Electrophysiology

Electrocardiogram Recognition and Ablation of Atrial Tachycardia

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Abstract
Focal atrial tachycardia (AT) is a relatively uncommon cause of supraventricular tachycardia, but when present is frequently difficult to treat medically. Atrial tachycardias tend to originate from anatomically determined atrial sites. The P-wave morphology on surface electrocardiogram (EGC) together with more sophisticated contemporary mapping techniques facilitates precise localisation and ablation of these ectopic foci. Catheter ablation of focal AT is associated with high long-term success and may be viewed as a primary treatment strategy in symptomatic patients.

Keywords
Atrial tachycardia, P-wave, catheter ablation

The least common type of supraventricular tachycardia is focal atrial tachycardia (AT), accounting for 5–15% of cases presenting to the electrophysiology (EP) laboratory for ablation.¹ Focal AT is defined by the presence of a discrete atrial focus with centrifugal spread of atrial activation away from that site.² It is generally poorly responsive to pharmacological therapy and may be responsible for the development of atria-mediated cardiomyopathy³ or initiation of other atrial arrhythmias such as atrial flutter or atrial fibrillation (AF). With the advent of radiofrequency (RF) ablation this type of tachycardia can be treated with high long-term success.⁴–⁵

Electrocardiographic P-wave morphology can provide a useful indication of the likely site of focal AT origin, which are generally distributed to characteristic anatomical locations.⁶–⁷ Studies evaluating mechanism of focal AT have demonstrated electrophysiological characteristics reflecting abnormal automaticity, triggered activity and micro-re-entry in different patients.⁸ This article will discuss localisation of atrial tachycardia using P-wave morphology and techniques of endocardial mapping to facilitate successful ablation.

Anatomical Distribution
Focal AT demonstrates a characteristic anatomical distribution and does not occur randomly throughout the atria. In published series, the right atrium (RA) is the most common location for foci, accounting for approximately 75%. Within the RA they are most commonly observed along the crista terminals (CT) (approximately 33%) particularly in the superior and mid-CT. Other common sites include the tricuspid annulus (TA), the coronary sinus (CS) ostium and within the CS, the perinodal (parahisian) region and septum, and from within the right atrial appendage (RAA). In the left atrium (LA) the majority of foci originate from the pulmonary veins (PVs), the mitral annulus (MA), left atrial appendage (LAA) and left septum being less common.⁹

P-wave Algorithm for Localising the Site of Atrial Tachycardia
Although successful ablation will depend ultimately on detailed mapping, the surface electrocardiogram (ECG) is nevertheless a helpful tool in directing mapping to particular areas of interest. The P-wave morphology is determined by the site of origin and the pattern of atrial activation during AT. A clear view of the P-wave, unencumbered by the preceding T wave or QRS complex is crucial to the interpretation of the P-wave. This may be facilitated by vagal manoeuvres, administration of adenosine or ventricular pacing. Several algorithms for localising AT in patients without structural heart disease based on pulse-width modulation (PWM) have been developed.¹⁰–¹³ Tang et al. observed that V1 and aVL were useful to distinguish between left and right atrial foci. A positive or biphasic P-wave in aVL predicted a right atrial focus with a sensitivity and specificity of 88 and 79%, respectively. An exception were foci originating in the right superior pulmonary vein (RSPV). A positive P-wave in V1 predicted a left atrial focus with a sensitivity and specificity of 93 and 88%, respectively. Close inspection of PWM during sinus rhythm and AT showed that the change in PWM in V1 from biphasic to positive was helpful in identifying foci originating in the RSPV.¹⁴ Tada et al. developed an algorithm for right atrial tachycardia foci only. In that study, a negative P-wave in lead aVR identified an AT originating from CT with a 100% sensitivity and 93% specificity. Negative P-waves in leads V5 and V6 defined inferomedial right-sided tachycardias with a sensitivity of 92% and specificity of 100%.¹⁵ Hachiya et al.¹⁶ developed an algorithm for left AT foci only. A positive P-wave in V1 identified a pulmonary vein origin. A biphasic or negative P-wave in V1 indicated a septal or superior MA or LAA origin. Yamane and colleagues¹⁷ assessed PWM during pacing from four pulmonary veins (PVs) and proposed criteria for distinguishing right from left PVs. A positive P-wave in lead aVL and the amplitude of P-wave of greater than 50µV indicated right PV origin with
specify a measured relationship to P-wave onset. Fractionated electrograms overdrive pacing is directly proportional to proximity of the pacing site to the focus, and tends to approximate 0ms when pacing at the site of focal origin.

The introduction of 3-D mapping systems has greatly facilitated the mapping and ablation of focal AT. The electroanatomical mapping system is based on sequential mapping technology and permits a detailed reconstruction of the chamber geometry and the activation sequence. However, this approach still requires regular ectopics or sustained tachycardia, and, as a consequence, electroanatomical maps cannot be constructed in up to 12% of patients. The EnSite non-contact mapping system provides a potential solution to this problem by permitting detailed activation maps to be constructed from isolated beats and non-sustained AT. However, in these cases, it may not be clear that the single mapped ectopic is representative of the clinical tachycardia and there is still no procedural end-point indicator of success. In addition, AT arising from closely apposed structures, such as the high RA and the RSPV or the perinodal and left septal areas, may only be differentiated by detailed and sometimes simultaneous mapping.

High-density multielectrode (PentaRay, Biosense-Webster) mapping may facilitate the rapid identification of the origin of complex AT. Using this approach, localised re-entry was evidenced at the site of origin in 30% of 27 focal ATs. Paced activation sequence mapping may be used to complement activation mapping, especially when the tachycardia is non-sustained or difficult to induce. The ablation catheter is manoeuvred to a position where the paced activation sequence on static intracardiac catheters and surface ECG PWM reproduces the spontaneous endocardial activation sequence and spontaneous PWM. Using this technique combined with activation mapping for right-sided ATs, Tracy et al. reported a success rate of 80%.

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Endocardial Mapping of Focal Atrial Tachycardia

In general, mapping of focal AT requires sufficient density of focal activity in the case of an ‘automatic’ focus or reliable inducibility with programmed stimulation. Patients are generally studied in the fastest awake state with minimal use of sedation. All antiarrhythmic drugs should be stopped a minimum of five half-lives before the procedure. In the absence of adequate spontaneous atrial activity, isoproterenol infusion and atrial pacing manoeuvres may be used to stimulate atrial ectopy. The absence of focal activity at the time of EP study remains the commonest cause of procedural failure.

Mapping Techniques

The most commonly used technique to locate AT focus is endocardial activation mapping. Wetzel et al. developed a stepwise approach for rapid identification of a tachycardia focus. Mapping was initiated with the acquisition of four points at the superior/septal part of the tricuspid annulus (TA) with subsequent mapping directed towards the right free wall left atrium or inferior triangle of Koch depending on these initial points. High-density mapping was only performed within the region of interest, thus allowing short procedure and fluoroscopy times. In addition to electroanatomical mapping with the ablation catheter alone, it is very useful to deploy a limited number of multipolar catheters. This facilitates rapid identification of the region of interest, provides a visual early reference point from which to map and allows rapid identification if there is a change in the tachycardia origin (as the endocardial activation pattern will change). Such catheters might include, in addition to those in the His region and within the coronary sinus, a 20-pole Cristal (CT) catheter or a Halo (TA) catheter. Ultimately, precise localisation must be achieved with detailed mapping in the region of interest. Generally, an activation time of >20–30ms prior to P-wave onset is observed at the successful site. If the onset of the P-wave is obscured by the T-wave, mapping can be performed to a stable intracardiac fiducial point, such as CS catheter bipolar, with a measured relationship to P-wave onset. Fractionated electrograms may be found at the successful ablation site during AT, but these are not always present and may depend on the anatomical location. Using unipolar recordings, the presence of a pure negative deflection (Q2 pattern) with a rapid initial slope localises the site of origin of the AT and has been successfully used by a number of groups.

The introduction of 3-D mapping systems has greatly facilitated the mapping and ablation of focal AT. The electroanatomical mapping system is based on sequential mapping technology and permits a detailed reconstruction of the chamber geometry and the activation sequence. However, this approach still requires regular ectopics or specificIsolated Waves Algorithm for Localising the Site of Atrial Tachycardia

Figure 1: P-wave Algorithm for Localising the Site of Atrial Tachycardia

<table>
<thead>
<tr>
<th>V1</th>
<th>Pos/neg</th>
<th>CT</th>
<th>SMA</th>
<th>CS ostium</th>
<th>Sinus rhythm P-wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos</td>
<td>No</td>
<td>V2-4</td>
<td>Neg in all inferior leads</td>
<td>RA RAo</td>
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<tr>
<td>Pos</td>
<td>No</td>
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<td>Neg in all inferior leads</td>
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CS = coronary sinus; CT = crista terminalis; CS = coronary sinus; LS = left septum; SMA = septal mitral annulus; LAA = left atrial appendage; RPV = right pulmonary vein; TA = tricuspid annulus; LA = left atrium; RSPV = right superior pulmonary vein; RAA = right atrial appendage; V1 = lead V1.
Electrophysiology

Figure 2: Successful Site of Radiofrequency Ablation of Focal Atrial Tachycardia Originating from the Superior Region of Mitral Annulus

A: Shows in left anterior oblique (LAO) view the 3D electromagnetic map (CARTO) and the site of ablation of focal atrial tachycardia originated from aortomitral continuity region on superior mitral annulus. B: Shows positioning of ablation catheter (left anterior oblique [LAO] view). C: Depicts pacing mapping and P-wave morphology of this focal atrial tachycardia (AT) arising from superior mitral annulus. Note a biphasic (isoelectric/positive) P-wave in lead V1, low P-wave amplitude in the limb leads and negative P-wave in aVL. D: Displays the atrial signal recorded by ablation catheter at the site of ablation 48ms ahead to His A recording.

Ablation of Focal Atrial Tachycardia

For the majority of focal ATs, RF is the energy source of choice. Irrigated ablation may be necessary, particularly in regions of low flow, such as trabeculated appendages or within the coronary sinus. Catheter stability may be enhanced by the use of long sheaths and is particularly valuable with ablation in the perinodal area. Another important modality for ablation of foci near the atrioventricular (AV) node is cryoablation. Successful ablation is often marked by acceleration of the AT during RF application prior to termination.

AT ablation series have reported success rates between 69% and 100% with low incidence of complications. Recurrence rates are generally low, varying from 0–33%. In one series, the only independent predictor of successful RF ablation was an RA locus. Lower acute success rates have been reported in patients with multiple foci and in older patients with structural heart disease.

Right-sided Focal Atrial Tachycardias – Features, P-Wave Morphology and Ablation

Crista Terminalis

Approximately two-thirds of RA focal ATs occurring in the absence of structural heart disease are distributed along the long axis of the CT. The vast majority of foci are located in the superior and mid-CT. These tachycardias most usually have a biphasic (positive–negative) P-wave in V1, similar to the sinus P-wave. Superior sites are associated with an upright inferior P-wave and inferior sites with a low amplitude or inverted inferior P-wave. The CT is an area of marked anisotropy with poor transverse and rapid linear conduction, creating substrate for micro-re-entry. In addition, the sinus node pacemaker complex is located along the CT and the presence of automatic tissue together with anisotropy may favour abnormal automaticity. The presence of poor local cell-to-cell coupling is suggested by the recording of an early and fractionated signal at the site of successful ablation in 93% of cases. Ablation of tachycardias arising from the CT carries a small risk of damage to the right phrenic nerve. Transient high-output atrial pacing prior to application of energy, to ensure that the diaphragm is not stimulated, can avoid this complication. In cases where phrenic nerve stimulation occurs at the site of earliest activity, the positioning of a pericardial balloon via a subxiphoid approach (to distance the nerve from the ablation site) has been used successfully.

Tricuspid Annulus

The TA is the next most common site of origin of right-sided focal AT. In one series the most common site of origin was the inferoanterior segment, but they may occur from around the tricuspid circumference. The P-wave is bifid negative in V1 and V2 with late precordial transition to an upright appearance. Inferior annular foci have deep negative P-waves in leads II, III, aVF, whereas superior foci are usually isoelectric or positive. McGuire et al. described the presence of atrial cells with AV-nodal electrophysiological properties around the entire TA as a putative mechanism for these tachycardias.

Perinodal Region

Focal ATs arising from the perinodal region are less common and carry a potential risk of AV block during radiofrequency ablation. Mapping of both sides of the IAS and from the non-coronary cusp is required prior to ablation of focal AT originating from the vicinity of the AV node as on many occasions an earlier site just away from the perinodal region will be detected. In addition, delivery of RF energy from within the non-coronary cusp appears safe from the...
point of view of heart block risk. Nevertheless, delivery of RF energy in the peri-nodal region may be required in some cases. Several studies have shown the safety of this approach when delivered in a titrated manner with continuous monitoring of AV conduction to minimise the risk of damage to the AV node. When the risk of inadvertent AV block is considered to be too high, cryoablation may be used. The PWM of perinodal and septal tachycardias is variable, and there is overlap between left- and right-sided foci. For right peri-nodal and right septal foci, an isoelectric P-wave in V1 is helpful if present (specificity and positive predictive value of 100%), but is only present in 50% of cases.

Coronary Sinus Ostium and Distal Coronary Sinus
The ostium of the CS is a not uncommon site of focal AT. The P-wave is similar to that seen in typical atrial flutter. In lead V1 an initial isoelectric segment is followed by an upright component. The P-wave is deeply negative in the inferior leads. Tachycardias are considered to arise from the ostium of the CS when the earliest activation is recorded and successful ablation achieved within 1cm of the CS ostium. In one series, foci tended to be found on the superior or posterior rim of the CS. Focal ATs have been described originating from CS musculature, several centimetres beyond the ostium. These foci can be recognised by the presence of a discrete sharp potential which can be observed both during sinus rhythm (late) and in tachycardia (early). The tachycardia mechanism is suggestive of triggered activity or abnormal automaticity. The finding of a broad positive P-wave in V1 (and across the precordium) together with a positive P-wave in AVR and aVL and negative P-waves in inferior leads is highly suggestive of AT arising from CS musculature. Ablation performed from the LA is unsuccessful in these patients. The tachycardia is sensitive to mechanical pressure during catheter manipulation within the coronary sinus. Focal ablation within the CS (a mean of 3–4cm from the CS ostium) resulted in long-term cure.

Right Atrial Appendage
Several publications have described atrial tachycardias originating from the RAA. These foci are more common in males, have a high proportion, are incessant and, therefore, commonly associated with tachycardiomyopathy. The majority of RAA tachycardias originate from the lateral base of the appendage but are also well described from the apical location. Due to their close anatomical
proximity, these tachycardias are generally indistinguishable from superior tricuspid annular foci by PWV, showing low amplitude upright P-waves in the inferior limb leads and negative P-waves in V1–V2, with variable precordial transition to positive in V6.5,6 Although recent series have reported high ablation success rates, these tachycardias originate in regions of thick trabeculated muscle and it may not be possible to achieve successful ablation from an endocardial approach. In situations where the catheter tip is located between trabeculae, irrigation is required to achieve adequate power output.

Superior Vena Cava
There are several reports describing focal AT originating from the superior vena cava (SVC). At this unusual site, a characteristic PWV was observed with P-wave highly positive in I, II, III, aVF, isoelectric in aVL and biphasic (positive to negative) in V1. SVC focal ablation was safe and effective without requiring SVC isolation in these series.6,7,8

Left-sided Focal Atrial Tachycardias – Features, P-Wave Morphology and Ablation Pulmonary Veins
The most common site of origin for left atrial foci responsible for atrial tachycardia is the pulmonary veins. The majority of these foci are located at the ostial region, although on occasion they have been observed deep within the PV. These foci more commonly originate from superior PVs (78%) than from inferior veins. The mechanism of focal AT arising from PVs is most consistent with abnormal automaticity or triggered automaticity and these foci are rarely, if ever, inducible with programmed electrical stimulation. The posterior origin of these foci is reflected by the universal finding of a positive P-wave in V1 and across the precordial leads. P-waves in lead V1 are narrow and uniphasic for right PV foci and broad and notched for left PV foci. A positive P-wave in lead I suggests a right-sided PV locus in contrast to an isoelectric or negative P-wave for a left PV locus. The superior PVs invariably have a positive P-wave in lead II.1,2 Patients with focal PV AT have a high ablation success rate and the long-term incidence of progressing to AF is low. Different ablation strategies have included focal mapping and ablation or alternately single PV circuiterential isolation.8 Both strategies carry a high success rate.

Mitril Annumlus
The MA is the second most common location of focal AT in the LA.9,10 Although AT foci have been described from a range of mitral annular sites, several studies have reported that the majority cluster at the superior region of MA in close proximity to aorto-mitril continuity adjacent to the left fibrous trigone.11,12 Gonzalez et al.13 hypothesised that remnants of the foetal conduction system in this region may provide the substrate for focal AT. AT arising from this region characteristically have a biphasic negative–positive appearance in V1 and isoelectric or negative P-wave in aVL. Inferior leads are usually low amplitude or isoelectric but inferior isolated PVs have also been reported. An anatomical definition of this region facilitates successful ablation (see Figure 2).

Left Atrial Appendage
The LAA is an unusual but well-recognised site of focal AT origin (see Figure 3). Atrial tachycardia from this site are frequently incessant and, therefore, may result in tachycardia-mediated cardiomyopathy.14 A PWV that suggests a LSPV focus but has a deeply inverted P-wave in leads I and aVL will suggest an LAA focus.15 The majority of ATs from this location have been reported to originate at the base of the appendage but occasionally these may be found at the apex. One case report described an AT with an epicardial LAA origin.16 RF ablation is a highly effective strategy for treatment of focal AT arising from LAA.17,18,19

Non-coronary Aortic Valve Cusp
In AT with earliest activation timing near the His bundle region, an origin from the non-coronary aortic cusp should be considered.20 In general, activation timing will be similar on the left and right sides of the septum, raising suspicion of a non-coronary cusp origin. In a series of nine patients with non-coronary cusp AT, Ouyang et al. described the P-wave as biphasic (negative/positive) in V1 and V2 in all patients. Unlike AT from the aorto-mitril continuity all had positive P-waves in leads I and aVL. These tachycardias did not occur spontaneously but in all cases were induced and terminated by atrial programmed stimulation or burst pacing.21

Conclusion
Focal AT is a relatively uncommon case of supraventricular tachycardia, but, when present, is frequently difficult to treat medically. Atrial tachycardias tend to originate from anatomically determined atrial sites. The P-wave morphology on surface ECG together with more sophisticated contemporary mapping techniques facilitates precise localisation and ablation of these ectopic foci. Catheter ablation of focal AT is associated with high long-term success and may be viewed as a primary treatment strategy in symptomatic patients.

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