Atrial Tachycardia After Circumferential Pulmonary Vein Ablation of Atrial Fibrillation
Mechanistic Insights, Results of Catheter Ablation, and Risk Factors for Recurrence

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Objectives
The aim of this study was to determine the mechanism of atrial tachycardia (AT) that occurs after ablation of atrial fibrillation (AF).

Background
Patients who undergo catheter ablation of AF may develop AT during follow-up.

Methods
Seventy-eight patients underwent an ablation procedure for AT after circumferential pulmonary vein ablation (CPVA) for AF. The 3-dimensional maps from the AF and AT procedures were compared to determine whether AT arose from a prior ablation line.

Results
A total of 155 ATs were mapped, and the mechanism was re-entry in 137 (88%) and focal in 18 (12%). The most common left atrial (LA) ablation targets were the mitral isthmus, roof, and septum. The critical isthmus in 115 of the 120 LA re-entrant ATs (96%) traversed a prior ablation line, consistent with a gap-related mechanism. Catheter ablation was successful in 66 of the 78 patients (85%). After a mean follow-up of 13 ± 10 months, 60 of the 78 patients (77%) were free of AT/AF without antiarrhythmic medications. Re-entrant septal AT was associated with recurrence (odds ratio 7.3; 95% confidence interval 1.5 to 36; p = 0.02), whereas PV isolation during the AT procedure was associated with a favorable outcome (odds ratio 0.17; 95% confidence interval 0.04 to 0.81; p = 0.03).

Conclusions
Approximately 90% of ATs after CPVA are re-entrant, and nearly all are related to gaps in prior ablation lines. These findings suggest that the prevalence of these arrhythmias may be reduced by limiting the number of linear lesions, demonstration of linear block, and pulmonary vein disconnection during the initial AF procedure. (J Am Coll Cardiol 2007;50:1781–7) © 2007 by the American College of Cardiology Foundation

Although circumferential pulmonary vein ablation (CPVA) is effective in eliminating atrial fibrillation (AF) (1,2), it may result in organized atrial tachycardias (ATs) (3–5) that require a repeat ablation procedure. The possible mechanisms of AT include macro–re-entry related to gaps in ablation lines (4–6) and organization of AF because of elimination of fibrillatory conduction. The precise mechanisms of AT after CPVA in a large series of patients have not been described.

Methods
Patient characteristics. Seventy-eight consecutive patients who underwent a repeat ablation procedure for AT were included in the study. These patients were drawn from a pool of 800 consecutive patients who underwent CPVA at our institution. The clinical characteristics of the patients are described in Table 1. The study patients had failed treatment with a rhythm-control (n = 40) and/or a rate-control medication (n = 78). The ablation procedure for AT was performed

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Manuscript received April 5, 2007; revised manuscript received June 29, 2007, accepted July 1, 2007.
Atrial tachycardia was considered to be caused by a small re-entry 20 to 40 ms shorter than that of the tachycardia was of a re-entrant AT, entrainment mapping at a cycle length the tachycardia cycle length and if the diameter of the potentials (ster). Sites harboring fractionated electrograms, double electroanatomical mapping system (Carto, Biosense Webster, Diamond Bar, California) and an 8-mm-tip ablation catheter (Navistar, Biosense Webster). Ablation lines were also created at the posterior left atrium (LA) or roof connecting the circular lesions and at the mitral isthmus. Radiofrequency energy was delivered with a target temperature of 50°C to 55°C and a power of 50 to 60 W (Stockert 70 RF generator, Biosense Webster). The end point of the procedure was voltage abatement of the local atrial electrogram; PV disconnection and conduction block across the various lines were not required. Mapping and ablation of AT. Treatment with antiarrhythmic medications was discontinued at least 5 half-lives before the procedure. Treatment with amiodarone was discontinued ≥6 weeks before the ablation procedure. Atrial tachycardia was persistent in 62 patients (79%) and paroxysmal in 16 patients (21%). In patients presenting to the laboratory in sinus rhythm (n = 16), rapid atrial pacing from the coronary sinus (CS) was used to induce AT. An activation map was then created using a 3-dimensional electroanatomical mapping system (Carto, Biosense Webster). Sites harboring fractionated electrograms, double potentials (≥50 ms), and very low amplitude electrograms (<0.05 mV) were labeled on the map.

The mechanism of AT was considered to be macro-re-entry if activation mapping accounted for at least 90% of the tachycardia cycle length and if the diameter of the re-entry circuit was ≥3 cm (7). The mechanism of the tachycardia was considered to be caused by a small re-entry circuit if the majority of the cycle length could be accounted for and if the diameter of the circuit was <3 cm. In all cases of a re-entrant AT, entrainment mapping at a cycle length 20 to 40 ms shorter than that of the tachycardia was performed to identify sites within the re-entry circuit. Sites where the post-pacing interval was within 20 ms of the tachycardia cycle length were considered to be within the re-entry circuit (8). Catheter ablation was performed in a linear fashion from a site within the re-entry circuit to an anatomical barrier or to an area with conduction block. Radiofrequency energy was delivered with an 8-mm-tip catheter (Navistar, Biosense Webster) at the same power and temperature settings as during the AF procedure or with a 3.5-mm irrigated-tip catheter (Thermocool, Biosense Webster) at a power of 25 to 35 W and with a temperature cutoff of 45°C.

If activation mapping failed to account for the majority of the tachycardia cycle length, the AT was considered to be either a re-entrant tachycardia from the contralateral atrium or CS, or a focal AT. A focal mechanism was confirmed if mapping showed centrifugal activation from a point source. Procedural end points. The end points of the procedure were termination of the AT by ablation and the inability to induce additional ATs. The induction protocol consisted of extrastimulus testing and rapid atrial pacing to atrial refractoriness, which was repeated during isoproterenol infusion. In our early experience with post-ablation ATs, the end point did not include demonstration of conduction block. In the latter 53 patients in this study, the end point also included demonstration of isthmus block in patients with mitral-dependent or roof-dependent ATs, as has been described previously (9,10).

After it was noticed that some patients experienced recurrent AT despite a prior successful ablation procedure for AT, in 34 patients (44%), an additional end point included PV isolation, defined as complete elimination or dissociation of all PV potentials.

Gap-related versus non-gap-related ATs. In patients with re-entrant ATs, the 3-dimensional maps from the AF and AT ablation procedures were compared in 4 views to determine whether the AT arose from a prior ablation line. If the AT re-entry circuit traversed an AF ablation line, it was considered to be a gap-related AT. Conversely, if a re-entrant AT was mapped to a portion of the LA that had not been ablated during the AF procedure, it was considered a non-gap-related AT.

Although ablation in the CS was not performed during the AF procedure, a re-entrant AT was deemed to be gap-related if it arose from the mid or distal CS. The rationale for this was that ablation lines in the posterior LA and/or mitral isthmus may have slowed conduction and facilitated re-entry by disrupting LA–CS muscular connections (5).

Multiple-loop circuits. A multiple-loop re-entrant tachycardia was deemed to be present if there were ≥2 simultaneous circuits using different isthmi. If the results of activation mapping suggested the presence of a multiple-loop tachycardia, this was corroborated with entrainment mapping. Ablation was commenced at the isthmus with the best post-pacing interval during entrainment mapping. If

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<th>Table 1 Clinical Characteristics of the Study Patients</th>
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<td>Number of patients</td>
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Continuous variables are shown as mean ± SD.
the tachycardia failed to terminate, ablation was performed at other isthmi as guided by entrainment mapping.

**Postprocedure management and follow-up.** Patients were monitored and treated with intravenous heparin overnight, then discharged with a prescription for warfarin and subcutaneous low-molecular-weight heparin (0.5 mg/kg twice daily) until the international normalized ratio was ≥2.0. Patients resumed the rate-control medications that they had been taking before the procedure.

The patients were seen in an outpatient clinic at 3 months and 6 months after the procedure, and as needed thereafter. At the 3-month visit, treatment with rate-control agents was discontinued if the patient reported no recurrence of arrhythmia-related symptoms. All patients then wore an auto-trigger event monitor (Lifestar AF Express, Life-Watch Inc., Buffalo Grove, Illinois) for 30 days for evaluation of asymptomatic arrhythmias. Warfarin therapy was discontinued, and aspirin was substituted if monitoring failed to show AT/AF.

**Statistical analysis.** Continuous data are presented as mean ± 1 SD. Factors associated with recurrent AT were analyzed by multivariate logistic regression analysis. These variables were analyzed per patient and not per episode of AT. A value of p < 0.05 was considered statistically significant.

**Results**

**ATs.** One hundred fifty-five ATs were mapped in the 78 patients. The mechanism was re-entry in 137 of the 155 ATs (88%) and focal in 18 (12%). The mean cycle lengths of the re-entrant and focal ATs were 256 ± 49 ms and 214 ± 40 ms, respectively. Macro–re-entry was responsible for 116 of the 137 re-entrant ATs (85%), and small re-entry circuits were responsible for the remaining 21 ATs (15%).

After eliminating the 17 ATs that used the cavotricuspid isthmus, the mitral isthmus was the most frequent ablation target, accounting for 50 of the 120 LA re-entrant ATs (42%). The LA roof and septum accounted for 24 (20%) and 16 (13%) of the re-entrant ATs, respectively. These data are depicted in Figure 1. Among the 21 ATs caused by small re-entrant circuits, the ablation target was the anterior pericostal aspect of the left superior PV in 6 (29%), the CS in 5 (24%), the anterior wall in 5 (24%), the posterior wall in 3 (14%), and the antrum of the right superior and right inferior PV in 1 each. Among the 18 focal ATs, the origin was from one of the PVs in 15 (83%), the LA septum in 2 (11%), the crista terminalis in 1, and the superior vena cava in 1.

**Gap-related AT.** Comparison of the maps from the AF and AT procedures showed that the re-entry circuit of 115 of the 120 LA re-entrant ATs (96%) traversed a prior ablation line, implying that they were gap-related (Figure 2). Among the 5 nongap-related re-entrant ATs, the critical isthmus was the anterior LA wall in 3 and the right atrial–CS connection in 2.

**Multiple-loop circuits.** Mapping showed that a multiple-loop circuit was present in 17 of the 78 patients (22%). The mitral isthmus and the LA anterior wall were engaged simultaneously in 4 of the 17 patients, the mitral isthmus and roof in 3, a loop around the right- and left-sided PVs in 2, mitral isthmus and a loop around the left-sided PVs in 1, cavotricuspid isthmus and right atrial septum in 1, LA septum and right atrial posterior wall in 1, and multiple left and right atrial sites in the remaining 5 patients. Among the 4 patients with an AT involving both the mitral isthmus and the LA anterior walls, both sides of the septum also were part of the circuit in 2 patients. Among the 3 patients with a multiple-loop circuit involving the mitral...
isthmus and the roof, the proximal CS also was involved in 1 patient (Figs. 3 to 5) and the septum in another.

**Septal ATs.** Entrainment mapping confirmed that the right atrial aspect of the septum was also part of the re-entrant circuit in 14 of 16 patients (87%) with septal ATs. Catheter ablation at the right atrial septum terminated the septal AT in 3 of 14 patients (21%). In 1 patient, ablation at the left and then the right aspect of the septum resulted in transient termination of the AT. Of the 18 septal (focal and re-entrant) ATs, transient slowing of the ventricular rate during AT or transient prolongation of the PR interval was noted during ablation in 3 cases (17%). All 3 instances occurred during radiofrequency ablation at the LA aspect of the septum.

**Catheter ablation.** Radiofrequency ablation was successful in eliminating 134 of 155 ATs (86%). Of the 116 macro-re-entrant tachycardias, catheter ablation was effective in terminating 45 of 50 ATs (90%) from the mitral isthmus, 20 of 24 ATs (83%) from the roof, 6 of 16 ATs (38%) from the septum, 6 of 6 ATs (100%) from the CS, 2 of 3 ATs (67%) from the anterior wall, and all 17 ATs from the cavo-tricuspid isthmus (100%). Radiofrequency ablation terminated 20
of 21 ATs (95%) using a small re-entry circuit. All 18 focal ATs were abolished with catheter ablation. Acute procedural success (i.e., tachycardia termination and lack of inducibility) was achieved in 66 of 78 patients (85%).

The end point also included demonstration of linear block in 30 patients with AT from the mitral isthmus and 17 patients with AT from the LA roof. Linear block was achieved in 21 of the patients with mitral isthmus AT and 14 patients with roof AT. Among the former, ablation in the CS was required in 13 patients (62%). Reasons for failure to achieve conduction block included procedure duration, high real-time impedance or chest discomfort.

![Figure 4 Entrainment Mapping in the Same Patient as in Figure 3](image)

(A) The post-pacing interval (PPI) from the ostial aspect of the coronary sinus (CS) is 250 ms, matching the tachycardia cycle length. (B) Entrainment mapping from the distal CS also shows a perfect return cycle. (C) Entrainment mapping from the distal CS after radiofrequency ablation (RFA). Despite a lack of change in the P-wave morphology or the tachycardia cycle length, a long PPI implies that the mitral/distal CS portion of the AT circuit has been eliminated. Also shown are electrocardiographic leads II, V1, and V5, and bipolar electrograms recorded by catheters placed in the left atrium (LAd and LAp) and right atrium (RAd and RAp). Os = ostium.

![Figure 5 Effect of Radiofrequency Ablation in the Same Patient as in Figures 3 and 4](image)

(A) Radiofrequency energy delivery at the LA roof slows the tachycardia cycle length from 250 to 275 ms. Concomitantly, the P-wave morphology abruptly changes from upright to biphasic in lead V1 (arrows), indicating that the 2 loops converging at the roof have been eliminated. (B) Effect of radiofrequency energy delivery in the proximal CS. After entrainment mapping showed that the PPI at the proximal CS was still the same as the tachycardia cycle length, ablation at this site eliminated the last loop, resulting in sinus rhythm. There were no inducible tachycardias thereafter. Abl = ablation; other abbreviations as in Figure 4.
during ablation in the CS, and the location of the esophagus.

**Recurrent atrial tachycardia during follow-up.** Despite a successful acute outcome, 18 of 66 patients (27%) developed recurrent AT during follow-up. Fourteen of these patients underwent a repeat procedure for AT. The critical isthmus in 11 of 14 patients (79%) was different than the one(s) found during the initial procedure. In 6 of these 14 patients (43%), an initially successful ablation at the mitral isthmus was followed by the development of a roof tachycardia or an initially successful ablation at the roof was followed by the development of a mitral isthmus tachycardia. Two additional patients underwent a repeat procedure with an irrigated-tip catheter for mitral isthmus AT because the initial procedure with an 8-mm-tip catheter was unsuccessful. The recurrent ATs were successfully ablated in 13 of these 16 patients (81%).

Thirty-four patients (44%) underwent PV isolation during either the first or the repeat ablation procedure for AT. There were no serious complications such as perforation, thromboembolism, or atrioesophageal fistula.

**Long-term efficacy.** Sixty of 78 patients (77%) were free of recurrent AT/AF in the absence of antiarrhythmic drug therapy at a mean follow-up of 13 ± 10 months after the last ablation procedure. An additional 8 patients reported significant clinical improvement, with occasional, well-tolerated episodes of AT/AF. Therefore, a clinically satisfactory outcome was achieved in 68 of 78 patients (87%).

Among various clinical and procedural characteristics, the presence of re-entrant septal AT was independently associated with recurrence during follow-up (odds ratio 7.3; 95% confidence interval 1.5 to 36; p = 0.02). Complete PV isolation during the AT procedure was associated with a lower likelihood of recurrence (odds ratio 0.17; 95% confidence interval 0.04 to 0.81; p = 0.03), as was a history of persistent AF (odds ratio 0.11; 95% confidence interval 0.02 to 0.74; p = 0.02).

**Discussion**

**Main findings.** A main finding of this study is that the vast majority of ATs that occurred after CPVA for AF were caused by a re-entrant mechanism. Furthermore, nearly all LA re-entrant ATs had a component of the re-entry circuit that traversed a prior ablation line, indicating that they were gap-related. The mitral isthmus, roof, and septum accounted for 75% of the ablation target sites for macro-re-entrant ATs from the LA. Catheter ablation was successful in 85% of patients, and most patients remained arrhythmia-free at long-term follow-up.

The observation that most ATs are caused by gaps in prior ablation lines implies that most postablation ATs are avoidable, either by limiting the amount of linear ablation and/or by confirming complete conduction block across linear lesions.

**Recurrent AT.** In approximately 25% of the patients in this study, recurrent arrhythmias developed despite a successful procedure for AT. It may be argued that this number could have been lower had the end point during the AT procedure included systematic demonstration of isthmus block. However, the critical isthmus in the majority of patients who underwent a repeat procedure for AT was different than that found during the initial AT procedure. Although linear block is a desirable end point, it is unlikely to have prevented recurrent AT in most of the patients in this study.

One possible explanation for the onset of different ATs after a successful AT procedure is that ablation across a given isthmus may facilitate re-entry at another isthmus. A linear lesion for AT combined with the linear lesions during the AF procedure may favor re-entrant AT by acting as multiple lateral barriers (11). The constraining effect imposed by these barriers may stabilize the putative re-entry circuit by preventing short circuiting. For example, linear ablation across the LA roof may have promoted macro-re-entry at the mitral isthmus (or vice versa), a phenomenon that often was observed in this study. This hypothesis is supported by a recent study that noted that the most frequent arrhythmia after linear ablation at the roof for AF was mitral isthmus-dependent atrial flutter (10). Importantly, this arrhythmia was only inducible after linear ablation at the roof. Therefore, an ablation line at 1 isthmus, irrespective of completeness, may alter LA conduction patterns and promote re-entry at another isthmus.

**Multiple-loop ATs.** An important finding in this study is that approximately 20% of patients showed multiple-loop circuits with as many as 4 simultaneous loops. It is important to recognize these complex arrhythmias because they may require a different approach than single-loop postablation ATs. If radiofrequency energy delivery fails to change the cycle length or the P-wave morphology despite voltage abatement, ablation then should be performed at another isthmus, as identified by entrainment mapping. Although it may seem that ablation at the first isthmus had no apparent effect on the tachycardia, it may very well have been effective in eliminating one of the loops of the multiple-loop AT.

**PV isolation.** Another finding of this study is that PV isolation during the AT ablation session was protective against recurrent arrhythmias during follow-up. This observation suggests that PVs not only are responsible for triggering/maintaining AF, but also may be critical in the development of AT after CPVA. Although complete PV disconnection may not be critical for the elimination of AF with the ablation strategy used in this study (12), it does seem to be important for preventing recurrent AT during follow-up, as has been noted by others (13,14). This implies that the prevalence of AT may be lower if complete PV isolation is achieved during the index procedure for AF.

**Septal ATs.** In this study, macro-re-entrant septal ATs were found to be relatively resistant to catheter ablation and tended to recur during follow-up. The fact that a septal tachycardia in 1 patient was transiently interrupted with...
radiofrequency energy delivery on either the left or right aspect of the interatrial septum suggests that the critical isthmus was intramural and inaccessible by conventional ablation techniques. A recent anatomical study reported that the septum is thicker than other sites in the LA, including the mitral isthmus, roof, and anterior and posterior walls (15). This may explain why septal ATs are difficult to ablate.

Of note is that if catheter ablation is unsuccessful from the LA side of the septum, targeting the right atrial aspect of the septum may be successful in eliminating the tachycardia. Irrespective of the side of the septum that is targeted, the operator should remain vigilant to the possibility of injury to the compact atrioventricular node.

**Prior studies.** Prior studies have also reported on organized ATs after catheter ablation of AF. However, these studies were small (3,4,13,16), and most had a relatively short duration of follow-up. The large number of patients and ATs in the present study made it possible to identify factors associated with a favorable outcome and recurrence. The focus of most of these studies was AT after PV isolation, albeit with differing techniques. The PV disconnection was not a procedural end point for patients who underwent CPVA for AF in the current study, which may account for the difference in prevalence of AT after CPVA (4) and PV isolation (16). Long linear lesions, as opposed to segmental PV isolation, may result in complex gap geometries that promote conduction block and facilitate re-entry (17).

**Study limitations.** All of the patients in this study underwent AF ablation using the strategy of CPVA, and therefore the results may not apply to other ablation strategies. However, re-entrant ATs similar to the ones described in this study have been reported after various AF ablation strategies (10,11,14). Furthermore, similar ATs have been observed in patients with structural heart disease who have not undergone catheter ablation (7,18), and in patients who have undergone surgical ablation of AF (19). Therefore, the results of this study are germane to patients with AT after treatment of AF by various modalities.

The limitations of activation mapping, especially in atria with large areas of low voltage, should be noted. It also may be challenging to interpret complex electrograms, especially during entrainment mapping.

**Conclusions**

The vast majority of arrhythmias that occur after CPVA are re-entrant and use gaps in prior ablation lines. Although mapping and ablation of these tachycardias may be challenging, catheter ablation is successful in most patients with postablation ATs. However, some patients may develop recurrent tachycardias from different isthmi despite a seemingly successful procedure. Avoidance of multiple ablation lines, demonstration of conduction block, and PV disconnection are likely to decrease the prevalence of postablation ATs.

**REFERENCES**