination of AT by ablation. For the focal AT, the earliest local potential was targeted. After AT termination, several additional lesions were applied in a coin-like configuration. In all cases, the ablation was done using open-irrigated radiofrequency catheters, closely monitoring the impedance drop.

2.2. Follow-up

All patients were followed regularly at the adult congenital heart disease clinic at the University of Tsukuba Hospital. The patients who underwent catheter ablation were followed at regular intervals. The first visit was typically after one month of catheter ablation with subsequent visits scheduled at three-month intervals in the first year and then annually if the patient remains asymptomatic. Otherwise, urgent consultation is arranged as soon as symptoms develop. The AT recurrence was determined by the patient's symptoms, 12-lead ECG, and Holter study. Repeated ablation was decided according to the patient's clinical status in case of AT recurrence. Four patients in the AT group were using amiodarone, and discontinued after the catheter ablation.

2.3. Statistical analysis

Continuous variables are expressed as mean ± SD or median and interquartile range (IQR) depending on the normal or abnormal distribution of the data. Categorial variables are expressed as numbers and percentages. The clinical, echocardiographic, and electrocardiographic data between the patients who developed AT and those without were compared using the unpaired *t*-test, Mann-Whitney test, or chi-square test as appropriate. The association between various factors and AT development was assessed using logistic regression analysis. A two-sided P value ≤ 0.05 was considered statistically significant. The analysis was performed using SPSS (version 26, SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Patients' characteristics

The baseline characteristics are shown in Table 1. The mean age was 34 ± 12 years. Forty-two (55 %) patients were females. The patients with AT were older than those without AT (40 ± 12 vs 31 ± 10 years; $P = 0.001$). BNP level was higher in the AT group [96 (40–116) vs 35 (16–60); $P < 0.001$]. Patients who needed three or more surgeries were significantly higher in the AT group [(9 (39 %) vs 8 (15 %); P = 0.019]. The patients with AT had more coexistent atrial fibrillation than those without AT [7 (30 %) vs 2 (4 %); $P < 0.001$.

3.2. Echocardiographic parameters

The details are shown in Table 2. The transthoracic echocardiography was performed during sinus rhythm. The left ventricular (LV) ejection fraction (EF) was lower in patients who suffered from AT compared with patients with no history of AT (58 ± 6 vs 62 ± 5; $P = 0.011$). The right atrial (RA) and left atrial (LA) areas were significantly larger in patients with AT compared to those without (29 ± 13 vs 15 ± 5; $P < 0.001$, 19 ± 3 vs 16 ± 4; $P < 0.001$, respectively). The RA/LA ratio between those who developed AT and those without AT differed

Table 1
Baseline characteristics.

	Total, n = 77	AT, n = 23	Non-AT, n = 54	*P* value
Age	34 ± 12	40 ± 12	31 ± 10	0.001
Female	42 (55 %)	12 (52 %)	30 (57 %)	0.785
BMI	22.8 ± 4	23.6 ± 4	22.5 ± 4	0.266
Hypertension	3 (4 %)	0 (0 %)	3 (6 %)	0.259
CIED	8 (11 %)	3 (14 %)	5 (9 %)	0.573
Palliative surgery	34 (44 %)	13 (57 %)	21 (39 %)	0.154
TAP	36 (47 %)	14 (61 %)	22 (41 %)	0.105
No. of surgeries ≥3	17 (22 %)	9 (39 %)	8 (15 %)	0.019
S.creatinine (mg/dl)	0.7 ± 0.2	0.7 ± 0.1	0.7 ± 0.2	0.520
eGFR (ml/min)	101 ± 2	96 ± 17	103 ± 21	0.178
Hb (g/dl)	13.9 ± 2	13.8 ± 1	13.9 ± 2	0.761
AST (u/l)	23 ± 10	24 ± 6	22 ± 11	0.555
ALT (u/l)	22 ± 16	25 ± 18	21 ± 14	0.233
BNP (pg/ml) m (IQR)	44 (20–79)	96 (40–116)	35 (16–60)	<0.001
Atrial fibrillation	9 (12 %)	7 (30 %)	2 (4 %)	<0.001
NSVT	10 (13 %)	5 (9 %)	5 (22 %)	0.136
VT	1 (1 %)	0 (0 %)	1 (2 %)	0.511
Amiodarone	4 (5 %)	4 (17 %)	0 (0 %)	0.002
Beta-blocker	24 (31 %)	14 (61 %)	10 (19 %)	<0.001

ALT = alanine aminotransferase, AST = aspartate aminotransferase, BMI = body mass index, BNP= B-type natriuretic peptide, CIED = cutaneous implantable electronic device, eGFR = estimated glomerular filtration rate, Hb = hemoglobin, NSVT = non-sustained ventricular tachycardia, TAP = transannular patch, and VT = ventricular tachycardia.

Table 2
Echocardiographic characteristics.

	Total, n = 77	AT, n = 23	Non-AT, n = 54	*P* value
LV EF%	61 ± 6	58 ± 6	62 ± 5	0.011
EDV (ml)	104 ± 3	105 ± 3	104 ± 3	0.822
ESV (ml)	42 ± 2	45 ± 17	40 ± 14	0.198
LAVI (ml/m^2)	28 ± 9	33 ± 9	26 ± 9	0.003
RVSP (mmHg)	39 ± 16	43 ± 16	37 ± 17	0.128
RA area (cm^2)	19 ± 10.5	29 ± 13	15 ± 5	<0.001
LA area (cm^2)	17 ± 4	19. ± 3	16 ± 4	<0.001
RA/LA ratio	1 ± 0.4	1.5 ± 0.6	1 ± 0.2	<0.001
RVEDVi	148 ± 24	148 ± 30	148 ± 22	0.896
RVEDA (cm^2)	31 ± 8	31. ± 6	31 ± 8	0.861
RVESA (cm^2)	19 ± 6	18 ± 5	19 ± 6	0.683
RV FAC%	40 ± 7	40 ± 7	40 ± 7	0.736
PA V (cm/s)	235 ± 80	244 ± 89	231 ± 77	0.541
RAP >8 mmHg	20 (27 %)	11 (48 %)	9 (17 %)	0.006
PR (moderate-severe)	41 (56 %)	12 (55 %)	29 (57 %)	0.855
TR (moderate-severe)	3 (4 %)	2 (9 %)	1 (2 %)	0.155
Restrictive physiology	13 (17 %)	8 (35 %)	5 (9 %)	0.007
TAPSE (mm)	17 ± 4	16 ± 4	18 ± 4	0.072
RV S′ wave (cm/s)	9.2 ± 3	8 ± 2	10 ± 3	0.029

EDV = end-diastolic volume, ESV = end-systolic volume, LA = left atrium, LAVI = left atrial volume index, LVEF = left ventricular ejection fraction, PA V = pulmonary artery velocity, RAP = right atrial pressure, PR = pulmonary regurgitation, RA = right atrium, RAP = right atrial pressure, RVEDA = right ventricular end-diastolic area, RV FAC = right ventricular fractional area change, RVESA = right ventricular end-systolic area, TAPSE = tricuspid annular plane systolic excursion, and TR = tricuspid regurgitation.

(1.5 vs 1; *P*= <0.001). Not only the area, the number of patients with right atrial pressure (RAP) over 8 mmHg was also higher in the AT group compared with the non-AT group [11 (48 %) vs 9 (17 %); *P* = 0.006]. Although RV FAC% and TAPSE were not statistically different between the AT and non-AT groups, the S' wave was significantly lower in the AT group (8 ± 2 vs. 10 ± 3; *P* = 0.029). The prevalence of restrictive physiology was higher in AT patients than in patients without AT [8 (35 %) vs 5 (9 %); *P* = 0.007]. Moderate-severe tricuspid regurgitation (TR) and pulmonary regurgitation (PR) were not statistically different between the AT and non-AT groups.

3.3. Electrocardiographic parameters

The detailed characteristics are given in Supplemental Table 1. The analysis was conducted on 76 patients as one patient without AT had complete atrioventricular block with no intrinsic ventricular rhythm. The QRS and PR duration were 132 ± 30 ms and 170 ± 37 ms, respectively. The QRS and PR duration and the QRS axis were not statistically different between the two groups, although patients with AT tended to have narrower QRS and longer PR intervals (128 ± 30 ms vs 134 ± 30 ms; *P* = 0.435, 177 ± 43 ms vs 168 ± 35 ms; *P* = 0.387, respectively). The pattern of the right bundle branch block (RBBB), complete or incomplete, was also not statistically different between the two groups. Six patients (one in the AT group and five in the non-AT group) had no ventricular conduction abnormality.

3.4. Factors associated with at development

The detailed analysis of logistic regression is shown in Supplemental Table 2.

For simplicity, we categorized the RA/LA ratio as >1 or ≤1. In univariable analysis, the age was associated with AT (OR = 1.07, 95 % CI = 1.023–1.154, P = 0.003). RA/LA ratio was also strongly associated with AT development (OR = 16.889, 95 % CI = 4.367–65.323. P= <0.001). AT was also associated with LV EF%, RAP> 8 mmHg, RV S' wave, and restrictive physiology. However, the association of AT with age, RA/LA ratio, and restrictive physiology remained significant in multivariable model analysis.

3.5. Atrial tachycardia and its mechanism

All patients with AT underwent catheter ablation, in which 32 AT were targeted. The mechanism of AT was determined by high-density 3D electroanatomic mapping and entrainment mapping from different atrial sites. In all patients, the AT was mapped and ablated in RA. In general, IART was the mechanism underlying 14 ATs (44 %), CTI-dependent AFL in 12 ATs (37 %), while the focal mechanism was only implicated in 6 ATs (19 %). Only one AT was ablated in sixteen patients, and no other AT could be induced despite aggressive induction with intravenous isoproterenol infusion and atrial pacing from different atrial sites. In seven patients, another AT was induced and targeted (two ATs in five patients and three ATs in two patients) in the same session. In the five patients where two ATs were ablated, the first ablated AT was AFL, and the second was focal in two patients. In comparison, the sequence was IART and CTI-dependent AFL in the other two patients. In one patient, the first AT was IART, and the second was focal.

In the two patients in whom 3 AT were ablated. The mechanism was IART, IART, and focal in one patient and focal, IART, and CTI-dependent AFL in the other (Fig. 1). The site of focal AT was at the low voltage area in the posterolateral RA wall corresponding to the atriotomy scar in 4 patients. However, in one patient, the focal AT was near the CS ostium, and in the second patient, it was at the septal site of the CTI blockline. In all patients, bipolar low voltage area was recorded in RA. All patients underwent CTI ablation regardless of the mechanism and the number of treated AT. Fig. 2 shows a patient with IART that was successfully mapped and ablated at the posterolateral wall of the RA. Supplemental Fig. 1 shows a patient with CTI-dependent AFL that was also successfully terminated with CTI ablation. However, after CTI ablation and bidirectional block were confirmed, another AT was induced. The mechanism was focal, and it was successfully mapped at the posterolateral wall of the RA. After AT suppression by ablation, no more AT could be induced (Supplemental Fig. 2).

3.6. Catheter ablation outcome

The median follow-up period was 37 months (IQR Q1-Q3: 21.5–125). 83 % of patients (19 out of 23) maintained sinus rhythm

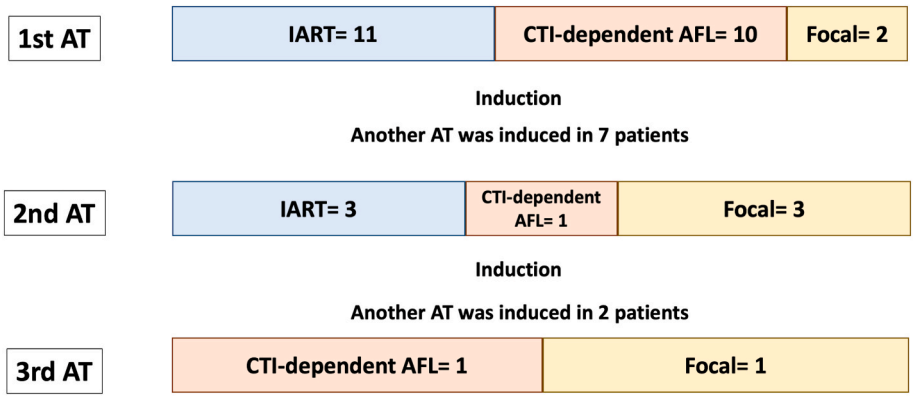

Fig. 1. A Diagram showing the mechanism and the number of treated atrial tachycardia.
The diagram shows that the clinical AT that was ablated was either IART (n = 11), CTI-dependent AFL (n = 10), or focal (n = 2). However, after induction by atrial pacing and extra-stimulation with intravenous isoproterenol infusion, another AT was induced in seven patients. The mechanism of the induced AT was IART (n = 3), CTI-dependent AFL (n = 1), and focal (n = 3). As shown, the prevalence of focal AT increased. Furthermore, another AT was induced in two patients. CTI-dependent AFL was in one patient, and focal AT was in the other patient. N.B. All the ablated ATs were in the same session.
AT = atrial tachycardia, IART = interatrial reentrant AT, CTI = cavotricuspid isthmus, and AFL = atrial flutter.

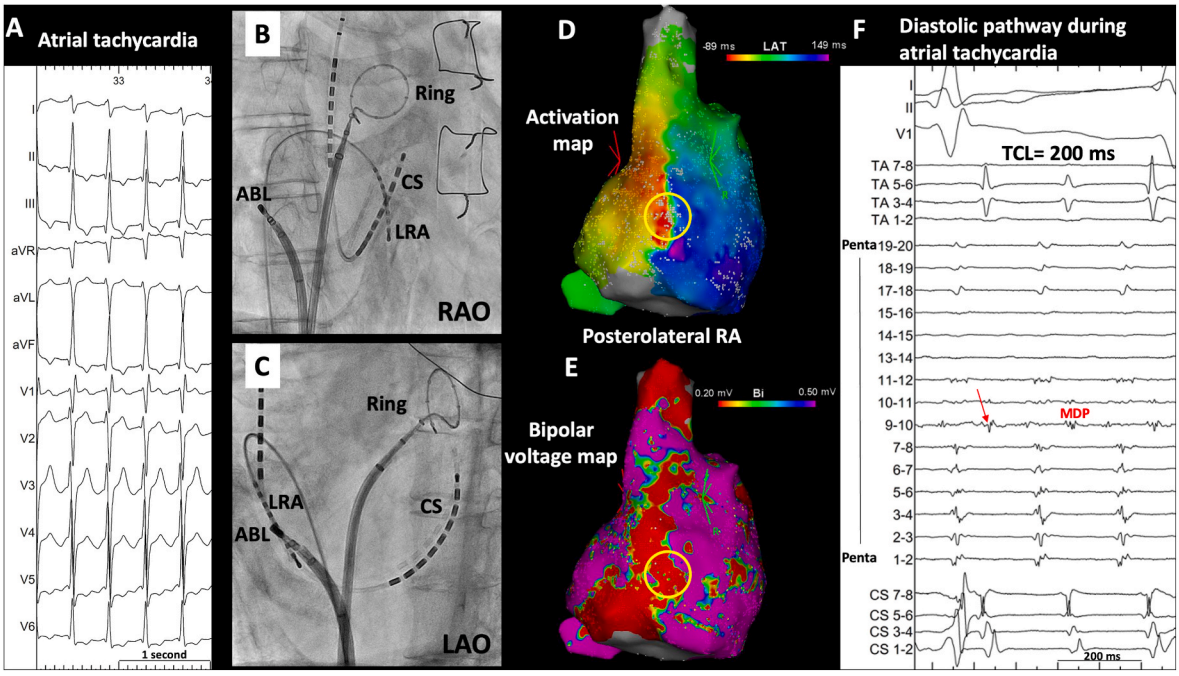

Fig. 2. Interatrial reentrant atrial tachycardia in a patient with repaired tetralogy of Fallot.
A: Shows 12-lead ECG of atrial tachycardia. **B and C:** Fluoroscopic images of RAO and LAO, respectively, show the ablation catheter at the termination site. A duodecapolar catheter was also visible and placed into the coronary sinus, and a decapolar catheter was placed at the lateral right atrial wall. The ring catheter was placed in LSPV as the patient underwent pulmonary vein isolation for documented atrial fibrillation. **D:** shows the activation map of atrial tachycardia using a 5-spline multi-polar mapping catheter (PentaRay®, Biosense Webster), revealing the critical component of the AT circuit at the posterolateral wall of the right atrium. **E:** shows the bipolar voltage map during AT, revealing that the AT isthmus was located within a low voltage zone at the surgical scar of the previous surgery. **F:** shows the PentaRay® catheter was at the critical path of the AT, revealing the mid-diastolic potential. Ablation of that site terminated the AT.
ABL = ablation catheter, CS = coronary sinus, LRA = lateral right atrium, MDP = mid-diastolic potential, Penta = PentaRay® catheter, RA = right atrium, and TCL = tachycardia cycle length.

during the follow-up period. Four patients had AT recurrence. Two of them underwent repeated catheter ablation. In one patient, the targeted AT in the index procedure was IART, and no AT could be induced at the end of the procedure. However, after eight months, he had AT recurrence. In the second session, three ATs were treated (IART, CTI-dependent AFL, and focal at RA posterolateral wall). The other patient underwent CTI ablation for CTI-dependent AFL via the right subclavian vein approach as the patient had bilateral femoral vein occlusion at the index procedure. After five months, the patient had AT recurrence. The mechanism of the recurrent AT was focal near the right atrial appendage. Three sessions were done after that. However, the AT could not be suppressed by endocardial catheter ablation, and eventually, the patient underwent surgical epicardial cryoablation at the time of pulmonary valve replacement, and the patient was free of AT during the follow-up period, as reported previously [12].

4. Discussion

The main findings of this study are that first, bi-atrial dilatation was associated with AT in repaired TOF patients. Additionally, the patients with AT had an RA/LA ratio of 1.5 compared to 1 in patients without AT. Second, the patients with AT had higher RA pressure and RV restrictive physiology, indicating that diastolic impairment, not only systolic dysfunction, plays a role in AT genesis. Third, catheter ablation is an effective treatment strategy for AT in those patients, and most patients maintained sinus rhythm during the follow-up. Aggressive induction by atrial pacing and extra-stimulation with isoproterenol infusion after ablation of the clinical AT could induce another AT in some patients mostly due to focal mechanism, which will likely manifest as AT recurrence. This strategy could explain the low recurrence rate in this study population, as we also targeted the induced one.

4.1. The echocardiographic characteristics in patients with AT

Repaired TOF patients who developed AT exhibited several distinctive echocardiographic characteristics, primarily related to the right side of the heart. RA dilatation has been consistently associated with AT in multiple studies [2,4,13]. The RA/LA ratio, which represents the proportion of the RA area to the LA area showed a significant association with AT in repaired TOF patients and served as an independent predictor for AT development. The RA area was found to be 1.5 times the LA area. In the general population, the RA/LA ratio was reported to be 0.81 ± 0.15 [14]. This parameter has been studied in various conditions such as in patients with atrial septal defect and acute pulmonary embolism, but not in patients with TOF [14,15]. Careful monitoring of this parameter in repaired TOF patients without AT could potentially serve as a warning signal for AT development. However, this finding requires validation through studies involving larger populations of repaired TOF.

Another important finding was the higher prevalence of restrictive physiology in patients with AT compared to those without AT, which signifies RV diastolic dysfunction and may further exacerbate RA dilatation [11]. In addition to RA/LA ratio, repaired TOF patients with AT also demonstrated impaired RV systolic function, evidenced by reduced S' wave. In the current study, age and restrictive physiology were associated with AT development alongside the high RA/LA ratio.

4.2. Characteristics of atrial tachycardia and ablation outcome

The mechanism of AT in repaired TOF patients generally falls into three categories: IART around a previous RA surgical scar, CTI-dependent AFL, and focal activity. In our study population, IRAT was the most common mechanism (44 % of the ablated ATs), followed by CTI-dependent AFL (37 %), and the least common was the focal mechanism (19 %). However, previous studies have shown that CTI-dependent AFL was the most common mechanism followed in frequency by IART [16–18]. The reason behind this discrepancy is unclear, possibly related to the different populations included or variations in the surgical techniques used in the corrective procedure. Another finding that is not surprising is that the origin of AT was almost exclusively from the RA, regardless of the AT mechanism, whether focal or reentry.

An important observation is that in seven patients another AT was induced after ablation of the clinical one. The AT mechanism was focal in about half of these cases. AT due to focal mechanism was recently observed in patients with ACHD who had AT recurrence after an index procedure during ten years of follow-up [19]. None of our patients in whom focal AT was induced and ablated had AT recurrence during the follow-up period. This approach may expose the potential substrate later responsible for AT recurrence, particularly due to the focal mechanism. In our study, 83 % of patients (19 out of 23) maintained sinus rhythm during the follow-up period. This recurrence rate was comparable to a multi-center study (32 (84 %) of 38 patients maintained sinus rhythm during a follow-up period of 45 ± 24 months) in which pacing and pharmacological induction were used after the termination of the clinical AT [16]. This was also evident in a recent study of ACHD patients, where those who had induced AT by programmed extra-stimulation after ablation of the first AT, which was also ablated in the same session, had better AT-free survival compared to patients in whom induction was not attempted after ablation of the presenting AT [20]. Thus, using induction protocol after ablation of the clinical AT and targeting the induced one, especially of the focal mechanism, could decrease the recurrence rate in the future. Another key factor accounting for the low recurrence rate is the improved mapping techniques using multipolar mapping catheters, allowing better delineation of the critical substrate responsible for the AT mechanism [21]. The recurrence rate is generally lower in repaired TOF patients than in complex ACHD patients such as Fontan patients. A recent report showed that Fontan patients exhibited a higher recurrence rate than other ACHD patients [13 (65 %) of 20 patients vs 49 (40 %) of 120 patients]. Furthermore, the time to AT recurrence was notably shorter in Fontan patients (12.5 months vs 50.1 months) [22].

In addition to AT, AF becomes more common in growing ACHD patients, and its prevalence increases with age. Catheter ablation is also increasingly used as a treatment option. Notably, some patients undergo AT and AF procedures in the same session. Careful planning and using multiple imaging modalities are crucial to address the anatomical complexity and enhance safety [23].

A constellation of several factors accounts for arrhythmogenicity in repaired TOF patients. Scars from previous surgeries may create anatomical barriers suitable for the reentrant circuit. Furthermore, adverse atrial remodeling, such as dilatation and hypertrophy, together with the hemodynamic disturbance resulting from regurgitant valves such as pulmonary and tricuspid regurgitation, facilitates the development of macro-reentrant AT, whether around the structural obstacles such as the valve annulus or around iatrogenic scar of the previous atriotomy [24]. However, the valve lesions in our patients were not associated with an increased risk of AT development. At the cellular level, the electrical and ionic channel abnormalities resulting from anatomical and hemodynamic alterations could create regions with abnormal automaticity or facilitate triggered activity-mediated arrhythmias, which manifest as focal AT [8,20]. Regardless of the AT mechanism, catheter ablation was effective in suppressing AT.

5. Limitations

This study has several limitations. First, it is a single-center retrospective study with inherent limitations. Second, the number of patients was not large enough to confidently extrapolate our findings to a larger population. However, despite these limitations, this study followed the patients longitudinally and further characterized the mechanism of AT, not only the clinical AT but also the induced one that was targeted in the same session. This approach may increase the chance of AT-free survival.

6. Conclusion

Biventricular dysfunction and enlarged bi-atrial size were associated with AT development in patients with repaired TOF. Furthermore, the RA/LA ratio was simple to calculate and a powerful predictor of AT development. Catheter ablation was an effective treatment modality for AT in repaired TOF patients, especially with the use of advanced electroanatomic mapping systems, which facilitate delineating the critical path of the AT circuit. An important implication of this study was that focal AT was inducible in certain patients after termination of the clinical AT, which may manifest as AT recurrence later. Thus, targeting the induced AT could be a prudent decision.

CRediT authorship contribution statement

Qasim J. Naeemah: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Miyako Igarashi:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization. **Noor K. Albakaa:** Writing – review & editing, Validation, Supervision, Investigation, Formal analysis. **Yuichi Hanaki:** Validation, Supervision. **Noboru Ichihara:** Validation, Supervision. **Chihiro Ota:** Validation, Supervision. **Akira Kimata:** Validation, Supervision. **Kojiro Ogawa:** Validation, Supervision. **Naoto Kawamatsu:** Validation, Supervision. **Tomoko Machino:** Validation, Supervision.**Yuki Komatsu:** Investigation. **Hiro Yamasaki:** Supervision, Software. **Akihiko Nogami:** Validation, Supervision. **Masaki Ieda:** Validation, Supervision. **Tomoko Ishizu:** Validation, Supervision.

Disclosures

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijcchd.2024.100558.

References

[1] Smith CA, McCracken C, Thomas AS, et al. Long-term outcomes of tetralogy of Fallot: a study from the pediatric cardiac care consortium. JAMA Cardiol 2019;4(1):34–41.
[2] Khairy P, Aboulhosn J, Gurvitz MZ, et al. Arrhythmia burden in adults with surgically repaired tetralogy of Fallot: a multi-institutional study. Circulation 2010;122(9):868–75.
[3] Avila P, Oliver JM, Gallego P, et al. Natural history and clinical predictors of atrial tachycardia in adults with congenital heart disease. Circ Arrhythmia Electrophysiol. 2017;10(9):1–11.
[4] Krieger EV, Zeppenfeld K, DeWitt ES, et al. American heart association adults with congenital heart disease committee of the council on lifelong congenital heart disease and heart health in the young and council on clinical cardiology. Arrhythmias in repaired tetralogy of Fallot: a scientific statement from the American heart association. Circ Arrhythmia Electrophysiol 2022;15:e000084.
[5] Khairy P, Van Hare GF, Balaji S, et al. PACES/HRS expert consensus statement on the recognition and management of arrhythmias in adult congenital heart disease: developed in partnership between the pediatric and congenital electrophysiology society (PACES) and the heart rhythm society (HRS). Endorsed by the governing bodies of PACES, HRS, the American college of cardiology (ACC), the American heart association (AHA), the European heart rhythm association (EHRA), the Canadian heart rhythm society (CHRS), and the international society for adult congenital heart disease (ISACHD). Heart Rhythm 2014;11:e102–65.
[6] Ghonim S, Gatzoulis MA, Ernst S, et al. Predicting survival in repaired tetralogy of Fallot. JACC Cardiovasc Imaging 2022;15:257–68.
[7] Zielonka B, Kim YY, Supple GE, et al. Improvement in ventricular function with rhythm control of atrial arrhythmias may delay the need for atrioventricular valve surgery in adults with congenital heart disease. Congenit Heart Dis 2019;14:931–8.
[8] Bessiere F, Mondesert B, Chaix MA, Khairy P. Arrhythmias in adults with congenital heart disease. Heart Rhythm O^2 2021;2:744–53.
[9] Rudski LG, Lai WW, Afilalo J, et al. Guidelines for the echocardiographic assessment of the right heart in adults: a report from the American society of echocardiography. J Am Soc Echocardiogr 2010;23:685–713.
[10] Lang RM, Badano LP, Mor-Avi V, et al. Recommendations for cardiac chamber quantification by echocardiography in adults: an update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. Eur Heart J Cardiovasc Imaging 2015;16:233–70.
[11] Rathore KS, Agrawal SK, Kapoor A. Restrictive physiology in tetralogy of Fallot: exercise and arrhythmogenesis. Asian Cardiovasc Thorac Ann 2006;14:279–83.
[12] Naeemah QJ, Igarashi M, Matsubara M, Ishizu T, Nogami A, Ieda M. Successful surgical epicardial cryoablation of refractory atrial tachycardia in a patient with repaired tetralogy of Fallot after multiple failed endocardial ablations. Heart Rhythm Case Reports 2023;9:190–4.
[13] Bonello B, Kempny A, Uebing A, et al. Right atrial area and ventricular outflow tract akinetic length predict sustained tachyarrhythmia in repaired tetralogy of Fallot. Int J Cardiol 2013 Oct 9;168(4):3280–6.
[14] Kelly NF, Walters DL, Hourigan LA, Burstow DJ, Scalia GM. The relative atrial index (RAI)- a novel, simple, reliable, and robust transthoracic echocardiographic indicator of atrial defects. J Am Soc Echocardiogr 2010;23:275–81.
[15] Chow V, Ng AC, Chung T, Thomas L, Kritharides L. Right atrial to left atrial area ratio on early echocardiography predicts long-term survival after acute pulmonary embolism. Cardiovasc Ultrasound 2013:11–7.
[16] de Groot NM, Lukac P, Schalij MS, et al. Long-term outcome of ablative therapy of post-operative atrial tachyarrhythmias in patients with tetralogy of Fallot: a European multi-center study. Europace 2012;14:522–7.
[17] Biviano A, Garan H, Hickey K, Whang W, Dizon J, Rosenbaum M. Atrial flutter catheter ablation in adults with repaired tetralogy of Fallot: mechanisms and outcomes of percutaneous catheter ablation in a consecutive series. J Interv Card Electrophysiol 2010;28:125–35.
[18] Ezzat VA, Ryan MJ, O'Leary J, et al. Radiofrequency ablation of atrial tachyarrhythmias in adults with tetralogy of Fallot- predictors of success and outcome. Cardiol Young 2017;27:284–93.
[19] Moore JP, Burrows A, Gallotti RG, et al. Electrophysiological characteristics of atrial tachycardia recurrence: relevance to catheter ablation strategies in adults with congenital heart disease. Heart Rhythm 2022;19:272–80.
[20] Waldmann V, Amet D, Zhao A, et al. Catheter ablation of intra-atrial reentrant/focal tachycardia in adult congenital heart disease: value of final programmed atrial stimulation. Heart Rhythm 2020;11:1953–9.
[21] Moore JP, Buch E, Gallotti RG, Shannon KM. Ultrahigh-density mapping supplemented with global chamber activation identifies non-cavotricuspid-dependent intra-atrial re-entry conduction isthmuses in adult congenital heart disease. J Cardiovasc Electrophysiol 2019;30:2797–805.
[22] Grubb CS, Lewis M, Whang W, et al. Catheter ablation for atrial tachycardia in adults with congenital heart disease: electrophysiological predictors of acute procedural success and post-procedure atrial tachycardia recurrence. J Am Coll Cardiol EP 2019;5:438–47.
[23] Baroutidou A, Otountzidis N, Papazoglou AS, et al. Atrial fibrillation ablation in congenital heart disease: therapeutic challenges and future perspectives. J Am Heart Assoc 2024;13(2):e032102.
[24] Waldmann V, Guichard J-B, Marijon E, Khairy P. Tachyarrhythmias in congenital heart diseases: from ion channels to catheter ablation. J. Cardiovasc. Dev.Dis. 2022;9:39.