
Atrial Tachycardia: Mechanisms, Diagnosis, and Management

Kurt C. Roberts-Thomson, MBBS, FRACP,
Peter M. Kistler, MBBS, PhD, FRACP, and
Jonathan M. Kalman, MBBS, PhD, FACC

Abstract: Atrial tachycardia is an uncommon arrhythmia and may be focal or macroreentrant. This review concentrates on focal atrial tachycardia. Over the last decade there have been a number of advances in delineating the mechanism and anatomic locations of focal atrial tachycardia. The lack of efficacy of antiarrhythmic therapy and the advent of radiofrequency ablation have altered our primary approach to the treatment of focal atrial tachycardia. This review discusses the clinical features, diagnosis, and treatment of focal atrial tachycardia. There is particular focus on the mechanisms, anatomic locations, and P wave morphology, as well as the techniques of mapping and radiofrequency ablation. (*Curr Probl Cardiol* 2005;30:529-573.)

Atrial tachycardia is an uncommon arrhythmia. The term atrial tachycardia (AT) encompasses several types of tachycardia that originate in the atria and do not require the participation of the atrioventricular node for maintenance of the arrhythmia. These tachycardias have differing arrhythmia mechanisms and are often related to anatomical structures. Mechanisms include abnormal automaticity, triggered activity, and reentry. Evaluation of the studies on this topic can be difficult as most of the studies have had small, heterogeneous populations, including patients with a variety of atrial tachycardias.

Dr. Roberts-Thomson, Dr. Kalman, and Dr. Kistler have no conflict of interest to disclose.
Curr Probl Cardiol 2005;30:529-573.
0146-2806/\$ – see front matter
doi:10.1016/j.cpcardiol.2005.06.004

Definition

Regular AT can be defined as focal or macroreentrant. In 2001, the Joint Expert Group from the Working Group of Arrhythmias of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology classified regular AT according to electrophysiological mechanisms and anatomical structures.¹ Focal AT was defined as atrial activation starting rhythmically at a small area (focus) from which it spreads out centrifugally and without endocardial activation over significant portions of the cycle length. The main tenet of this definition is that, in contrast to activation seen in macroreentrant AT, atrial activity originates from a point source. In macroreentry, reentrant activation occurs around a large central obstacle, usually several centimeters in diameter. In these circuits electrical activity can be recorded throughout the entire atrial cycle length. These include typical atrial flutter and other well-characterized macroreentrant circuits in the right and left atrium which are also frequently referred to as types of “atrial flutter.”

These circuits have been extensively and elegantly described in the March 2005 issue of *Current Problems in Cardiology*.² Therefore, these circuits will not be further considered and in this review we will concentrate on focal AT.

Epidemiology

Sustained AT is relatively rare. In asymptomatic young individuals, the prevalence of AT has been calculated to be 0.34%, with a prevalence of 0.46% in symptomatic patients.³ AT accounts for 5 to 15% of adults undergoing electrophysiological studies,⁴⁻⁸ with higher rates in children. Automatic AT tends to be a condition that affects the young, whereas AT due to microreentry is more common in older populations, although many exceptions to this generalization occur.⁹ Older patients are more likely to have right-sided AT and multiple AT.⁹ In contrast to atrioventricular nodal reentry and atrioventricular reentrant tachycardia, there appears to be equal numbers of males and females affected.⁴ In a cohort of patients described by Kammeraad et al,¹⁰ nonautomatic AT occurred predominately in women. However, Chen et al¹¹ did not note a gender difference.

Clinical Features

Focal AT is usually manifest by atrial rates between 130 and 250 beats per minute (bpm), but may be as low as 100 bpm or as high as 300 bpm. In general, younger patients tend to have faster AT, with rates up to 340 bpm described in infants.¹² The P wave morphology is usually different

to sinus rhythm but foci arising from the region of the crista terminalis (particularly the superior crista) may have morphology consistent with a sinus origin. The properties of the atrial focus may be similar to that of the sinus node in that they are responsive to changes in activity and autonomic tone, with the rate varying according to activity. Rates during sleep may be up to 40 bpm less than those during waking hours.¹³

Melvin M. Scheinman: The clinical characteristics of cristal tachycardias may mimic sinus tachycardia or may be mimicked by inappropriate sinus tachycardia (IST). IST is distinguished by characteristic clinical features as well as the 24-hour Holter recording and is well discussed later in the chapter.

The onset of symptoms may occur at any age, from birth through to old age. In a study which included adults and children, Rodriguez et al⁴ showed that the majority of patients had their first arrhythmic event between the ages of 10 and 39 years. Patients experience a variety of symptoms, including palpitations, dizziness, chest pain, dyspnea, fatigue, and syncope. Feeding problems, vomiting, and tachypnea may be seen in young children. Detection of AT is usually straightforward. Most patients can be diagnosed by a routine ECG; however, those with paroxysmal AT may require Holter monitoring or a loop recorder. Nonsustained AT is commonly found on Holter recordings and is seldom associated with symptoms.

Melvin M. Scheinman: Bursts of nonsustained atrial tachycardia are commonly recorded in the Holter recordings of older individuals. These episodes are frequently not accompanied by symptoms and hence do not require therapy. While there is concern that this arrhythmia may presage the onset of atrial fibrillation, there are no data to suggest that such therapy will prevent atrial fibrillation. Judicious neglect of these arrhythmias would appear to be the best strategy.

Natural History of Atrial Tachycardia

Poutiainen et al³ demonstrated that a follow-up ECG on patients diagnosed with AT 3 to 16 years earlier showed that 26% of patients continued to have an ectopic atrial rhythm. Only 22% of patients were taking antiarrhythmic medication. Some patients had a change in P wave morphology suggestive of fusion of sinus and ectopic rhythms, leading the authors to propose that the ectopic foci gradually degenerate and slow with time. Spontaneous remission has been reported in 24 to 63% of both



FIG 1. Incessant atrial tachycardia. Note the long R-P interval. P waves are inverted in inferior leads ruling out a sinus tachycardia. The differential diagnosis of this ECG includes atypical (fast-slow) AVNRT or AVRT with a slowly conducting accessory pathway (PJRT—permanent form of junctional reciprocating tachycardia).

adults and children following cessation of medical therapy.^{5,13-16} Klersy et al⁵ investigated factors that predicted spontaneous remission. While on univariate analysis, the age of onset of the arrhythmia, heart rate during tachycardia, presence of a cardiomyopathy, and clinical presentation (paroxysmal versus permanent) predicted remission; following logistic regression analysis, the only independent predictor was the age of onset of the arrhythmia. In fact, the AT disappeared in 55% of patients under the age of 25, compared to 14% of patients aged 26 or older. This has been attributed to regression of AT resulting from abnormal automaticity, a more common mechanism in younger patients.

Prognosis and Complications

The outlook of patients with focal AT is usually benign, with the exception of patients with incessant forms (Fig 1), which may lead to tachycardia-induced cardiomyopathy.¹⁷ Chen et al⁹ analyzed the literature up until 1997 and reported that 63% of patients with focal AT had left ventricular dysfunction. Of these, 73% had tachycardia-induced cardiomyopathy. Tachycardia-induced cardiomyopathy was caused by AT due

to abnormal automaticity in 80% of cases. Patients with faster heart rates seem more likely to develop cardiomyopathy. However, it remains unclear why some patients develop cardiomyopathy and others maintain normal left ventricular function. The cardiomyopathy usually reverses spontaneously following correction of the tachycardia, with the majority of patients achieving normal or near-normal left ventricular function.^{14,17} Embolic events and stroke have rarely been reported in patients with atrial tachycardia.¹⁸

Melvin M. Scheinman: We have had patients present with severe myocardial dysfunction referred for treatment of congestive heart failure and in several instances even placed on the heart transplant list due to a tachycardic myopathy. Atrial tachycardia with 2:1 block where the second P wave is hidden within the QRS complex may mimic sinus tachycardia. Similarly, cristal tachycardias may mimic persistent sinus tachycardia. Appropriate treatment of these arrhythmias may improve or cure cardiac failure.

Mechanisms

Focal AT exhibits a wide range of electrophysiologic characteristics that reflect differing mechanisms. However, in the absence of a gold standard for determining tachycardia mechanism, these remain largely descriptive. The three putative mechanisms of focal AT are automaticity, triggered activity, and microentry.

The initial mechanistic information came from excised atrial foci. Wyndham et al¹⁹ demonstrated the presence of triggered activity in a right atrial appendage focus by pacing maneuvers in vivo and with in vitro microelectrode studies on the excised tissue. Abnormal automaticity has also been similarly demonstrated in atrial foci.^{20,21}

Most cases of AT, where histology was performed, showed normal myocardium at the AT focus. However, abnormal myocardium has also been observed.^{19,21-24} McGuire et al²² reported four patients with abnormalities: two with extensive myocardial fibrosis and two with myocyte hypertrophy and endocardial fibrosis. All had structural heart disease. Other reports have found mononuclear cell infiltration, mesenchymal cell proliferation, islets of fatty tissue, thinning, and blebs.^{19,21,23,24} These may produce the substrate required for microentry or abnormal automaticity.

In a comprehensive study by Chen et al,¹¹ the mechanisms of AT were evaluated in 36 patients by a variety of pacing and pharmacologic maneuvers. Automatic AT were identified in seven patients by the

following characteristics: (1) AT could be initiated only with isoproterenol; (2) programmed stimulation could not initiate or terminate AT; (3) AT could be transiently suppressed with overdrive pacing; (4) propranolol terminated all of the AT; (5) adenosine, dipyridamole, verapamil, Valsalva maneuver, carotid sinus massage, and edrophonium could not terminate any of the AT; (6) monophasic action potential recordings did not find afterdepolarizations.

AT related to triggered activity occurred in nine patients with the following features: (1) the initiation of AT was reproducible with atrial pacing and was dependent on achieving a critical range of atrial pacing cycle lengths; (2) just before the onset of AT, delayed afterdepolarizations were observed in the monophasic action potential recordings; (3) termination of AT was reproducible with programmed stimulation; (4) entrainment was not found but overdrive suppression and overdrive termination were demonstrated; (5) adenosine, dipyridamole, propranolol, verapamil, Valsalva maneuvers, carotid sinus massage, and edrophonium terminated all of the AT.

AT due to microreentry were identified in 20 patients. Their characteristics included the following: (1) AT could be reproducibly initiated and terminated with programmed stimulation; (2) fulfillment of the criteria for manifest and concealed entrainment; (3) the interval between the initiating premature beat and the first beat of AT was inversely related to the premature coupling interval of atrial extrastimuli; (4) adenosine, dipyridamole, and verapamil terminated the AT in most cases.

The limiting factor in the analysis of mechanisms is the significant overlap in electrophysiologic characteristics. For example, programmed stimulation may initiate and terminate both triggered activity and microreentry. However, while triggered activity may be dependent on cycle length, abbreviation of pacing cycle lengths may also predispose to reentry.

The use of adenosine to differentiate between AT mechanisms has provided some inconsistent results. Engelstein et al²⁵ demonstrated that adenosine did not terminate AT due to intra-atrial (macro) reentry; suppressed but did not terminate automatic AT; terminated presumed triggered activity in one case; and terminated sinus node reentry tachycardia in all cases. Kall et al²⁶ reported suppression but not termination in 44% of automatic AT, and termination in 38% of patients with AT in keeping with triggered activity or microreentry. Haines et al²⁷ observed a complete lack of response to adenosine in patients with intra-atrial reentry tachycardia. Chen et al¹¹ demonstrated that AT due to (micro) reentry terminated with adenosine in 89% of patients, that automatic AT were

transiently suppressed in 57% of patients but without termination, and that all cases due to presumed triggered activity were terminated.

These apparent differences may be due to variations in tachycardia definitions. Intra-atrial reentry tachycardias have properties consistent with macroreentry, whereas sinus node reentry tachycardia has characteristics more in keeping with microreentry. Results may also be complicated by nonspecific effects of adenosine such as induction of atrial extrasystoles resulting in tachycardia termination.

On a theoretical level, adenosine might be expected to affect all three potential mechanisms for focal AT. Adenosine inhibits intracellular cAMP generation, decreasing L-type calcium currents, resulting in inhibition of catecholamine-stimulated afterdepolarizations, thereby suppressing triggered activity.²⁸ Microreentry has been suggested to involve calcium-dependent atrial myocardium and would be suppressed by the same mechanism. Activation of the adenosine-sensitive potassium current (I_{Kado}) leads to hyperpolarization of the resting membrane potential and potentially suppresses automatic activity.²⁸

Two studies where there was strict differentiation between focal or macroreentrant AT clarify the above results.^{29,30} Markowitz et al²⁹ observed that focal automatic AT were transiently suppressed but not terminated with adenosine, and AT with characteristics consistent with microreentry or triggered activity terminated with adenosine. Macroreentrant AT were insensitive to adenosine. Iwai et al³⁰ observed similar responses to adenosine but used three-dimensional electroanatomic mapping (CARTO) to delineate the tachycardia circuit, ensuring the AT were focal.

While the recent definition of focal AT¹ identifies centrifugal activation, Higa et al^{31,32} used noncontact mapping to demonstrate that, in some patients, activation from a focal point of origin was conducted over a preferential pathway to a break-out point. From this point, activation then proceeded in a centrifugal pattern. The concept of preferential conduction in the atrium is well described³³ and should be differentiated from a protected isthmus. Ablation of these tachycardias was successful at the site of origin and the proximal portion of the preferential pathway rather than more distally or at the breakout point.

Higa et al³¹ also demonstrated the existence of low-voltage zones, suggesting the existence of localized atrial pathology or myopathy in patients with atrial tachycardia. The majority of atrial tachycardias in this series originated within or on the border of a low-voltage zone. Many of these arose from the crista terminalis, which shows conduction anisotropy

with rapid linear conduction and slowed transverse conduction.³⁴ Studies of atrial activation using electroanatomic mapping in patients with sinus node dysfunction and patients with congestive cardiac failure have demonstrated a similar phenomenon.^{35,36} It is possible that such abnormalities, albeit more localized, represent the substrate for focal AT. Consistent with these observations, several studies have frequently found low-amplitude, fractionated electrograms at the site of successful ablation in patients with focal AT, representing slowed conduction and possibly atrial pathology.^{37,38}

The presence of structural heart disease may predispose to focal atrial tachyarrhythmias. Stambler et al³⁹ demonstrated this by inducing congestive cardiac failure in dogs by rapid ventricular pacing. After a mean of 20 days, sustained AT was inducible in 14 of 15 dogs. Pacing maneuvers and the presence of delayed afterdepolarizations suggested triggered activity, resulting from intracellular calcium overload, as the likely mechanism.

Melvin M. Scheinman: The authors have well summarized the possible mechanisms of atrial tachycardia. It would appear that atrial macroreentrant arrhythmias while not responsive to adenosine will frequently be associated with AV block. In our experience, this response is diagnostic of atrial tachycardia.

In addition, use of newer catheters with splines allowing for multiple recordings over small atrial sites will likely facilitate the diagnoses of microentry. A preliminary report from Haissaguerre's group suggests that many focal tachycardias are due to microentry.

Apart from the response to medications and pacing, the clinical significance of the different tachycardia mechanisms is unknown. Chen et al⁹ performed a literature search to determine whether mechanistic information altered ablation outcomes in patients with atrial tachycardia. AT were categorized as either automatic or nonautomatic. Analysis found that the mechanism of AT did not predict successful ablation or recurrence of AT after the initial success.

Diagnosis of Focal AT

The majority of focal AT can be diagnosed from the ECG. However, differentiation of focal AT from other forms of SVT (AVNRT or AVRT) or from macroreentrant atrial tachycardia may be difficult.

Focal AT versus Other Forms of SVT (AVNRT or AVRT)

AT may be difficult to differentiate from other forms of supraventricular tachycardia. This is particularly the case as atrial tachycardia can occur with either a short R-P interval or a long R-P interval, depending on the tachycardia rate and the speed of AV nodal conduction. It can therefore mimic either AVNRT or AVRT. Clues to the diagnosis include the presence of an inferior P wave axis (this excludes AVRT or AVNRT as it suggests an origin high in the atrium) or the ability to demonstrate “unhooking” or variability of the R to P relationship. In AVRT and AVNRT this relationship will be constant as it is integral to the tachycardia mechanism. In atrial tachycardia the R-P relationship is incidental and hence possibly variable. Automatic atrial tachycardias may also manifest with recurrent self-limiting bursts of tachycardia, which can exhibit warm-up and cool-down phases (Fig 2).

In the electrophysiology laboratory a variety of tachycardia features and pacing maneuvers may be useful in the differentiation of AT from atrioventricular nodal reentrant tachycardia (AVNRT) and atrioventricular reentrant tachycardia (AVRT).⁴⁰⁻⁴⁹ In perhaps the most definitive article on this subject, Knight et al⁵⁰ investigated the diagnostic value of these features and pacing maneuvers in 196 patients with supraventricular tachycardia, of whom 25 had AT. Multiple baseline observations and tachycardia features were evaluated. Pacing maneuvers assessed included atrial pacing during SVT just below the tachycardia cycle length; atrial pacing during SVT at the longest cycle length that resulted in AV block; ventricular pacing during SVT just below the tachycardia cycle length; burst ventricular pacing for three to six beats at a cycle length of 200 to 250 ms; and scanning diastole with a premature ventricular extrastimulus.

Although no single feature or maneuver could always identify atrial tachycardia, certain features were useful: AT required isoproterenol for induction more often than AVNRT or AVRT, although the predictive value was poor. Spontaneous termination of tachycardia with AV block excluded AT (seen in 28%). Surprisingly, the presence of AV block with persistent tachycardia did not discriminate between AVNRT and AT.

Melvin M. Scheinman: The sequence of two atrial complexes following ventricular pacing during “apparent” entrainment is highly suggestive of atrial tachycardia. It is well to appreciate that patients with AV nodal reentry can have tachycardia termination with pacing and continued pacing may reinitiate tachycardia with an AAV sequence owing to conduction over a fast and then slow nodal pathway with reinitiation of tachycardia.

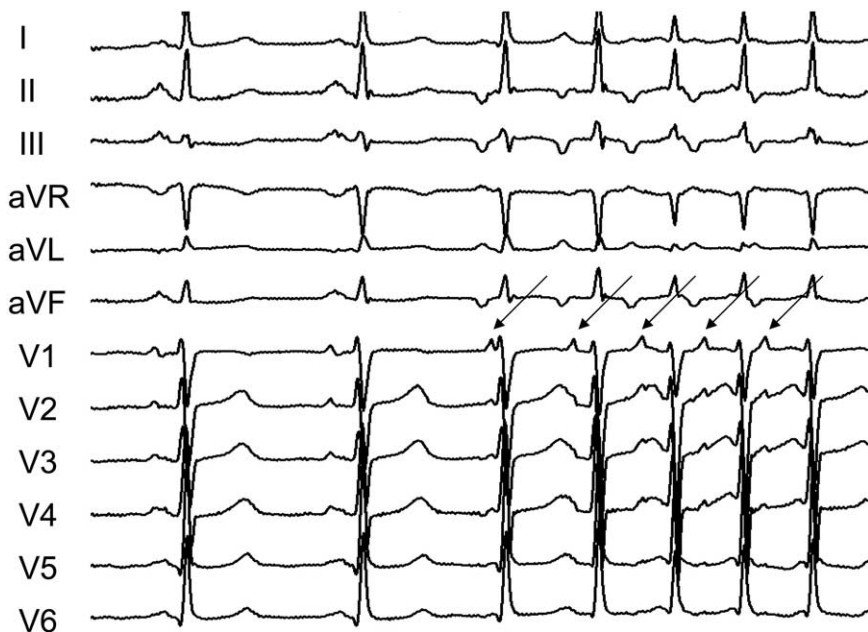


FIG 2. Continuous 12-lead ECG showing abrupt onset of atrial tachycardia originating from the ostium of the coronary sinus. Note the sudden onset with warm-up over several beats and the superiorly directed P wave vector both ruling out sinus tachycardia. Note also that there is no constant R-P relationship ruling out AVNRT or AVRT. Also shown is that the P wave morphology in V₁, while initially appearing to be upright, when timed to onset of the P wave in inferior leads actually has an isoelectric component before the upright component. This appearance is frequently seen in tachycardias originating from the ostium of the coronary sinus and from the septum.

In addition, advancement of the atrial complex during His bundle refractoriness proves the existence of an accessory pathway but does not exclude an atrial tachycardia mechanism with a bystander accessory pathway.

An inferior P wave axis excludes AVNRT but does not exclude an antero-septal accessory pathway, which can be associated with a retrograde P wave activation with inferior axis.

An A-A-V response after ventricular pacing with atrial entrainment and an atrial activation sequence different to tachycardia were diagnostic of atrial tachycardia (Fig 3). Inability to entrain the atrium during ongoing tachycardia due to VA block had an 80% positive-predictive value for atrial tachycardia. Conversely, tachycardia termination during burst ventricular pacing that did not depolarize the atrium excluded the diagnosis of AT. When a premature ventricular

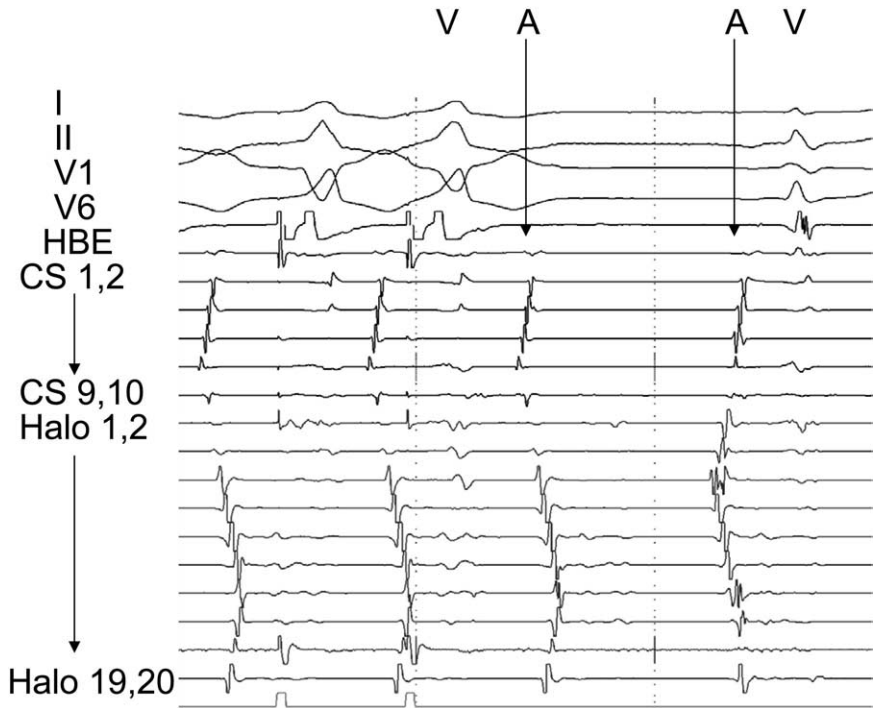


FIG 3. This figure shows ventricular pacing during tachycardia for the example shown in Fig 1. Shown are surface ECG leads I, II, V₁, and V₆ together with intracardiac recordings from the coronary sinus (cs) and a halo catheter placed around the tricuspid annulus (TA). Note after cessation of pacing the last paced V is followed by an “entrained” A, followed by a spontaneous tachycardia A and tachycardia V. This ventricular-atrial-atrial-ventricular response following the cessation of ventricular pacing with atrial entrainment is virtually diagnostic of atrial tachycardia.

beat was introduced during the His refractory period, either advancement of atrial activation or tachycardia termination without atrial depolarization excluded AT.

The presence of a fixed VA interval on the first beat after atrial pacing (within 10 ms of the VA interval during tachycardia) had a high negative-predictive value for atrial tachycardia. However, this observation did not completely exclude AT as apparent VA linking may occur due to coincidental events. Conversely if the VA interval could be “unhooked” after the cessation of pacing, then AT is likely to be present. However, variable VA conduction can occur after pacing in AVNRT and therefore this observation is not specific for atrial tachycardia.

Focal Atrial Tachycardia versus Macroreentrant Atrial Tachycardia

Most classically during focal atrial tachycardia, it is possible to observe a discrete P wave with an intervening isoelectric interval. However, when the atrial rate is very rapid and if atrial conduction slowing is present, there may be no isoelectric baseline and the appearance may mimic that of macroreentrant atrial tachycardia. Conversely, while macroreentrant atrial tachycardia (and atrial flutter) frequently demonstrates a continuous undulation without an isoelectric period on the electrocardiograph, patterns resembling focal atrial tachycardia (with an isoelectric period) have also been described. Ultimately, an electrophysiological study is required for a definitive diagnosis of focal AT.

In focal atrial tachycardia, endocardial mapping can localize the origin of activation to a small area from which there is generally radial spread. Occasionally, the presence of anatomic or functional barriers conduction may result in regions of preferential conduction. Nevertheless, in focal atrial tachycardia, intracardiac recordings demonstrate large portions of the cycle length without activity, correlating with the isoelectric interval on the surface ECG (Fig 4). Conversely, in macroreentrant atrial tachycardia it is generally possible to record activity throughout the length of the tachycardia cycle. Furthermore, while focal atrial tachycardia due to microreentry may be successfully entrained, the ability to entrain an AT with characteristics of being “in the circuit” from two sites >2 cm apart is diagnostic of macroreentry.¹

Of note, the rate ranges of both focal atrial tachycardia and macroreentrant atrial tachycardia are too wide to be reliably used for determination of arrhythmia mechanism. As mentioned previously, the rate range of focal atrial tachycardia is usually between 130 and 250 bpm, but may be as low as 100 bpm or as high as 300 bpm. Similarly, while macroreentrant atrial arrhythmias usually have a rate between 240 and 310 bpm, conduction delays within the circuit due to either atrial pathology or use of conduction slowing antiarrhythmics can slow the rate to <150 bpm.

Recently, with the advent of 3D mapping systems, circuits with properties between those of micro- and macroreentry have been described. These reentrant circuits occur in a localized region with a diameter of 1 to 2 cm and have been described around a pulmonary vein, in the anterior left atrium, and in the septum. Evidence of markedly slowed conduction is usually present and many of these patients have had prior ablation procedures.

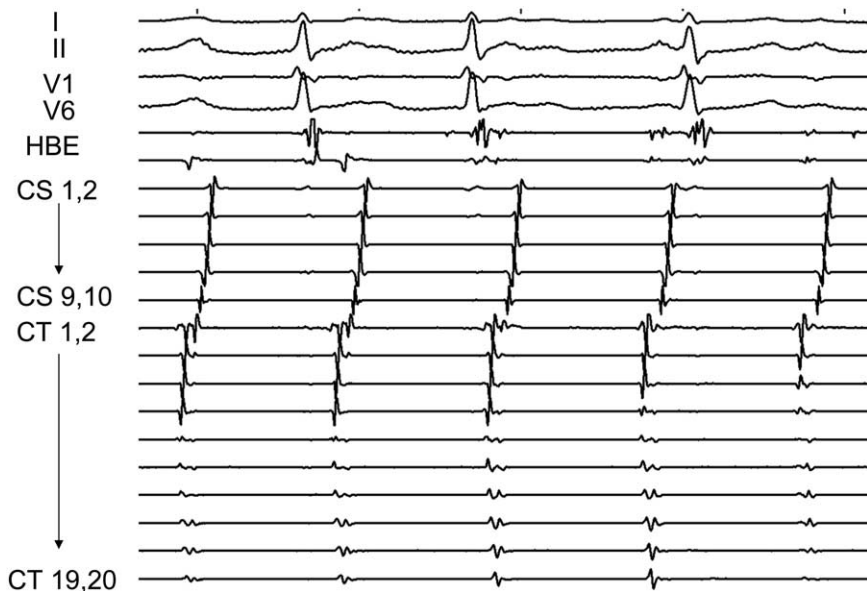


FIG 4. This figure shows intracardiac recordings during atrial tachycardia. Shown are surface ECG leads I, II, V₁, and V₆ together with intracardiac recordings from the coronary sinus (cs), the His bundle, and 20-pole catheter placed along the Crista terminalis (CT). The tachycardia in this case originated from the superior crista terminalis. Note that the recordings span only approximately 20% of the tachycardia cycle with electrical quiescence in between. This electrical quiescence corresponds with the isoelectric period on the surface ECG and is characteristic of focal atrial tachycardia.

Site of AT Focus

It is recognized that focal atrial tachycardias do not occur randomly throughout the atria but rather have a characteristic anatomic distribution. In the right atrium they tend to cluster around the crista terminalis, coronary sinus, parahisian region, tricuspid annulus, and right atrial appendage. In the left atrium, the majority originate from the pulmonary veins, with the mitral annulus, left atrial appendage, and left septum being less common.

Crista Terminalis

Kalman et al³⁷ demonstrated that approximately one-half to two-thirds of right atrial tachycardias arise from the crista terminalis. The crista terminalis is an area of marked anisotropy with poor transverse and rapid linear conduction,³⁴ creating a substrate for microentry. In addition, the sinus node complex is located along the crista terminalis,⁵¹ and the

presence of automatic tissue with anisotropy may favor abnormal automaticity. Ablation of tachycardias arising from the superior crista terminalis carries a small risk of damage to the right phrenic nerve with right diaphragmatic paralysis. Although most reports suggest that this is transient, prior to the application of radiofrequency, it is important to perform atrial pacing at high output to ensure the diaphragm is not paced via stimulation of the phrenic nerve.

Sinus Node Reentry

Early descriptions of atrial tachycardia designated a group of tachycardias as sinus node reentry. These tachycardias were defined as those that could be induced and terminated with programmed stimulation with P wave morphology identical or similar to that of the sinus P wave. However, since these early descriptions, it is now well recognized that the sinus node is not a discrete structure but rather a diffuse pacemaker complex located along the long axis of the crista terminalis. As such the sinus P wave morphology varies markedly according to where on the crista terminalis the focus arises. Atrial tachycardias have been described arising from sites along the length of this structure. Finally, reentry strictly limited to the histologic sinus node area has never been demonstrated. For these reasons it may be best to include those tachycardias previously designated as sinus node reentry within the category of atrial tachycardia arising from the crista terminalis.⁵²

Coronary Sinus Ostium

The coronary sinus (CS) ostium is an unusual site of origin of AT, accounting for approximately 7% of patients undergoing AT ablation.⁵³ Kistler et al⁵³ observed that the focus tended to be on the superior and posterior lips of the CS. The behavior of the AT was consistent with microreentry or triggered activity in 62% and automaticity in 38%. The ostium of the CS is characterized by the abrupt change in myocardial fiber orientation in the region of the Thebesian valve.⁵⁴ This region of change in fiber orientation may potentially provide the anisotropic conduction necessary for the initiation of reentry.

Atrial Septum

Several authors have described series of patients with AT originating from the septum.⁵⁵⁻⁶⁰ The majority of these AT have features consistent with a reentrant mechanism. The behavior and location of the AT suggest that the AV node or its transitional tissues are involved in the origin of the AT. Due to its close proximity to the AV node, care needs to be taken to

avoid AV block during ablation. However, successful radiofrequency ablation is achievable in the majority of cases, without complication.

Tricuspid Annulus

Morton et al⁶¹ described a series of patients with focal AT originating from the tricuspid annulus. These tricuspid annular AT comprised 13% of a consecutive series of right AT. Septal sites were excluded to clearly distinguish these from tricuspid annular sites. In that report, the majority of the AT foci were located in the inferoanterior segment of the tricuspid annulus but other reports describe foci from around the entire circumference of the tricuspid annulus. The tachycardia characteristics were consistent with a microreentrant mechanism in 66% and an automatic mechanism in 33%. The presence of cells with AV-nodal-type characteristics around the entire tricuspid annulus has been described in animals.^{62,63} These cells were histologically similar to the atrial cells but resembled nodal cells in their cellular electrophysiology, response to adenosine, and lack of connexin 43. They may also serve as the substrate for AT originating from around the TA.

Pulmonary Veins

The role of pulmonary vein (PV) ectopy in the pathogenesis of atrial fibrillation has been well described.⁶⁴ Whether AT from the pulmonary veins represents the same process is unclear. Kistler et al⁶⁵ described 27 patients with PV AT, comprising 16% of a total AT series. In contrast to PV AF, AT foci tend to be ostial, with longer cycle lengths. The majority of AT (78%), as with PV AF, originated from the superior veins with a smaller percentage from the inferior veins. Unlike patients with PV triggers and atrial fibrillation where there are usually multiple triggers in multiple veins, those patients whose sole clinical arrhythmia is atrial tachycardia appear to have an isolated or focal process and as such are curable in the long term with focal ablation. In the group of patients with pulmonary vein AT there was no tendency to develop further atrial arrhythmias during long-term follow-up. Also, when patients with PV AT presented with recurrence, in almost all instances this is from the original focus. The mechanism of pulmonary vein AT was most consistent with abnormal automaticity. In this group, high success rates can be achieved with focal ablation.

Melvin M. Scheinman: The authors' laboratory has nicely distinguished the differences between pulmonary vein tachycardia, which is associated with initiation of atrial fibrillation, versus pulmonary vein tachycardia. The latter

arises from the ostium of the vein and they have shown that it is safe to ablate these tachycardias at the ostium. In contrast, circumferential ablation at multiple ostial sites or ablation within the vein carries a significant risk of pulmonary venous stenosis and attendant risk of loss of pulmonary parenchyma.

Mitral Annulus

In the left atrium, the mitral annulus is the second most common location of focal AT. In left atrial series, 28 to 36% of AT are located on the mitral annulus.^{66,67} Kistler et al⁶⁸ were the first to describe an unusual mitral annular site of origin from the region of the aorto-mitral continuity in the region of the left fibrous trigone. In this series, seven patients (4%) of a consecutive series of 172 right and left atrial AT had foci in this unusual location.^{55,67,68} Gonzalez et al⁶⁷ subsequently demonstrated that early in murine development the specialized conduction system ran between these two structures and hypothesized that remnants of this system may provide the substrate for focal AT arising in this region. Wit et al^{69,70} showed that muscle fibers of the anterior mitral valve leaflet are continuous with the left atrial myocardium and these exhibit AV-nodal-type characteristics with both spontaneous automaticity and anisotropic conduction properties, suggesting several potential tachycardia mechanisms.

Other Locations

Unusual sites of focal AT include the right atrial appendage, left atrial appendage,⁶⁶ superior vena cava,⁷¹ body of the coronary sinus,^{72,73} fossa ovalis, and the left side of the septum.⁵⁹

P Wave Morphology

The P wave morphology of focal AT is determined by the site of origin of atrial activity and the pattern of atrial activation and can provide useful clues to the likely site of tachycardia origin. Studies looking at P wave morphology have mainly involved patients with structurally normal atria. These P wave configurations cannot be extrapolated to patients with abnormal atrial anatomy. Analysis of P wave morphology is frequently compromised by being totally or partially obscured by the preceding T wave. When evaluating the P wave morphology, it is very important to analyze the initial P wave vector and ensure that this is not partially obscured by the T wave. To this end, we have included for analysis only those P waves clearly preceded by an isoelectric baseline. When necessary, the P wave may be separated from the T wave by vagal maneuvers,

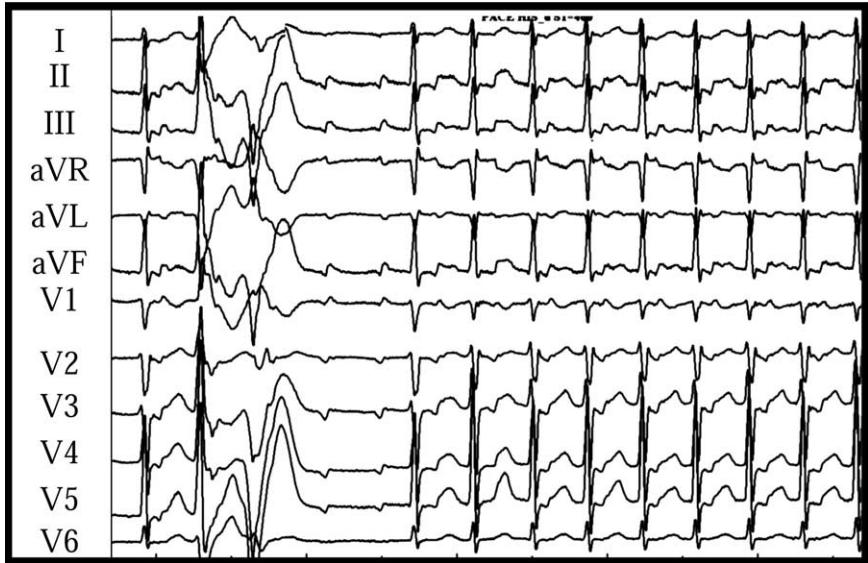


FIG 5. Continuous 12-lead ECG of a patient with left septal atrial tachycardia. Note the difficulty in assessing P wave morphology when the P wave is buried within the T wave. In this case a burst of ventricular pacing separated the P waves off the T wave allowing clear assessment of the P wave morphology. This may also be achieved with vagal maneuvers or adenosine.

adenosine, or following termination of ventricular pacing (Fig 5). Analysis of the P wave morphology is also limited by its spatial resolution. Man et al⁷⁴ assessed the spatial resolution of P wave morphology using unipolar atrial pace mapping at different sites. Pacing at sites as far apart as 32 mm in the coronary sinus and 17 mm in the right atrium resulted in P waves identical in appearance.

Notwithstanding these limitations, P wave morphology can provide useful clues to tachycardia location.

Melvin M. Scheinman: An additional confounding problem of matching the P wave to the site of origin of atrial tachycardia is that the P wave configuration is in large part dependent on left atrial activation. Hence despite differences in site of origin, similar sequences of left atrial activation may yield nearly identical P waves. For example, flutter waves in patients with typical counterclockwise flutter may be similar to those with foci in the coronary sinus muscle.

The Sinus P Wave

Physiologically, the sinus node is not a discrete, localized structure but in fact the sinus P wave arises from a pacemaker complex which extends

from the junction of the superior vena cava and right atrial appendage, along the sulcus terminalis virtually to the inferior vena cava.⁵¹ In patients with normal sinus node function the sinus node activity is located in the superior two-thirds or spans the length of the crista terminalis and the sinus node impulse exits simultaneously on either side of the crista terminalis, with rapid activation in both septal and anterior directions.³⁶

Schamroth⁷⁵ described the sinus P wave as pyramidal in shape, not exceeding 2.5 mm in height or 110 ms in duration in any standard leads. The normal mean frontal plane axis ranges from 0 to +70°; however, it is usually between +40 and +60°. The P wave is therefore tallest in lead II. With the mean frontal axis between +30 and +60°, leads I, II, III, aVF, and aVL have positive deflections. Movement of the heart due to respiration may slightly alter the P wave axis, especially in lead aVL if the axis is +60° and lead III if the axis is +30°. In both these leads the P wave may be positive, isoelectric, or negative. In lead V₁, the P wave is biphasic, initially positive followed by a slightly larger negative deflection.

Sinus Tachycardia versus AT

The P wave morphology of sinus tachycardia is identical to the sinus P wave (Fig 6). Differentiating AT from sinus tachycardia on the ECG can at times be difficult, particularly for tachycardias originating at the superior crista terminalis. Although the P wave in AT usually has a different morphology to the sinus P wave, in AT from the superior crista terminalis these differences may be subtle (Fig 7). Frequent spontaneous ectopic activity or nonsustained bursts of tachycardia may allow a direct comparison if the tachycardia P wave is visible. Like sinus rhythm, focal AT may have a long R-P interval, defined as greater than 50% of the R-R interval, but at very rapid rates with AV nodal conduction delay the apparent R-P may be short. An abrupt onset and termination of the tachycardia or warm-up and cool-down over three to four beats favors AT, whereas sinus tachycardia gradually increases and decreases in rate over approximately 30 seconds to several minutes.

AT versus AVNRT/AVRT

The most important differentiating factor on ECG between AT and AVNRT and AVRT is the R-P relationship. Both typical AVNRT and AVRT have a short R-P interval which does not vary (the former superimposed on the QRS and the latter in the ST segment) and the P wave morphology usually cannot be clearly discerned (Figs 8 and 9). In AT there is no fixed relationship between the R and P wave and

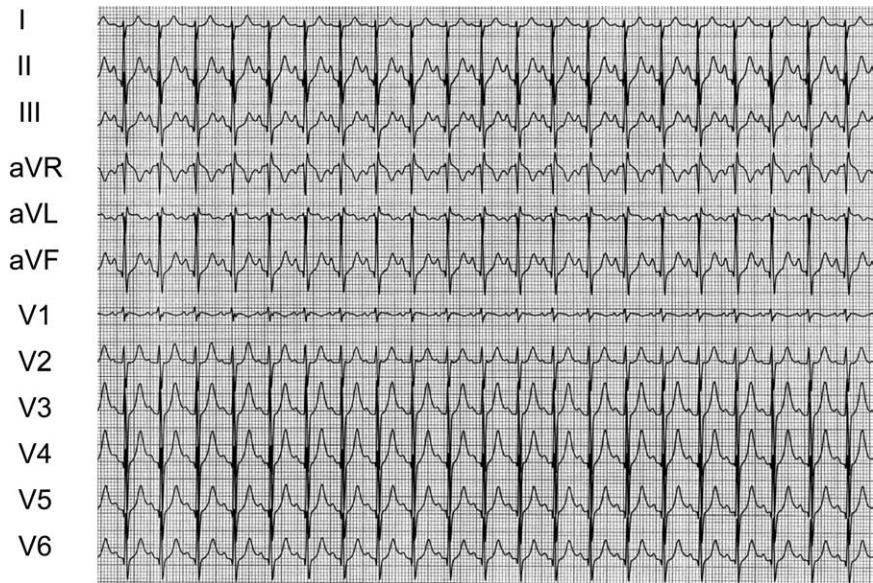


FIG 6. Continuous 12-lead ECG of sinus tachycardia at 150 bpm from a patient with inappropriate sinus tachycardia. This ECG appearance is indistinguishable from an atrial tachycardia originating from the superior crista terminalis. The differentiation is made on a number of clinical and electrophysiologic criteria (see text).

“unhooking” of the R-P (when present) invariably indicates atrial tachycardia. AT most usually is associated with a long R-P interval but may have a short R-P at rapid rates. Both atypical AVNRT and a concealed accessory pathway with slow retrograde conduction may have long R-P intervals but both of these will exhibit a superiorly directed P wave vector. While the P wave vector may also be superiorly directed for atrial tachycardias originating from the CS ostium and annular structures, other atrial tachycardias will demonstrate an inferior vector which effectively excludes atypical AVNRT or AVRT.

Right AT versus Left AT

The two leads which have been shown to be the best discriminators between foci originating in the left and right atrium are V₁ and aVL.^{76,77} Tang et al⁷⁶ assessed P wave morphology in 31 patients, 14 with left atrial foci. All but one of the left atrial AT had a positive P wave in V₁. This is due to the posterior midline location of the left atrium and subsequent anterior activation. The criterion that a positive P wave in V₁ indicates a left atrial focus had a sensitivity of 93%, specificity of 88%, positive-

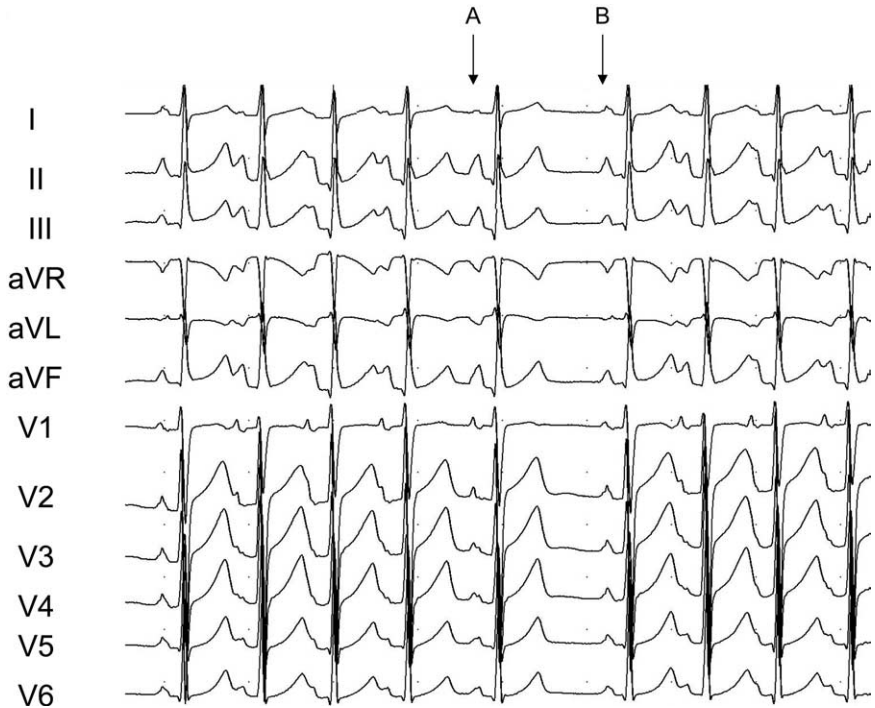


FIG 7. Bursts of atrial tachycardia from the high medial extent of the crista terminalis. This demonstrates the similarity in P wave morphology between sinus rhythm and atrial tachycardia from this region. Note in this example that tachycardia warms up over two to three beats with tight coupling such that the P wave falls in the preceding T wave. This appearance and behavior rules out sinus tachycardia. A. Beat of atrial tachycardia. B. Sinus beat.

predictive accuracy of 87%, and negative-predictive accuracy of 94%. A negative P wave in V_1 predicted a right atrial focus. Care must be taken to observe the initial P wave vector as P waves in V_1 with an initial isoelectric segment followed by an upright component frequently indicate an origin near the coronary sinus ostium or from the right septum. If the isoelectric segment is overlooked and the P wave is simply described as upright, this will lead to incorrect localization to the left atrium. A positive or biphasic P wave in lead aVL indicates a right atrial focus with a sensitivity of 88%, specificity of 79%, positive-predictive accuracy of 83%, and a negative-predictive accuracy of 85%.

While these criteria are useful to predict general regions of AT foci, certain anatomic locations tend to be associated with specific P wave morphologies.



FIG 8. 12-Lead ECG of atrioventricular nodal reentrant tachycardia (AVNRT). Note the short R-P interval which remains constant. In this case the P wave is seen at the end of the S wave in lead V₁ (arrow). Due to the superimposition of the QRS complex, morphological assessment of the P wave is virtually impossible.

Crista Terminalis

Due to the length of the crista terminalis, there is a variety of P wave morphologies from AT foci located on this structure. The majority of AT from the mid and superior crista terminalis have biphasic P waves in lead V₁, similar to the sinus P wave, with an initial positive component followed by a negative component.³⁷ AT from the low crista terminalis often have negative P wave in V₁. The P wave in lead I is positive from most crista sites. Lead aVR is negative. Tada et al⁷⁸ used this to differentiate posteriorly located crista sites from more anteriorly located sites in the right atrium which had upright P waves in aVR. Foci located in the superior crista terminalis have positive P waves in the inferior leads, whereas the P waves are isoelectric or biphasic in these leads for mid crista locations and negative for inferior foci.

Coronary Sinus Ostium

Tachycardia foci from the CS ostium have characteristic P wave morphology in the precordial leads. Lead V₁ has an initial component which is either isoelectric or mildly inverted followed by an upright



FIG 9. 12-Lead ECG of orthodromic atrioventricular reentrant tachycardia due to a left lateral pathway. In this case the P wave is seen just prior to the peak of the T wave (arrow). Note the R-P interval is longer than in AVNRT. P wave morphology is difficult to assess due to the presence of the T wave.

component (Fig 10).⁵³ Across the precordial leads the initial component becomes more negative and the second component becomes isoelectric. Lead aVL is positive and the P waves are deeply negative in the inferior leads. The P wave morphology is similar to that of typical atrial flutter, which has an exit zone at the CS ostium.⁷⁹ Foci located within the body of the CS will have a P wave in V₁, which is upright from the onset without an isoelectric segment, and P waves are frequently upright across the precordial leads.

Atrial Septum

AT originating from the anterior and mid septum have narrower P waves than during sinus rhythm.^{57,59} Lead V₁ is isoelectric or biphasic, with an initial negative or isoelectric component, followed by a positive component. Anteroseptal foci have positive P waves in the inferior leads, whereas midseptal foci tend to be negative.⁵⁸ The majority of left septal foci have a completely positive P wave in V₁, but the morphology may be variable (Fig 11).^{57,59}

Aortic-mitral continuity

Coronary sinus ostium

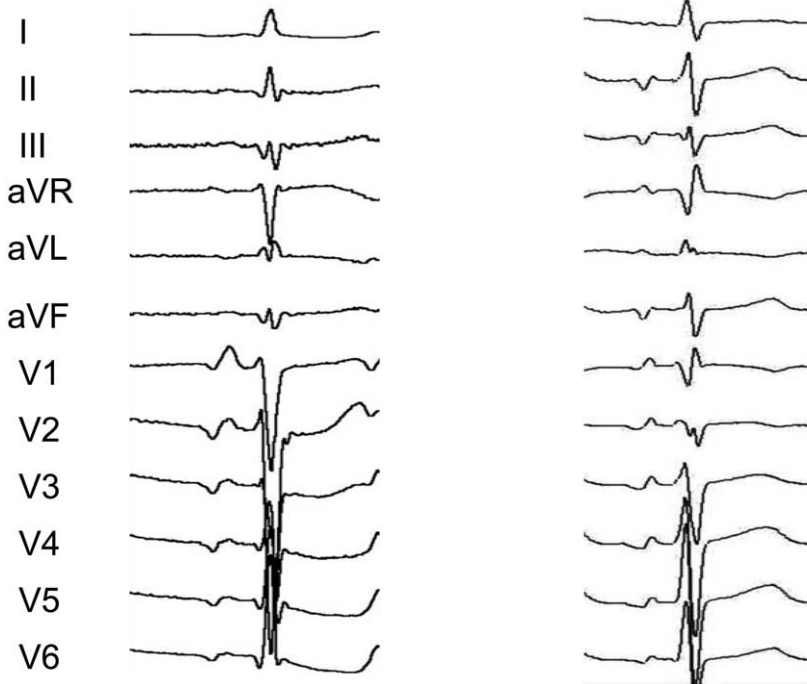


FIG 10. Atrial tachycardia from the coronary sinus ostium and the superior mitral annulus at the aortic-mitral continuity. Note the similar P wave morphologies in lead V₁ and the precordial leads. Atrial tachycardia from the CS os has negative P waves in the inferior leads and a positive P wave in lead aVL. Atrial tachycardia from the superior mitral annulus at the aortic-mitral continuity has low-amplitude P waves in the limb leads. Lead aVL is negative and the inferior leads are positive.

Tricuspid Annulus

Tricuspid annular AT have negative P waves in V₁, which may also be notched (Fig 12).^{61,78} This is due to the anterior location of the tricuspid annulus, resulting in atrial activation in the posterior direction, away from V₁. Lead aVL is invariably positive. The morphology of the P wave in the other leads depends on the site of the focus on the tricuspid annulus. Inferior foci tend to have negative P waves in leads II, III, and aVF, whereas superior foci are usually isoelectric or positive. Foci from the adjacent right atrial appendage have similar P wave morphologies to the superior tricuspid annulus.

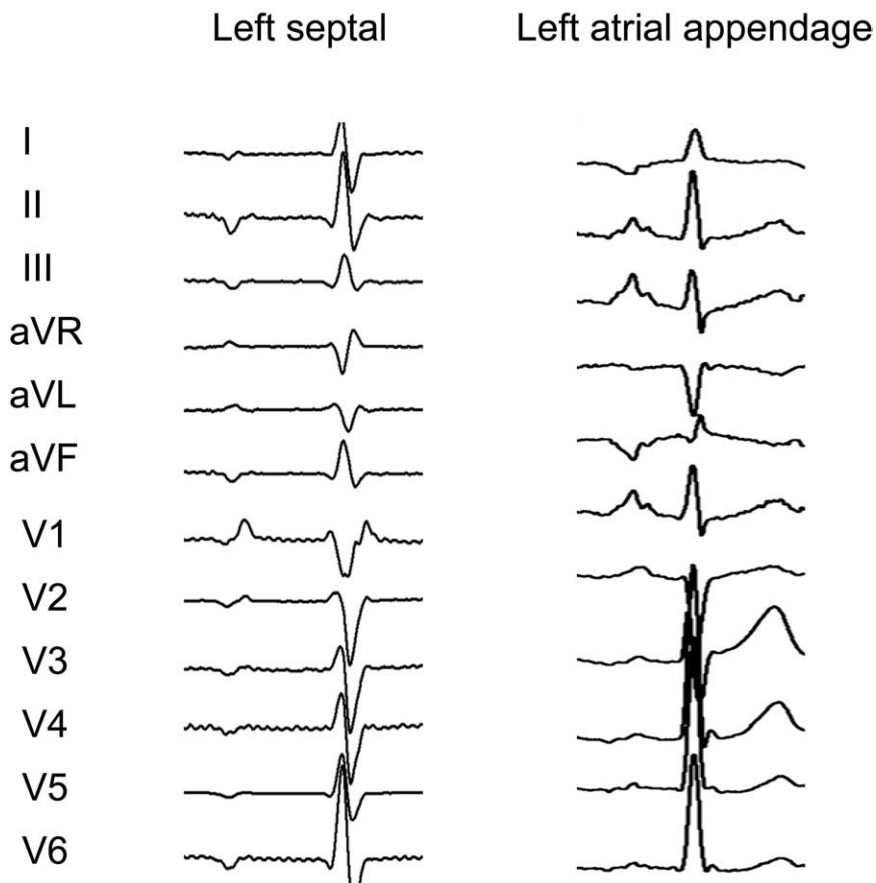


FIG 11. P waves from atrial tachycardias located on the left side of the septum and left atrial appendage. Note the initial negative deflection in lead V₁ of the P wave from the left septum. The morphology is similar to atrial tachycardia from the aortic-mitral continuity and CS os. P waves originating from the left atrial appendage are similar to those from the left upper pulmonary vein. The P waves in the inferior leads and V₁ are positive, broad, and notched. Lead I is often more negative than those P waves from the left upper pulmonary vein.

Pulmonary Veins

Focal AT from the pulmonary veins (PV) have a positive P wave across the precordium, from V₁ to V₆ (Fig 13).^{65,76} P wave characteristics assist in the localization of the focus to a particular PV. P waves from the left-sided PVs are generally broad in V₁ and are notched, particularly in the inferior leads, but also in V₁.⁶⁵ A positive P wave in lead I is highly suggestive of a focus in the right-sided PV and an inverted P wave suggestive of a left-sided PV. An upright P wave in aVL is consistent with

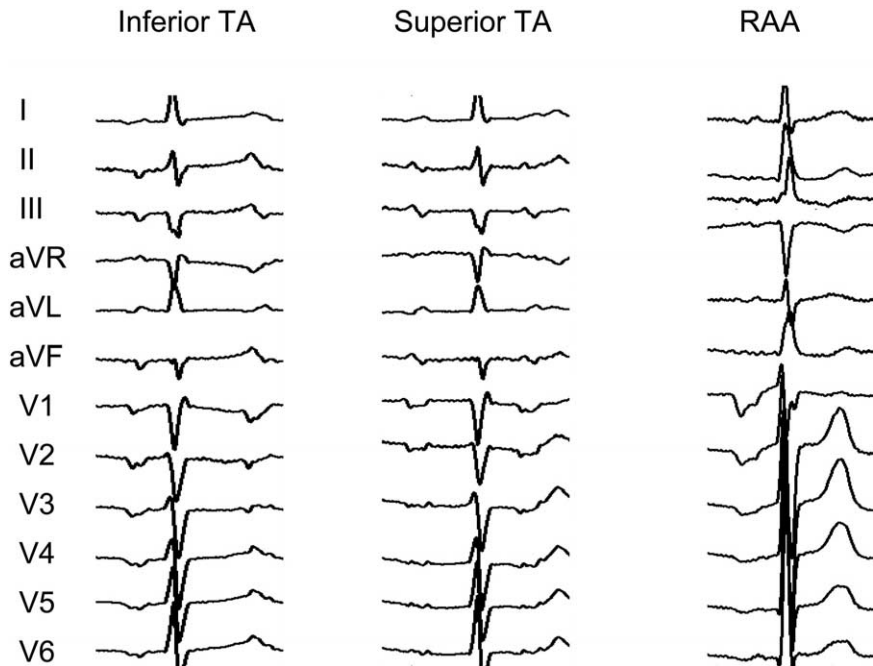


FIG 12. P wave morphology of atrial tachycardia from the inferoanterior tricuspid annulus (TA), superior TA, and the right atrial appendage (RAA). P waves from the TA are negative in the precordial leads. Note the bifid appearance of the P wave in the precordial leads, commonly seen in these sites. Inferior locations have negative P wave in the inferior leads. Superior locations and those arising from the right atrial appendage (RAA) have low-amplitude P wave in the inferior leads. Note the similarity between the superior TA and the RAA, consistent with their proximity.

a right-sided PV focus.^{65,66,77,80} However, right-sided PV may also have negative P waves in aVL.^{65,76} Left pulmonary vein sites generally have broader P waves than right-sided pulmonary vein sites.⁶⁵ An algorithm by Ellenbogen and Wood⁸¹ used a P wave duration of ≥ 80 ms to differentiate left pulmonary veins from right. The inferior leads may be used to differentiate superior from inferior PV sites as the P waves from the superior PV are upright with high amplitude with lower amplitude P waves from the inferior PV. Foci from the left atrial appendage have positive P waves in lead V₁ and a similar appearance to foci from the left upper PV but are deeply negative in lead I (Fig 11).

Mitral Annulus

Kistler et al⁶⁸ demonstrated that AT from the superior mitral annulus at the aorto-mitral continuity had biphasic P waves in V₁, with an initial

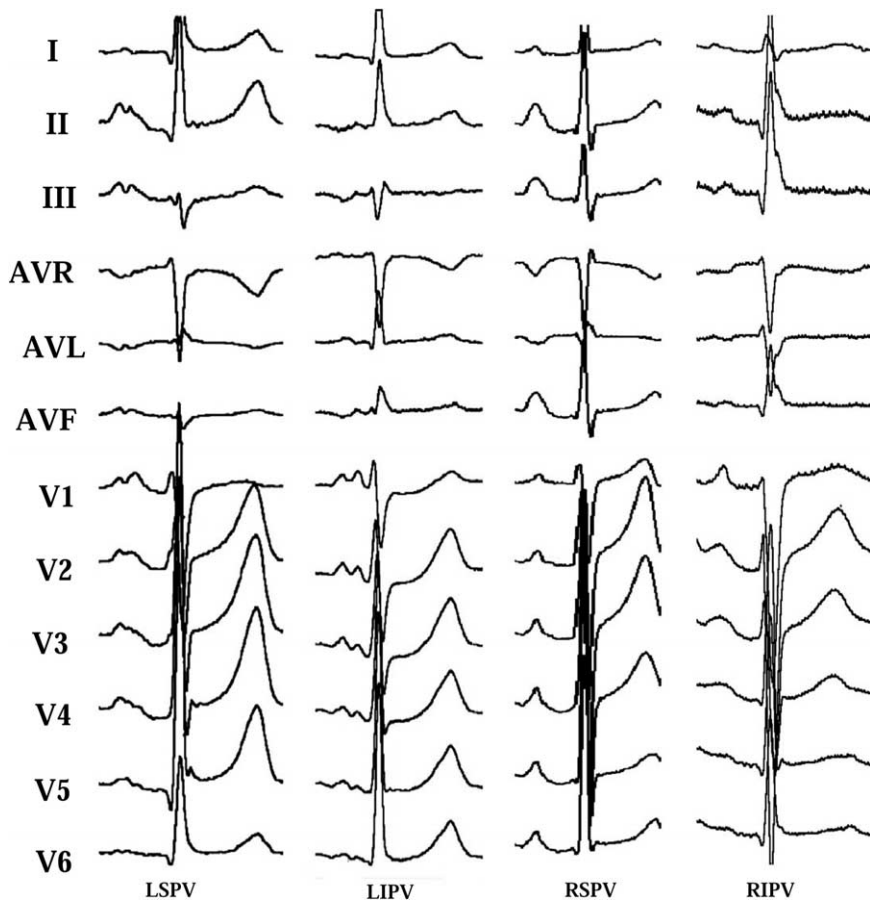


FIG 13. P waves originating from the left superior pulmonary vein (LSPV), left inferior pulmonary vein (LIPV), right superior pulmonary vein (RSPV), and the right inferior pulmonary vein (RIPV). Left-sided pulmonary veins are characterized by notching of the P waves in the inferior leads and lead V₁, significantly broader V₁, and isoelectric or negative lead I. Large-amplitude P waves in the inferior leads suggest a superior vein, low-amplitude or isoelectric P waves suggest inferior veins. (From Kistler et al. *Circulation* 2003;108:1968-75. Reproduced with permission.⁶⁵)

sharp negative deflection followed by positive deflection (Fig 10). P waves in the limb leads for AT at this site are of low amplitude, with negative P waves in aVL and positive P waves in the inferior leads.⁶⁶⁻⁶⁸

Inappropriate Sinus Tachycardia

Inappropriate sinus tachycardia (IAST) is a poorly defined clinical syndrome characterized by an elevated resting heart rate, exceeding 100

bpm, or an exaggerated heart rate response to exercise or stress.⁸²⁻⁸⁶ The diagnosis can be made after documentation of (1) the presence of a persistent sinus tachycardia (heart rate more than 100 bpm) during the day with an excessive rate increase in response to activity and nocturnal normalization of rate as confirmed by 24-hour Holter monitoring; (2) the tachycardia and symptoms are nonparoxysmal; (3) the P wave morphology and endocardial activation are identical to sinus rhythm; (4) exclusion of a secondary systemic cause (eg, hyperthyroidism, pheochromocytoma).⁸⁷ Patients are generally young women, aged between 20 and 45 years, with a diverse range of symptoms, including palpitations, dyspnea, chest discomfort, and presyncope.^{83,86} The degree of disability can vary, from asymptomatic patients to those completely incapacitated. A high proportion of patients are health care professionals.⁸⁸ Clinical diagnosis involves careful correlation between symptoms and documented tachycardia and exclusion of secondary causes and atrial tachycardia.

The underlying mechanism of inappropriate sinus tachycardia is not well understood. This is partly related to the heterogenous nature of the condition. Suggested mechanisms include enhanced intrinsic automaticity, enhanced sympathetic tone, increased sympathetic receptor sensitivity, and reduced parasympathetic tone.^{83,84,89} There is overlap with another dysautonomic syndrome, postural orthostatic tachycardia.⁹⁰

Electrophysiological findings include the demonstration of an automatic mechanism, with gradual increase in rate in response to isoproterenol and gradual decrease in rate when sympathetic stimuli are removed. The tachycardia is unresponsive to programmed stimulation. Inappropriate sinus tachycardia can at times be difficult to differentiate from a focal atrial tachycardia arising high on the crista terminalis. In comparison to IAST, focal AT (1) has sudden onset and termination; (2) frequently demonstrates tightly coupled activity with the P wave in the T wave at the time of onset. In contrast, IAST has gradual increase in rate; (3) has a fixed site of origin. Speeding may occur in response to isoproterenol but site of origin does not alter. In contrast, in IAST the sites of activation shift superiorly along the crista with isoproterenol; (4) demonstrates normal heart rate in between paroxysms of atrial tachycardia.

The use of pharmacological therapy depends on the degree of disability. The ACC/AHA/ESC Guidelines for the Management of Supraventricular Arrhythmias⁸⁸ advocate the use of beta-blockers as the initial choice, although no randomized, double-blinded, placebo controlled trials exist. Verapamil and diltiazem may also be effective.⁸⁸ A significant proportion of patients fail medical therapy and these patients have been offered radiofrequency ablation.^{82,85,86,90} Mapping should be undertaken on

isoproterenol, searching for the site of earliest activation, located at the most superomedial region of the crista terminalis. Ablation of the sinus node is continued inferiorly until there is a reduction in the sinus rate of 25%.⁸² Sinus node modification is not a focal ablation and Marrouche et al⁸⁶ estimated the ablated area to measure 12 by 19 mm. Care needs to be taken to avoid phrenic nerve damage.^{82,85,86}

Different studies have used different mapping and ablation techniques. Lee et al⁸² used activation mapping and intracardiac echocardiography to define the region of the sinus node. The use of intracardiac echocardiography reduced the number of radiofrequency applications and fluoroscopy time. Marrouche et al⁸⁶ used three-dimensional mapping (CARTO) to identify the target site of ablation, with an acute success rate of 100%. Man et al⁸⁵ demonstrated that the use of activation mapping alone could only ablate 76% of patients successfully. Prior to ablation, evaluation of autonomic function is required as there appears to be little improvement in these symptoms. Shen et al⁹⁰ performed sinus node modification on patients with inappropriate sinus tachycardia and postural orthostatic

TABLE 1. Patient and atrial tachycardia characteristics from series of focal atrial tachycardias treated with radiofrequency ablation

	No. of patients	No. of AT	Male (%)	Mean age	Structural HD (%)	Mechanism	TCL (ms)
Walsh et al ²⁴	12	12	NA	12	100	12A	NA
Chen et al ¹²⁹	7	10	86	57	29	10R	406
Kay et al ¹²⁵	15	16	47	50	40	9A/2NonA/4SNR	NA
Goldberger et al ¹³⁰	15	15	47	38	33	11A/4R	372
Tracy et al ¹¹²	10	#	70	32	30	NA	364
Chen et al ¹¹	36	43	69	57	31	27R/7A/9T	373
Lesh et al ³⁸	14	15	NA	36	57	3SNR/12A	374
Wang et al ¹²³	12	14	33	33	25	12A/2SNR	400
Poty et al ¹²⁴	36	#	39	40	36	16R/2A	NA
Pappone et al ¹¹⁴	45	45	56	29	51	45A	335
Natale et al ¹¹⁵	24	29	42	59	NA	NA	NA
Kalman et al ³⁷	27	31	37	41	11	NA	378
Anguera et al ¹²⁸	105	105	30	48	17	40R/23A/42unk	385
Weiss et al ¹¹⁸	15	15	40	51	0	NA	379
Schmitt et al ¹²¹	10	10	50	55	70	2A/8NonA	NA
Hoffmann et al ¹¹⁶	42	45	33	51	10	15A/30NonA	373
Kammeraad et al ¹⁰	38	45	18	46*	0	45NonA	380
Hija et al ³¹	13	14	54	45	23	NA	394

Series of atrial tachycardias from specific sites are not included. Only patients with focal atrial tachycardia are included. AT, atrial tachycardia; TCL, tachycardia cycle length; NA, not available; A, automatic; R, reentry; T, triggered; NonA, nonautomatic; SNR, sinus node reentry; # = 3 patients had multiple AT; *median.

tachycardia. Despite a reduction in heart rate following ablation, symptoms related to autonomic dysfunction were unchanged. Short-term success rates can be accomplished in between 70 and 100% of patients with inappropriate sinus tachycardia; however, long-term outcomes have been disappointing.^{82,85,86,90} Indeed, in view of the high late recurrence rates and the probability that the mechanism of tachycardia is not intrinsic to the sinus node in many patients we have largely abandoned this procedure in our institution. A new selective I_f current inhibitor, ivabradine, developed for use in angina, slows the sinus rate and may have a role in therapy.⁹¹

Melvin M. Scheinman: The diagnosis of IST should properly be made on the basis of clinical criteria as outlined by the authors. The invasive EP laboratory evaluation adds little. I fully agree with the pessimistic outlook relative to the value of catheter ablation of the sinus node with respect to achieving long-term control of the arrhythmia.

Multifocal Atrial Tachycardia

Multifocal atrial tachycardia (MAT) has been defined as a rhythm with an atrial rate >100 bpm, at least three morphologically distinct P waves, irregular P-P intervals, and an isoelectric baseline between P waves.⁹² There is debate regarding whether there needs to be two or three distinct P waves in addition to the sinus P wave.^{93,94} MAT most commonly occurs in elderly patients during an acute exacerbation of chronic pulmonary disease. It appears to be a poor prognostic marker,⁹² although the high mortality rate is likely to be due to the severe underlying illnesses rather than the arrhythmia itself. MAT is thought to be due to triggered activity from increased intracellular calcium produced by hypoxemia, hypokalemia, acidemia, and high levels of catecholamines.^{95,96} The cornerstone of treatment is reversal of the precipitating cause and treatment of the underlying condition. If the tachycardia persists, careful evaluation of the clinical significance of the arrhythmia is required prior to antiarrhythmic therapy. Metoprolol has been shown to be more effective than verapamil in treating MAT but is frequently contraindicated in this population. Arsura et al⁹⁷ compared verapamil and metoprolol in a randomized, double-blind, placebo-controlled trial. A response to therapy was seen in 20, 44, and 89% of patients treated with placebo, verapamil, and metoprolol, respectively. Metoprolol was more effective than verapamil for rate control. Metoprolol should be first-line therapy, although care needs to be taken as it may worsen bronchospasm.

High-dose magnesium has also been shown to be effective. McCord et al⁹⁸ performed a single-blind, placebo-controlled trial of intravenous magnesium in patients already on antiarrhythmic therapy. Four of nine patients in the magnesium group and none of the five patients in the placebo group were in sinus rhythm at the end of the infusion. Studies on the use of verapamil have shown inconsistent results.^{96,97,99} DC cardioversion and focal radiofrequency ablation have not proven effective in this patient population. However ablation of the AV node and pacemaker insertion could be considered if other measures fail.

Management

The efficacy of various therapies is difficult to assess because the clinical definition of focal AT is often difficult to rigorously apply and no large studies have evaluated the effect of nonablative therapies on focal AT (Table 1).

Acute Treatment

Vagal maneuvers are generally unsuccessful in terminating focal AT. The role of DC cardioversion is also limited. Automatic AT is unresponsive to DC cardioversion,¹⁰⁰ although it may be successful for those whose mechanism is microreentry or triggered activity. Similarly, overdrive pacing suppresses automatic AT but does not result in termination,^{11,101} whereas it is often successful in AT due to microreentry and triggered activity.¹¹ As discussed earlier, focal AT may be adenosine sensitive. Atrial tachycardia due to microreentry and triggered activity is frequently terminated, and transient suppression of automatic AT is often seen.¹¹

AV-nodal blocking agents are useful in controlling the ventricular rate. Intravenous beta-blockers may also terminate AT due to abnormal automaticity and triggered activity.^{11,16} Nonautomatic AT are also frequently terminated by verapamil.¹¹ Class Ic drugs may suppress automaticity or prolong action potential duration and several studies have shown these to be efficacious in terminating focal AT.¹⁰²⁻¹⁰⁴

Long-Term Pharmacological Therapy

The available studies regarding long-term medical therapy of focal AT are observational, with small numbers. Most focus on automatic AT, and there are few involving adults, with children and infants comprising the majority of the patients. There is widespread agreement that antiarrhythmic agents have low efficacy in the treatment of focal AT.

The ACC/AHA/ESC Guidelines for the Management of Supraventricular Arrhythmias⁸⁸ recommend the use of calcium channel blockers and

beta-blockers as first-line agents due to their low side-effect profile. Mehta et al¹⁶ found that in patients on digoxin the addition of propranolol suppressed the AT in 5 of 10 children. This is similar to results of other pediatric studies^{14,105}; however, the use of beta-blockers alone in adults appears to have no effect.¹⁰⁶ Prager et al¹⁰⁶ also observed verapamil to be completely ineffective. These medications, along with digoxin, have a role in controlling the ventricular rate.

Class Ia, class Ic, and class III agents are regarded as second-line agents.⁸⁸ Studies have demonstrated success rates of only 10 to 20% with quinidine and procainamide, with acceleration of the tachycardia sometimes observed.^{16,106} Class Ic medications appear relatively efficacious. In 13 patients, Kuck et al¹⁰³ showed flecainide completely suppressed the AT in seven patients, with partial suppression in another five patients. Its effectiveness has been confirmed by some studies^{102,107} but not others.^{13,106} Other class Ic agents, encainide and propafenone, have shown some success.^{13,100,102,104,108} The class III antiarrhythmic drugs, sotalol and amiodarone, appear to provide the best results. In five patients who had failed a mean of three antiarrhythmic drugs, the addition of sotalol to digoxin suppressed the AT in all patients.¹⁰⁹ Several investigators have reported a good response of automatic AT to amiodarone^{16,110,111}; however long-term therapy may be limited by its side effects.

In view of the limited long-term efficacy of pharmacologic therapy, radiofrequency ablation may be considered a first-line therapeutic modality for patients with significant symptoms.

Mapping and Ablation

A range of different techniques have been used for mapping and ablation of focal atrial tachycardia.

Endocardial Activation Mapping

Endocardial activation mapping is the most commonly used technique to identify the location of the AT focus. In our center, endocardial activation mapping begins with catheters placed in the bundle of His area and the coronary sinus. Other specially designed catheters which accommodate specific structures, the 20-pole Cristal (crista terminalis) catheter and Halo (tricuspid annulus) catheter, may help to locate the focus. However, precise localization must be achieved with detailed mapping in the region of interest. Generally activation time of >20 to 30 ms before the P wave are observed at successful sites but this is highly variable.

When P wave onset cannot be consistently observed, mapping can be performed to a stable intracardiac fiducial point with a known relationship to P wave onset.

A complementary method is the so-called leap-frog mapping technique whereby two ablation catheters are moved alternately to identify a site of earlier activation. Once a site is located, the catheter becomes a reference point and the other searches for a site of even earlier activation.

The close proximity of the posterior right atrium and the right pulmonary veins can produce similar endocardial activation sequences for tachycardias in these two locations. Yamada et al⁷⁷ used a multielectrode catheter to show double potentials in the posterior right atrium in patients with AT from these sites. During tachycardia, if the amplitude of the first potential was greater than that of the second potential, this indicated a right posterior atrial focus. Right PV foci demonstrated a larger second potential than first potential. Analysis of the P wave configuration showed that lead V₁ was the best ECG lead to differentiate between these sites.

Paced Endocardial Activation Sequence Mapping

Paced activation sequence mapping has been used to complement activation mapping. The ablation catheter is maneuvered to a position where the paced activation sequence reproduces the spontaneous endocardial sequence (Fig 14). Tracy et al¹¹² matched the paced endocardial map to the spontaneous map for right atrial tachycardias. Using this technique combined with activation mapping, they reported a success rate of 80%. Paced activation sequence mapping may be helpful when the tachycardia is nonsustained or difficult to induce. Using a standardized set of right atrial catheters, Deen et al¹¹³ demonstrated a characteristic right atrial activation map created by pacing each pulmonary vein corresponded closely with the map from the same pulmonary vein during rapid atrial tachycardia and initiation of focal AF. The pulmonary vein of origin could be distinguished on the basis of this characteristic pattern.

Mechanical Interruption

Pappone et al¹¹⁴ evaluated the predictive value of intentionally applying pressure to identify successful ablation sites. Mechanical interruption was observed in 76% of successful ablation sites but also in 28% of unsuccessful sites, with a sensitivity, specificity, and positive-predictive value of 76, 71, and 45%, respectively. In this study, mechanical interruption was nevertheless a better predictor of success than pace mapping or an activation time to P wave of >30 ms. It also improved the specificity and positive-predictive value of the other techniques.



FIG 14. Activation mapping and pace mapping in a patient with atrial tachycardia originating from the left lower pulmonary vein. Shown are the surface leads I, aVF, V₁, and V₆ with intracardiac recordings from a His catheter, CS catheter, 20-pole crista catheter, and an ablation catheter. In this case the fiducial point was activation of CS 1,2, which had a known relation to the onset of the P wave. The pulmonary veins were mapped with the ablation catheter and the site of earliest activation was at the left lower pulmonary vein, 60 ms ahead of the fiducial point (left panel). Pacing from this site reproduced the activation sequence of the spontaneous beat (right panel). The application of radiofrequency at this site was successful. (From Deen et al. *J Cardiovasc Electrophysiol* 2002;13:101-7. Reproduced with permission.¹¹³)

New Mapping Techniques

The advent of 3D mapping systems has simplified the mapping and ablation of focal atrial tachycardia and allowed a significant reduction in fluoroscopic time and radiation exposure. The three-dimensional electroanatomic system (CARTO; Biosense Webster) is based on sequential mapping technology allowing detailed reconstruction of chamber geometry and activation sequence. Natale et al¹¹⁵ demonstrated that electroanatomic mapping was able to quickly and accurately construct a 3D geometry of the chamber and map the location of the AT focus. A number of studies have demonstrated the ability of electroanatomic mapping to provide a high-resolution map in the region of earliest activation and precisely locate the focus in relation to endocardial geometry (Fig 15).¹¹⁵⁻¹¹⁹ The main limitation is the requirement for regular ectopics or

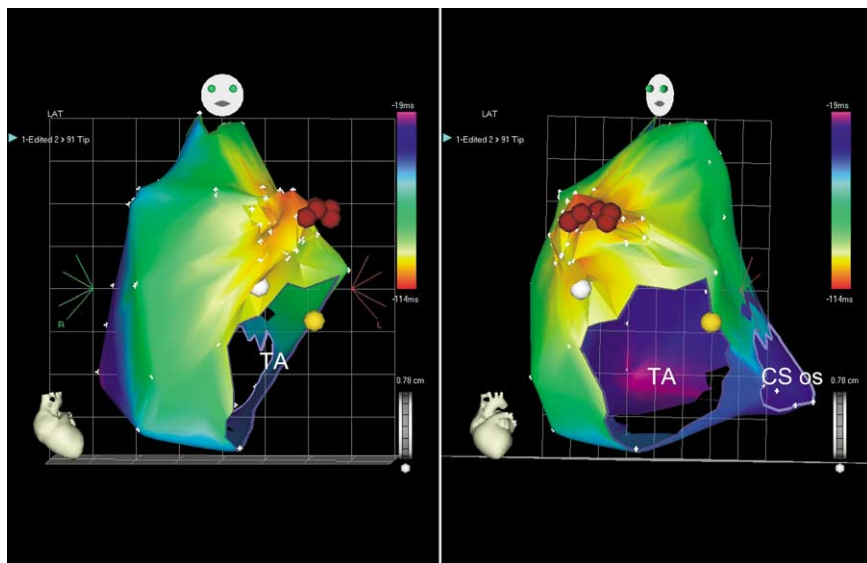


FIG 15. 3D electroanatomic (CARTO) maps in a patient with an atrial tachycardia originating from the tip of the right atrial appendage. The left panel shows an anterior-posterior view of the right atrium. The right panel views the right atrium from the left anterior oblique view. The yellow dot localizes the His position. Note the centrifugal activation from the site of origin (red to blue) and the precise localization of the focus in relation to endocardial geometry. The red dots indicate the sites of radiofrequency ablation. TA = tricuspid annulus; CS os = coronary sinus ostium.

sustained tachycardia. Hoffmann et al¹¹⁶ found that in 12% of patients electroanatomic maps were unable to be constructed due to nonsustained or noninducible tachycardia.

The noncontact mapping system (EnSite; Endocardial solutions, St Paul, MN) consists of 64 wires mounted on a 7.6-mL balloon.¹²⁰ This allows reconstruction of chamber geometry and simultaneous recording of >3300 virtual unipolar electrograms enabling entire activation from a single beat. One of the primary difficulties in mapping atrial tachycardia is its noninducibility in a proportion of patients. For the patient with infrequent atrial tachycardia activity, the noncontact mapping system allows an ideal solution, providing detailed maps from isolated beats and from nonsustained AT.^{31,32,121} Schmitt et al¹²¹ used noncontact mapping to identify the site of earliest activation and found that analysis of only a few tachycardia cycles was required to localize the tachycardia origin. The nonfluoroscopic guiding feature of the system was then used to move the catheter to the target site for ablation.

Multielectrode basket catheters have also been used to help map

nonsustained AT. Schmitt et al¹²² used a 64-electrode basket catheter to map the right atrium in patients with a variety of AT. The basket catheter was able to be deployed in all patients and stable electrograms were recorded from 88% of the electrodes. Of note, in 60% of cases, no earlier activity than that reflected with the basket catheter could be found with a roving standard catheter. However, good contact was not achieved in the regions of the isthmus, right atrial appendage, and superior vena cava. This may limit mapping of AT from these structures.

Characteristics of the Ablation Signal

Several criteria have been proposed to identify the AT focus. Fractionated electrograms are frequently found at the successful ablation site^{31,37,38,56,123}; however not all studies have reported this.^{24,124,125} In patients with AT located mainly on the crista terminalis, Kalman et al³⁷ observed fractionated signals at the site of successful ablation. In studies by both Lesh et al³⁸ and Wang et al,¹²³ a fractionated ablation signal was seen in a variety of right and left atrial sites. Fractionated electrograms may reflect localized abnormalities in atrial conduction, with poor cell-to-cell coupling causing slowed conduction from a poorly coupled automatic focus or small reentrant circuit. Lesh et al³⁸ suggested that the uncoupling between the normal surrounding atrial myocardium and an automatic focus may be a required element in the arrhythmia mechanism in some cases.

Unipolar recordings have also been used to successfully identify the site of tachycardia origin.^{124,126} The presence of a pure negative deflection (QS-pattern) with a rapid initial slope theoretically localizes the site of origin of the AT (Fig 16). Tang et al¹²⁶ analyzed the unipolar electrogram at both the successful and the unsuccessful ablation sites of focal AT. All the successful sites were characterized by the presence of the QS morphology. An RS pattern was observed at unsuccessful sites. Poty et al¹²⁴ reported an acute success rate of 86% using unipolar recordings to identify the target site for ablation.

Focal Ablation

Catheter ablation by direct current shocks directed to atrial foci was first reported in 1985.¹²⁷ With the advent of radiofrequency ablation this has become the treatment of choice in patients with significant symptoms. AT ablation series have reported success rates between 69 and 100% (Table 2).^{10,11,24,31,37,38,112,114-116,118,121,123-125,128-130} Recurrence rates are generally low, varying between 0 and 33%. In an analysis of 16 studies by Chen et al,⁹ the recurrence rate was 7%. In that study, the authors



FIG 16. Intracardiac recordings during atrial tachycardia from the inferior tricuspid annulus. Shown are the surface leads I, II, V₁, and V₆ together with intracardiac recordings from the His catheter, coronary sinus catheter, and a Halo catheter placed around the tricuspid annulus. Unipolar signals from the Halo catheter are shown. A pure negative deflection, QS morphology (encircled), on the Halo catheter, identified the origin of the atrial tachycardia. Note the rest of the Halo recordings show RS morphology. Radiofrequency applied at this site successfully ablated the tachycardia.

analyzed predictors of success of radiofrequency ablation. A right atrial location was the only independent predictor of successful radiofrequency ablation. In contrast, Anguera et al¹²⁸ noted that patients who were male, had multiple foci, and had repetitive forms of AT had lower acute success rates. Similarly, older patients, patients with other cardiac diseases, and those with multiple foci had a higher risk of recurrence.⁹

Surgery

Prior to the advent of radiofrequency ablation, surgery was the treatment of choice for focal AT refractory to medical therapy. However, as ablation techniques have become more advanced surgical treatment for focal AT is unusual. Surgical techniques performed include excision, cryoablation, left atrial isolation, and regional isolation. Surgery is efficacious in eliminating AT with success rates of 66 to

TABLE 2. Ablation parameters and success rates of series of focal atrial tachycardia treated with radiofrequency ablation

	A-P interval	Power	Acute success (%)	Recurrence (%)	Mapping
Walsh et al ²⁴	-40	20-30W	83	9	
Chen et al ¹²⁹	-37	20-40W	100	0	
Kay et al ¹²⁵	-21	30W	100	20	
Goldberger et al ¹³⁰	NA	NA	80	33	
Tracy et al ¹¹²	-37	NA	80	25	
Chen et al ¹¹	-34	20-40W	94	5	
Lesh et al ³⁸	-44	20-50W	93	7	
Wang et al ¹²³	-38	NA	69	11	
Poty et al ¹²⁴	-45	10-50W	86	13	
Pappone et al ¹¹⁴	-38	15-25W	93	7	Mechanical
Natale et al ¹¹⁵	NA	NA	100	3	CARTO
Kalman et al ³⁷	-47	<50W	93	16	ICE
Anguera et al ¹²⁸	-46	10-50W	76	10	
Weiss et al ¹¹⁸	-35	50W	100	13	CARTO
Schmitt et al ¹²¹	NA	NA	70	0	Noncontact
Hoffmann et al ¹¹⁶	NA	5-40W	84	6	CARTO
Kammeraad et al ¹⁰	NA	NA	76	7	
Higa et al ³¹	-51	40-50W	92	9	Noncontact

Series from specific sites not included. Only patients with focal atrial tachycardia included. *A-P interval*, activation time at the site of successful ablation to the onset of the P wave; *NA*, not available; *Mechanical*, mechanical interruption; *ICE*, intracardiac echocardiography.

100%.^{22,23,101,106,131-133} However, anesthesia and hypothermia may result in noninducibility of the AT, preventing intraoperative mapping.^{101,106,131} Sinus node dysfunction requiring pacemaker implantation may also occur^{22,106} and atrial scarring may produce the substrate for later macroreentry.

Conclusion

Over the last decade there have been significant advances in our knowledge regarding focal AT. Predisposing factors and mechanisms have been identified but require further clarification. The anatomic distribution of focal AT has been well described and careful assessment of P wave morphology provides a useful guide to the location of the focus in patients without structural heart disease. Prior to the ablation era, treatment was limited by the poor efficacy of pharmacological therapy. However with the advent of radiofrequency ablation, successful cure may be achieved in a high proportion of patients.

Melvin M. Scheinman: The authors are to be congratulated on a very thorough and authoritative review of the atrial tachycardias. They have

beautifully reviewed the existing literature and produced a coherent and valuable document for clinical cardiologists. I learned a great deal and plan to use this chapter as an up-to-date resource for teaching and patient care.

REFERENCES

1. Saoudi N, Cosio F, Waldo A, et al. A classification of atrial flutter and regular atrial tachycardia according to electrophysiological mechanisms and anatomical bases; a Statement from a Joint Expert Group from The Working Group of Arrhythmias of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. *Eur Heart J* 2001;22(14):1162-82.
2. Lee KW, Yang Y, Scheinman MM. Atrial flutter: a review of its history, mechanisms, clinical features, and current therapy. *Curr Probl Cardiol* 2005;30(3):121-67.
3. Poutiainen AM, Koistinen MJ, Airaksinen KE, et al. Prevalence and natural course of ectopic atrial tachycardia. *Eur Heart J* 1999;20(9):694-700.
4. Rodriguez LM, de Chillou C, Schlapfer J, et al. Age at onset and gender of patients with different types of supraventricular tachycardias. *Am J Cardiol* 1992;70(13):1213-15.
5. Klersy C, Chimienti M, Marangoni E, et al. Factors that predict spontaneous remission of ectopic atrial tachycardia. *Eur Heart J* 1993;14(12):1654-56.
6. Wellens HJ, Brugada P. Mechanisms of supraventricular tachycardia. *Am J Cardiol* 1988;62(6):10D-15D.
7. Wellens HJ. Atrial tachycardia. How important is the mechanism? *Circulation* 1994;90(3):1576-77.
8. Steinbeck G, Hoffmann E. 'True' atrial tachycardia. *Eur Heart J* 1998;19 (Suppl E):E10-E19.
9. Chen SA, Tai CT, Chiang CE, et al. Focal atrial tachycardia: reanalysis of the clinical and electrophysiologic characteristics and prediction of successful radiofrequency ablation. *J Cardiovasc Electrophysiol* 1998;9(4):355-65.
10. Kammeraad JA, Balaji S, Oliver RP, et al. Nonautomatic focal atrial tachycardia: characterization and ablation of a poorly understood arrhythmia in 38 patients. *Pacing Clin Electrophysiol* 2003;26(3):736-42.
11. Chen SA, Chiang CE, Yang CJ, et al. Sustained atrial tachycardia in adult patients. Electrophysiological characteristics, pharmacological response, possible mechanisms, and effects of radiofrequency ablation. *Circulation* 1994;90(3):1262-78.
12. Mehta AV, Ewing LL. Atrial tachycardia in infants and children: electrocardiographic classification and its significance. *Pediatr Cardiol* 1993;14(4):199-203.
13. von Bernuth G, Engelhardt W, Kramer HH, et al. Atrial automatic tachycardia in infancy and childhood. *Eur Heart J* 1992;13(10):1410-15.
14. Koike K, Hesslein PS, Finlay CD, et al. Atrial automatic tachycardia in children. *Am J Cardiol* 1988;61(13):1127-30.
15. Naheed ZJ, Strasburger JF, Benson DW Jr, et al. Natural history and management strategies of automatic atrial tachycardia in children. *Am J Cardiol* 1995;75(5):405-7.
16. Mehta AV, Sanchez GR, Sacks EJ, et al. Ectopic automatic atrial tachycardia in children: clinical characteristics, management and follow-up. *J Am Coll Cardiol* 1988;11(2):379-85.

17. Packer DL, Bardy GH, Worley SJ, et al. Tachycardia-induced cardiomyopathy: a reversible form of left ventricular dysfunction. *Am J Cardiol* 1986;57(8):563-70.
18. Keane JF, Plauth WH, Nadas AS. Chronic ectopic tachycardia of infancy and childhood. *Am Heart J* 1972;84:748-53.
19. Wyndham CR, Arnsdorf MF, Levitsky S, et al. Successful surgical excision of focal paroxysmal atrial tachycardia. Observations in vivo and in vitro. *Circulation* 1980;62(6):1365-72.
20. De Bakker JM, Hauer RN, Bakker PF, et al. Abnormal automaticity as mechanism of atrial tachycardia in the human heart—electrophysiologic and histologic correlation: a case report. *J Cardiovasc Electrophysiol* 1994;5(4):335-44.
21. Josephson ME, Spear JF, Harken AH, et al. Surgical excision of automatic atrial tachycardia: anatomic and electrophysiologic correlates. *Am Heart J* 104(5 Pt. 1):1076-85, 1982.
22. McGuire MA, Johnson DC, Nunn GR, et al. Surgical therapy for atrial tachycardia in adults. *J Am Coll Cardiol* 1989;14(7):1777-82.
23. Hendry PJ, Packer DL, Anstadt MP, et al. Surgical treatment of automatic atrial tachycardias. *Ann Thorac Surg* 1990;49(2):253-59.
24. Walsh EP, Saul JP, Hulse JE, et al. Transcatheter ablation of ectopic atrial tachycardia in young patients using radiofrequency current. *Circulation* 1992;86(4):1138-46.
25. Engelstein ED, Lippman N, Stein KM, et al. Mechanism-specific effects of adenosine on atrial tachycardia. *Circulation* 1994;89(6):2645-54.
26. Kall JG, Kopp D, Olshansky B, et al. Adenosine-sensitive atrial tachycardia. *Pacing Clin Electrophysiol* 1995;18(2):300-6.
27. Haines DE, DiMarco JP. Sustained intraatrial reentrant tachycardia: clinical, electrocardiographic and electrophysiologic characteristics and long-term follow-up. *J Am Coll Cardiol* 1990;15(6):1345-54.
28. Lerman BB, Belardinelli L. Cardiac electrophysiology of adenosine. Basic and clinical concepts. *Circulation* 1991;83(5):1499-1509.
29. Markowitz SM, Stein KM, Mittal S, et al. Differential effects of adenosine on focal and macroreentrant atrial tachycardia. *J Cardiovasc Electrophysiol* 1999;10(4):489-502.
30. Iwai S, Markowitz SM, Stein KM, et al. Response to adenosine differentiates focal from macroreentrant atrial tachycardia: validation using three-dimensional electro-anatomic mapping. *Circulation* 2002;106(22):2793-99.
31. Higa S, Tai CT, Lin YJ, et al. Focal atrial tachycardia: new insight from noncontact mapping and catheter ablation. *Circulation* 2004;109(1):84-91.
32. Higa S, Tai CT, Lin YJ, et al. Mechanism of adenosine-induced termination of focal atrial tachycardia. *J Cardiovasc Electrophysiol* 2004;15(12):1387-93.
33. Janse MJ, Anderson RH. Specialized internodal atrial pathways: fact or fiction?. *Eur J Cardiol* 1974;2:117-36.
34. Saffitz JE, Kanter HL, Green KG, et al. Tissue-specific determinants of anisotropic conduction velocity in canine atrial and ventricular myocardium. *Circ Res* 1994;74(6):1065-70.
35. Sanders P, Morton JB, Davidson NC, et al. Electrical remodeling of the atria in congestive heart failure: electrophysiological and electroanatomic mapping in humans. *Circulation* 2003;108(12):1461-68.
36. Sanders P, Morton JB, Kistler PM, et al. Electrophysiological and electroanatomic

- characterization of the atria in sinus node disease: evidence of diffuse atrial remodeling. *Circulation* 2004;109(12):1514-22.
37. Kalman JM, Olgin JE, Karch MR, et al. "Cristal tachycardias": origin of right atrial tachycardias from the crista terminalis identified by intracardiac echocardiography. *J Am Coll Cardiol* 1998;31(2):451-59.
 38. Lesh MD, Van Hare GF, Epstein LM, et al. Radiofrequency catheter ablation of atrial arrhythmias. Results and mechanisms. *Circulation* 1994;89(3):1074-89.
 39. Stambler BS, Fenelon G, Shepard RK, et al. Characterization of sustained atrial tachycardia in dogs with rapid ventricular pacing-induced heart failure. *J Cardiovasc Electrophysiol* 2003;14(5):499-507.
 40. Leitch J, Klein GJ, Yee R, et al. Invasive electrophysiologic evaluation of patients with supraventricular tachycardia. *Cardiol Clin* 1990;8(3):465-77.
 41. Josephson ME, Wellens HJ. Differential diagnosis of supraventricular tachycardia. *Cardiol Clin* 1990;8(3):411-42.
 42. Kadish AH, Morady F. The response of paroxysmal supraventricular tachycardia to overdrive atrial and ventricular pacing: can it help determine the tachycardia mechanism? *J Cardiovasc Electrophysiol* 1993;4(3):239-52.
 43. Benditt DG, Pritchett EL, Smith WM, et al. Ventriculoatrial intervals: diagnostic use in paroxysmal supraventricular tachycardia. *Ann Intern Med* 1979;91(2):161-66.
 44. Ross DL, Uther JB. Diagnosis of concealed accessory pathways in supraventricular tachycardia. *Pacing Clin Electrophysiol* 1984;7(6 Pt. 1):1069-85.
 45. Hirao K, Otomo K, Wang X, et al. Para-Hisian pacing. A new method for differentiating retrograde conduction over an accessory AV pathway from conduction over the AV node. *Circulation* 1996;94(5):1027-35.
 46. Kerr CR, Gallagher JJ, German LD. Changes in ventriculoatrial intervals with bundle branch block aberration during reciprocating tachycardia in patients with accessory atrioventricular pathways. *Circulation* 1982;66(1):196-201.
 47. Knight BP, Zivin A, Souza J, et al. A technique for the rapid diagnosis of atrial tachycardia in the electrophysiology laboratory. *J Am Coll Cardiol* 1999;33(3):775-81.
 48. Josephson M. Supraventricular tachycardia. In: Josephson M, editor. *Clinical Cardiac Electrophysiology*. Philadelphia, PA: Malvern, Lea & Febiger, 1993. p. 181-274.
 49. Jackman WM, Nakagawa H, Heidebuchel H, et al. Three forms of atrioventricular nodal (junctional) reentrant tachycardia: differential diagnosis, electrophysiological characteristics, and implications for anatomy of the reentrant circuit. In: Zipes DP, Jalife J, editors. *Cardiac Electrophysiology: From Cell to Bedside*. Philadelphia, PA: Saunders, 1995. p. 620-37.
 50. Knight BP, Ebinger M, Oral H, et al. Diagnostic value of tachycardia features and pacing maneuvers during paroxysmal supraventricular tachycardia. *J Am Coll Cardiol* 2000;36(2):574-82.
 51. Boineau JP, Canavan TE, Schuessler RB, et al. Demonstration of a widely distributed atrial pacemaker complex in the human heart. *Circulation* 1988;77(6):1221-37.
 52. Lesh MD, Kalman JM. To fumble flutter or tackle "tach"? Toward updated classifiers for atrial tachyarrhythmias. *J Cardiovasc Electrophysiol* 1996;7(5):460-66.

53. Kistler PM, Fynn SP, Haqqani, H, et al. Focal atrial tachycardia from the ostium of the coronary sinus: electrocardiographic and electrophysiological characterisation and radiofrequency ablation. *J Am Coll Cardiol* (in press).
54. Chauvin M, Shah DC, Haissaguerre M, et al. The anatomic basis of connections between the coronary sinus musculature and the left atrium in humans. *Circulation* 2000;101(6):647-52.
55. Matsuoka K, Kasai A, Fujii E, et al. Electrophysiological features of atrial tachycardia arising from the atrioventricular annulus. *Pacing Clin Electrophysiol* 2002;25(4 Pt. 1):440-45.
56. Iesaka Y, Takahashi A, Goya M, et al. Adenosine-sensitive atrial reentrant tachycardia originating from the atrioventricular nodal transitional area. *J Cardiovasc Electrophysiol* 1997;8(8):854-64.
57. Frey B, Kreiner G, Gwechenberger M, et al. Ablation of atrial tachycardia originating from the vicinity of the atrioventricular node: significance of mapping both sides of the interatrial septum. *J Am Coll Cardiol* 2001;38(2):394-400.
58. Chen CC, Tai CT, Chiang CE, et al. Atrial tachycardias originating from the atrial septum: electrophysiologic characteristics and radiofrequency ablation. *J Cardiovasc Electrophysiol* 2000;11(7):744-49.
59. Marrouche NF, Sippensgroenewegen A, Yang Y, et al. Clinical and electrophysiologic characteristics of left septal atrial tachycardia. *J Am Coll Cardiol* 2002;40(6):1133-39.
60. Lai LP, Lin JL, Chen TF, et al. Clinical, electrophysiological characteristics, and radiofrequency catheter ablation of atrial tachycardia near the apex of Koch's triangle. *Pacing Clin Electrophysiol* 1998;21(2):367-74.
61. Morton JB, Sanders P, Das A, et al. Focal atrial tachycardia arising from the tricuspid annulus: electrophysiologic and electrocardiographic characteristics. *J Cardiovasc Electrophysiol* 2001;12(6):653-59.
62. McGuire MA, De Bakker JM, Vermeulen JT, et al. Atrioventricular junctional tissue. Discrepancy between histological and electrophysiological characteristics. *Circulation* 1996;94(3):571-77.
63. McGuire MA, De Bakker JM, Vermeulen JT, et al. Origin and significance of double potentials near the atrioventricular node. Correlation of extracellular potentials, intracellular potentials, and histology. *Circulation* 1994;89(5):2351-60.
64. Haissaguerre M, Jais P, Shah DC, et al. Spontaneous initiation of atrial fibrillation by ectopic beats originating in the pulmonary veins. *N Engl J Med* 1998;339(10):659-66.
65. Kistler PM, Sanders P, Fynn SP, et al. Electrophysiological and electrocardiographic characteristics of focal atrial tachycardia originating from the pulmonary veins: acute and long-term outcomes of radiofrequency ablation. *Circulation* 2003;108(16):1968-75.
66. Hachiya H, Ernst S, Ouyang F, et al. Topographic distribution of focal left atrial tachycardias defined by electrocardiographic and electrophysiological data. *Circ J* 2005;69(2):205-10.
67. Gonzalez MD, Contreras LJ, Jongbloed MR, et al. Left atrial tachycardia originating from the mitral annulus-aorta junction. *Circulation* 2004;110(20):3187-92.
68. Kistler PM, Sanders P, Hussin A, et al. Focal atrial tachycardia arising from the mitral annulus: electrocardiographic and electrophysiologic characterization. *J Am Coll Cardiol* 2003;41(12):2212-19.

69. Wit AL, Fenoglio JJ Jr, Hordof AJ, et al. Ultrastructure and transmembrane potentials of cardiac muscle in the human anterior mitral valve leaflet. *Circulation* 1979;59(6):1284-92.
70. Wit AL, Fenoglio JJ Jr, Wagner BM, et al. Electrophysiological properties of cardiac muscle in the anterior mitral valve leaflet and the adjacent atrium in the dog. Possible implications for the genesis of atrial dysrhythmias. *Circ Res* 1973;32(6):731-45.
71. Dong J, Schreieck J, Ndrepepa G, et al. Ectopic tachycardia originating from the superior vena cava. *J Cardiovasc Electrophysiol* 2002;13(6):620-24.
72. Tritto M, Zardini M, De Ponti R, et al. Iterative atrial tachycardia originating from the coronary sinus musculature. *J Cardiovasc Electrophysiol* 2001;12(10):1187-89.
73. Volkmer M, Antz M, Hebe J, et al. Focal atrial tachycardia originating from the musculature of the coronary sinus. *J Cardiovasc Electrophysiol* 2002;13(1):68-71.
74. Man KC, Chan KK, Kovack P, et al. Spatial resolution of atrial pace mapping as determined by unipolar atrial pacing at adjacent sites. *Circulation* 1996;94(6):1357-63.
75. Schamroth L. Normal sinus rhythm. In: Schamroth L, editor. *The Disorders of Cardiac Rhythm*. Oxford: Blackwell Scientific Publications, 1980.
76. Tang CW, Scheinman MM, Van Hare GF, et al. Use of P wave configuration during atrial tachycardia to predict site of origin. *J Am Coll Cardiol* 1995;26(5):1315-24.
77. Yamada T, Murakami Y, Muto M, et al. Electrophysiologic characteristics of atrial tachycardia originating from the right pulmonary veins or posterior right atrium: double potentials obtained from the posterior wall of the right atrium can be useful to predict foci of atrial tachycardia in right pulmonary veins or posterior right atrium. *J Cardiovasc Electrophysiol* 2004;15(7):745-51.
78. Tada H, Nogami A, Naito S, et al. Simple electrocardiographic criteria for identifying the site of origin of focal right atrial tachycardia. *Pacing Clin Electrophysiol* 21(11 Pt. 2):2431-39, 1998.
79. Schwartzman D, Callans DJ, Gottlieb CD, et al. Conduction block in the inferior vena caval-tricuspid valve isthmus: association with outcome of radiofrequency ablation of type I atrial flutter. *J Am Coll Cardiol* 1996;28(6):1519-31.
80. Yamane T, Shah DC, Peng JT, et al. Morphological characteristics of P waves during selective pulmonary vein pacing. *J Am Coll Cardiol* 2001;38(5):1505-10.
81. Ellenbogen KA, Wood MA. Atrial tachycardia. In: Zipes DP, Jalife J, editors. *Cardiac Electrophysiology: From Cell to Bedside*. Philadelphia, PA: Saunders, 2004. p. 500-12.
82. Lee RJ, Kalman JM, Fitzpatrick AP, et al. Radiofrequency catheter modification of the sinus node for "inappropriate" sinus tachycardia. *Circulation* 1995;92(10):2919-28.
83. Krahn AD, Yee R, Klein GJ, et al. Inappropriate sinus tachycardia: evaluation and therapy. *J Cardiovasc Electrophysiol* 1995;6(12):1124-28.
84. Morillo CA, Klein GJ, Thakur RK, et al. Mechanism of 'inappropriate' sinus tachycardia. Role of sympathovagal balance. *Circulation* 1994;90(2):873-77.
85. Man KC, Knight B, Tse HF, et al. Radiofrequency catheter ablation of inappropriate sinus tachycardia guided by activation mapping. *J Am Coll Cardiol* 2000;35(2):451-57.
86. Marrouche NF, Beheiry S, Tomassoni G, et al. Three-dimensional nonfluoroscopic

- mapping and ablation of inappropriate sinus tachycardia. Procedural strategies and long-term outcome. *J Am Coll Cardiol* 2002;39(6):1046-54.
87. Cossu SF, Steinberg JS. Supraventricular tachyarrhythmias involving the sinus node: clinical and electrophysiologic characteristics. *Prog Cardiovasc Dis* 1998;41(1):51-63.
 88. Blomstrom-Lundqvist C, Scheinman MM, Aliot EM, et al. ACC/AHA/ESC guidelines for the management of patients with supraventricular arrhythmias—executive summary. a report of the American college of cardiology/American heart association task force on practice guidelines and the European society of cardiology committee for practice guidelines (writing committee to develop guidelines for the management of patients with supraventricular arrhythmias) developed in collaboration with NASPE-Heart Rhythm Society. *J Am Coll Cardiol* 2003;42(8):1493-531.
 89. Bauernfeind RA, Amat YL, Dhingra RC, et al. Chronic nonparoxysmal sinus tachycardia in otherwise healthy persons. *Ann Intern Med* 1979;91(5):702-10.
 90. Shen WK, Low PA, Jahangir A, et al. Is sinus node modification appropriate for inappropriate sinus tachycardia with features of postural orthostatic tachycardia syndrome? *Pacing Clin Electrophysiol* 2001;24(2):217-30.
 91. Mulder P, Barbier S, Chagraoui A, et al. Long-term heart rate reduction induced by the selective I(f) current inhibitor ivabradine improves left ventricular function and intrinsic myocardial structure in congestive heart failure. *Circulation* 2004;109(13):1674-79.
 92. Shine KI, Kastor JA, Yurchak PM. Multifocal atrial tachycardia. Clinical and electrocardiographic features in 32 patients. *N Engl J Med* 1968;279(7):344-49.
 93. Kastor JA. Multifocal atrial tachycardia. *N Engl J Med* 1990;322(24):1713-17.
 94. Chung EK. Appraisal of multifocal atrial tachycardia. *Br Heart J* 1971;33(4):500-04.
 95. Scher DL, Arsura EL. Multifocal atrial tachycardia: mechanisms, clinical correlates, and treatment. *Am Heart J* 1989;118(3):574-80.
 96. Levine JH, Michael JR, Guarnieri T. Treatment of multifocal atrial tachycardia with verapamil. *N Engl J Med* 1985;312(1):21-25.
 97. Arsura E, Lefkin AS, Scher DL, et al. A randomized, double-blind, placebo-controlled study of verapamil and metoprolol in treatment of multifocal atrial tachycardia. *Am J Med* 1988;85(4):519-24.
 98. McCord JK, Borzak S, Davis T, et al. Usefulness of intravenous magnesium for multifocal atrial tachycardia in patients with chronic obstructive pulmonary disease. *Am J Cardiol* 1998;81(1):91-93.
 99. Salerno DM, Anderson B, Sharkey PJ, et al. Intravenous verapamil for treatment of multifocal atrial tachycardia with and without calcium pretreatment. *Ann Intern Med* 1987;107(5):623-28.
 100. Bauersfeld U, Gow RM, Hamilton RM, et al. Treatment of atrial ectopic tachycardia in infants < 6 months old. *Am Heart J* 1995;129(6):1145-48.
 101. Gillette PC, Wampler DG, Garson A Jr, et al. Treatment of atrial automatic tachycardia by ablation procedures. *J Am Coll Cardiol* 1985;6(2):405-09.
 102. Kunze KP, Kuck KH, Schluter M, et al. Effect of encainide and flecainide on chronic ectopic atrial tachycardia. *J Am Coll Cardiol* 1986;7(5):1121-26.
 103. Kuck KH, Kunze KP, Schluter M, et al. Encainide versus flecainide for chronic atrial and junctional ectopic tachycardia. *Am J Cardiol* 1988;62(19):37L-44L.

104. Pool PE, Quart BD. Treatment of ectopic atrial arrhythmias and premature atrial complexes in adults with encainide. *Am J Cardiol* 1988;62(19):60L-62L.
105. Gillette PC, Garson A Jr. Electrophysiologic and pharmacologic characteristics of automatic ectopic atrial tachycardia. *Circulation* 56(4 Pt. 1):571-75, 1977.
106. Prager NA, Cox JL, Lindsay BD, et al. Long-term effectiveness of surgical treatment of ectopic atrial tachycardia. *J Am Coll Cardiol* 1993;22(1):85-92.
107. Berns E, Rinkenberger RL, Jeang MK, et al. Efficacy and safety of flecainide acetate for atrial tachycardia or fibrillation. *Am J Cardiol* 1987;59(15):1337-41.
108. Lucet V, Do ND, Fidelle J, et al. [Anti-arrhythmia efficacy of propafenone in children. Apropos of 30 cases]. *Arch Mal Coeur Vaiss* 1987;80(9):1385-93.
109. Colloridi V, Perri C, Ventriglia F, et al. Oral sotalol in pediatric atrial ectopic tachycardia. *Am Heart J* 1992;123(1):254-56.
110. Guccione P, Paul T, Garson A Jr. Long-term follow-up of amiodarone therapy in the young: continued efficacy, unimpaired growth, moderate side effects. *J Am Coll Cardiol* 1990;15(5):1118-24.
111. Coumel P, Fidelle J. Amiodarone in the treatment of cardiac arrhythmias in children: one hundred thirty-five cases. *Am Heart J* 100(6 Pt. 2):1063-69, 1980.
112. Tracy CM, Swartz JF, Fletcher RD, et al. Radiofrequency catheter ablation of ectopic atrial tachycardia using paced activation sequence mapping. *J Am Coll Cardiol* 1993;21(4):910-17.
113. Deen VR, Morton JB, Vohra JK, et al. Pulmonary vein paced activation sequence mapping: comparison with activation sequences during onset of focal atrial fibrillation. *J Cardiovasc Electrophysiol* 2002;13(2):101-07.
114. Pappone C, Stabile G, De Simone A, et al. Role of catheter-induced mechanical trauma in localization of target sites of radiofrequency ablation in automatic atrial tachycardia. *J Am Coll Cardiol* 1996;27(5):1090-97.
115. Natale A, Breeding L, Tomassoni G, et al. Ablation of right and left ectopic atrial tachycardias using a three-dimensional nonfluoroscopic mapping system. *Am J Cardiol* 1998;82(8):989-92.
116. Hoffmann E, Reithmann C, Nimmermann P, et al. Clinical experience with electroanatomic mapping of ectopic atrial tachycardia. *Pacing Clin Electrophysiol* 2002;25(1):49-56.
117. Marchlinski F, Callans D, Gottlieb C, et al. Magnetic electroanatomical mapping for ablation of focal atrial tachycardias. *Pacing Clin Electrophysiol* 1998;21(8):1621-35.
118. Weiss C, Willems S, Rueppel R, et al. Electroanatomical Mapping (CARTO) of ectopic atrial tachycardia: impact of bipolar and unipolar local electrogram annotation for localization the focal origin. *J Interv Card Electrophysiol* 2001;5(1):101-07.
119. Hoffmann E, Nimmermann P, Reithmann C, et al. New mapping technology for atrial tachycardias. *J Interv Card Electrophysiol* 2000;4(suppl 1):117-1220.
120. Schilling RJ, Peters NS, Davies DW. Simultaneous endocardial mapping in the human left ventricle using a noncontact catheter: comparison of contact and reconstructed electrograms during sinus rhythm. *Circulation* 1998;98(9):887-98.
121. Schmitt H, Weber S, Schwab JO, et al. Diagnosis and ablation of focal right atrial tachycardia using a new high-resolution, non-contact mapping system. *Am J Cardiol* 2001;87(8):1017-21.

122. Schmitt C, Zrenner B, Schneider M, et al. Clinical experience with a novel multielectrode basket catheter in right atrial tachycardias. *Circulation* 1999;99(18):2414-22.
123. Wang L, Weerasooriya HR, Davis MJ. Radiofrequency catheter ablation of atrial tachycardia. *Aust N Z J Med* 1995;25(2):127-32.
124. Poty H, Saoudi N, Haissaguerre M, et al. Radiofrequency catheter ablation of atrial tachycardias. *Am Heart J* 1996;131(3):481-89.
125. Kay GN, Chong F, Epstein AE, et al. Radiofrequency ablation for treatment of primary atrial tachycardias. *J Am Coll Cardiol* 1993;21(4):901-09.
126. Tang K, Ma J, Zhang S, et al. Unipolar electrogram in identification of successful targets for radiofrequency catheter ablation of focal atrial tachycardia. *Chin Med J Engl* 2003;116(10):1455-58.
127. Silka MJ, Gillette PC, Garson A Jr, et al. Transvenous catheter ablation of a right atrial automatic ectopic tachycardia. *J Am Coll Cardiol* 1985;5(4):999-1001.
128. Anguera I, Brugada J, Roba M, et al. Outcomes after radiofrequency catheter ablation of atrial tachycardia. *Am J Cardiol* 2001;87(7):886-90.
129. Chen SA, Chiang CE, Yang CJ, et al. Radiofrequency catheter ablation of sustained intra-atrial reentrant tachycardia in adult patients. Identification of electrophysiological characteristics and endocardial mapping techniques. *Circulation* 1993;88(2):578-87.
130. Goldberger J, Kall J, Ehlert F, et al. Effectiveness of radiofrequency catheter ablation for treatment of atrial tachycardia. *Am J Cardiol* 1993;72(11):787-93.
131. Seals AA, Lawrie GM, Magro S, et al. Surgical treatment of right atrial focal tachycardia in adults. *J Am Coll Cardiol* 1988;11(5):1111-17.
132. Ott DA, Gillette PC, Garson A Jr, et al. Surgical management of refractory supraventricular tachycardia in infants and children. *J Am Coll Cardiol* 1985;5(1):124-29.
133. Graffigna A, Vigano M, Pagani F, et al. Surgical treatment for ectopic atrial tachycardia. *Ann Thorac Surg* 1992;54(2):338-43.