Catheter Ablation of Ventricular Tachycardia

From Indication to Three-Dimensional Mapping Technology

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Abstract

The majority of ventricular tachycardias (VTs) occurs in patients with structural heart disease, predominantly coronary heart disease. Implantable cardioverter defibrillators (ICDs) are first-line therapy in patients with VT and structural heart disease. In patients who receive an ICD after a spontaneous sustained VT, recurrent VT episodes or an electrical storm are major problems. In addition, in patients with an ICD implanted for primary prevention of sudden cardiac death, 20% will experience at least one VT episode within 3–5 years after ICD implantation. Catheter ablation has a high acute success rate in eliminating clinical VT. However, several factors make catheter ablation of VT more difficult than ablation of supraventricular tachyarrhythmias. (1) The infarct region is often large. (2) The induced VT can be unstable or hemodynamically only poorly tolerated and therefore "unmappable". (3) Though most commonly located in the subendocardium, the critical VT zone can occasionally be epicardial or intramural in location. (4) In many cases, several reentrant circuits may coexist making ablation of a single form of VT a palliative procedure which does not obviate the risk of sudden death. Thus, catheter ablation of sustained VT in the setting of structural heart disease can only be considered an adjunctive therapy which, in general, will require ICD therapy. Numerous "modern" mapping technologies have been developed, which have increased success rates of catheter ablation of VT in patients with and without structural heart disease. The aim of the present article is to review current three-dimensional mapping systems in comparison to conventional mapping and to describe a reasonable, tailored approach for the individual patient with VT.

Key Words:
Ventricular tachycardia · Catheter ablation · Mapping

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Ventrikuläre Tachykardien. Verbesserte Möglichkeiten der Katheterablation durch dreidimensionale Navigationssysteme

Zusammenfassung

Die meisten ventrikulären Tachykardien (VT) treten bei Patienten mit struktureller Herzerkrankung auf. Implantierbare Kardioverter-Defibrillatoren (ICD) sind heutzutage Therapie der ersten Wahl bei diesen Patienten, um einen plötzlichen Herztod zu verhindern. Bei Patienten, die einen ICD nach Auftreten einer anhaltenden VT erhalten, besteht eine hohe Rezidivgefahr für erneute VT-Episoden. Darüber hinaus erleiden etwa 20% der Patienten, die primärprophylaktisch mit einem ICD versorgt werden, zumindest eine VT-Episode innerhalb von 3–5 Jahren nach ICD-Implantation. Die Katheterablation von VT stellt allein oder in Kombination mit einer medikamentösen antiarrhythmischen Therapie heutzutage eine wichtige Möglichkeit zur Behandlung von VT dar. Gegenüber der Ablationsbehandlung supraventrikulärer Tachykardien ist die Ablation von VT vielfach durch schlechte Auslösebedingungen, hämodynamische Instabilität während laufender Tachykardie und das Auftreten multipler VT erschwert. Vielfach liegen mehrere Reentrytachykardien vor, so dass die VT-Ablation bei struktureller Herzerkrankung in der Regel eine palliative Maßnahme ist. Demgegenüber kann die Mehrzahl von VT bei fehlender struktureller Herzerkrankung (sog. idiopathische VT) kurativ abladiert werden. Zur Ablation steht neben konventionellen Mapping-Verfahren heutzutage eine Reihe „moderner" dreidimensionaler Mapping-Technologien zur Verfügung, mit deren Hilfe die Erfolgsraten von VT-Ablationen deutlich gestiegen sind. Ziel der vorliegenden Arbeit ist es, eine Übersicht über vorhandene dreidimensionale Mapping-Verfahren zu geben und deren Stellenwert bei der Katheterablation von VT zu diskutieren.

Schlüsselwörter:
Ventrikuläre Tachykardie · Katheterablation · Mapping

Table 1. Class I and II indications for implantable cardioverter defibrillator (ICD) according to the ACC/AHA/HRS 2008 guidelines [1]. ACC: American College of Cardiology; AHA: American Heart Association; ARVC: arrhythmogenic right ventricular cardiomyopathy; HCM: hypertrophic cardiomyopathy; HRS: Heart Rhythm Society; LV: left ventricle; LVEF: left ventricular ejection fraction; SCD: sudden cardiac death; MI: myocardial infarction; NYHA: New York Heart Association; VF: ventricular fibrillation; VT: ventricular tachycardia.

Tabelle 1. Indikationen für implantierbare Defibrillatoren (ICD) entsprechend den ACC/AHA/HRS-Leitlinien von 2008 [1]. ACC: American College of Cardiology; AHA: American Heart Association; ARVC: arrhythmogene rechtsventrikuläre Kardiomyopathie; HCM: hypertrophische Kardiomyopathie; HRS: Heart Rhythm Society; LV: linker Ventrikel; LVEF: linksventrikuläre Ejektionsfraktion; MI: Myokardinfarkt; NYHA: New York Heart Association; SCD: plötzlicher Herztod; VF: Kammerflimmern; VT: ventrikuläre Tachykardie.

Class I

- ICD is indicated in survivors of cardiac arrest due to VF/VT after evaluation to define the cause of the event and to exclude any completely reversible causes (level of evidence: A)
- ICD is indicated in patients with structural heart disease and spontaneous sustained VT (level of evidence: B)
- ICD is indicated in patients with syncope of undetermined origin with clinically relevant, hemodynamically significant sustained VT or VF induced at electrophysiological study (level of evidence: B)
- ICD is indicated in patients with LVEF < 35% due to prior MI who are at least 40 days post MI and are in NYHA functional class II or III (level of evidence: A)
- ICD is indicated in patients with dilated cardiomyopathy who have an LVEF ≤ 35% and who are in NYHA functional class II or III (level of evidence: B)
- ICD is indicated in patients with LV dysfunction due to prior MI who are at least 40 days post MI, have an LVEF < 30%, and are in NYHA functional class I (level of evidence: A)
- ICD is indicated in patients with nonsustained VT due to prior MI, LVEF < 40%, and inducible VF or sustained VT at electrophysiological study (level of evidence: B)

Class IIa

- ICD is reasonable for patients with unexplained syncope, significant LV dysfunction, and dilated cardiomyopathy (level of evidence: C)
- ICD is reasonable for patients with HCM who have one or more risk factors for SCD (level of evidence: C)
- ICD is reasonable for the prevention of SCD in patients with ARVC who have one or more risk factors for SCD (level of evidence: C)
- ICD is reasonable for patients with long QT syndrome who are experiencing syncope and/or VT while receiving β-blockers (level of evidence: B)
- ICD is reasonable for patients with Brugada's syndrome who have had a syncope or a documented VT that has not resulted in cardiac arrest (level of evidence: C)
- ICD is reasonable for patients with catecholaminergic polymorphic VT who have had a syncope and/or documented VT while receiving β-blockers (level of evidence: C)
- ICD is reasonable for patients with cardiac sarcoidosis, giant cell myocarditis, or Chagas' disease (level of evidence: C)

Class IIb

- ICD may be considered in patients with nonischemic heart disease who have an LVEF ≤ 35% and who are in NYHA functional class I (level of evidence: C)
- ICD may be considered in patients with long QT syndrome and risk factors for SCD (level of evidence: C)
- ICD may be considered in patients with syncope and advanced structural heart disease in whom thorough invasive and noninvasive investigation have failed to define a cause (level of evidence: C)
- ICD therapy may be considered in patients with familial cardiomyopathy associated with sudden death (level of evidence: C)
- ICD therapy may be considered in patients with LV noncompaction (level of evidence: C)

Introduction

The majority of ventricular tachycardias (VTs) occurs in patients with structural heart disease, predominantly coronary heart disease. "Ischemic" VT may present itself in different forms. (1) In the acute phase of myocardial infarction, during ongoing ischemia and necrosis, repetitive episodes of ventricular tachyarrhythmias, mostly polymorphic often degenerating into ventricular fibrillation (VF), may occur. (2) In the chronic stage after myocardial infarction, when scar tissue has developed and stable reentrant circuits may be present, stable monomorphic VT is the typical presentation. (3) In advanced stages of left ventricular dysfunction and heart failure, "ischemic" VT may again either manifest itself as monomorphic VT or polymorphic VT. Thus, "ischemic" VT or VF is not always the direct consequence of ischemia but depends on its sequelae like scarring.

Implantable cardioverter defibrillators (ICDs) are first-line therapy in patients with VT and structural heart disease. Table 1 lists indications for ICD therapy according to the recent ACC/AHA/HRS (American College of Cardiology/American Heart Association/Heart Rhythm Society) 2008 guidelines [1] for management of patients with ventricular arrhythmias and the prevention of sudden cardiac death. Of patients who receive an ICD after a spontaneous sustained VT, 40–60% will experience recurrent episodes [2]. Electrical storm defined as at least three separate episodes or sustained VT within 24 h, occurs in up to 20% of patients [3]. In addition, in patients with an ICD implanted for primary prevention of sudden cardiac death, 20% will experience at least one VT episode within 3–5 years after ICD implantation [4].

Catheter ablation has a high acute success rate in eliminating clinical VT. However, several factors make catheter ablation of VT more difficult than ablation of supraventricular tachyarrhythmias. (1) The infarct region is often large. (2) The induced VT can be unstable or hemodynamically only poorly tolerated and therefore "unmappable". (3) Though most commonly located in the subendocardium, the critical VT zone can occasionally be epicardial or intramural in location. (4) In many cases, several reentrant circuits may coexist making ablation of a single form of VT a palliative procedure which does not obviate the risk of sudden death. (5) The aim of ablation may be to get rid of the dominant form of VT although attempts may be made to abolish also other forms of (so far?) not clinically relevant but inducible VT. Nevertheless, catheter ablation of sustained VT in the setting of acute or chronic myocardial infarction can only be considered an adjunctive therapy which, in general, will require ICD therapy.

Numerous "modern" mapping technologies have been developed, which have increased success rates of catheter ablation of VT in patients with and without structural heart disease [5]. These mapping tools are used to target arrhythmias that seemed out of reach years ago including hemodynamically unstable VT and VF. The aim of the present article is to illustrate the benefits of three-dimensional (3-D) mapping systems in comparison to conventional mapping and to describe a reasonable, tailored approach for the individual patient with VT.

Mapping of Ventricular Tachycardia

Monomorphic VT is the most common form of sustained VT and usually occurs after myocardial infarction. Reentry accounts for the majority of these VTs. Endocardial catheter mapping and intraoperative mapping have shown that these arrhythmias originate within or at the border zone of diseased myocardium. The size of the reentrant circuit may be large, especially in patients with a left ventricular aneurysm, or may be confined to a small area. Briefly, the conditions necessary for reentry to occur may be the following: (1) a zone of unidirectional block and (2) an impulse traveling around the zone of unidirectional block, activating the tissue distal to it with delay, invading the zone of the block retrogradely, and reexciting the tissue where the impulse originated. For reentry to occur, the impulse that is conducting around the reentrant circuit must always find excitable tissue in the direction it is propagating. Initiation and termination of VT by pacing stimuli, the demonstration of electrical activity bridging diastole, and a variety of other clinically used techniques are consistent with reentry.

Classic Methods of Contact Catheter Mapping

The aim of mapping is to characterize and localize the substrate of arrhythmias. It implies the recording of electrical activity from electrodes positioned within the heart. Accurate mapping of VT is crucial for successful ablation. Indications for VT ablation are listed in Table 2. Endocardial mapping is achieved by a variety of different methods. In the early years of cardiac mapping, a lot of the emphasis was on hardware. The number of recording channels and the computer capacity often were the limiting factors. As these issues have resolved, it has become evident that most of the problems are now related to data analysis. Mapping techniques differ in their complexity, and usually mirror the complexity of the target arrhythmia. Additionally, for many types VT ablation is increasingly performed on anatomic as well as electrophysiological data.

Table 2. Indications for catheter ablation of ventricular tachycardia (VT). ICD: implantable cardioverter defibrillator; LV: left ventricle.

Tabelle 2. Indikationen für die Katheterablation ventrikulärer Tachykardien (VT). ICD: implantierbarer Kardioverter-Defibrillator; LV: linker Ventrikel.

Class I: Ablation is indicated in patients after myocardial infarction with an ICD
- who present with repetitive monomorphic VT that leads to multiple shocks
- who present with drug-refractory incessant VT or "electrical storms"
- that cannot be avoided despite adequate reprogramming of the antitachycardia pacing mode and
- that cannot be prevented by β-blocker and/or antiarrhythmic drug therapy or
- when patients are intolerant to these drugs (level of evidence: C)

Class I: Ablation is indicated in patients after myocardial infarction with an ICD to avoid inadequate shocks
- who present with repetitive sustained VT which made antiarrhythmic drug therapy mandatory
- that decreased the rate of VT below an acceptable intervention rate into the range of exercise-induced sinus rhythm despite concomitant β-blocker therapy (level of evidence: C)

Class I: Ablation is indicated in the rare cases with bundle branch reentry after myocardial infarction (level of evidence: C)

Class IIa: Ablation is indicated in patients after myocardial infarction with an ICD who present with infrequent monomorphic VTs
- that have been terminated successfully by more than one electrical shock that most probably cannot be avoided in the long-term future despite adequate reprogramming of the antitachycardia pacing mode and
- where it is difficult to predict whether future events can be avoided by β-blocker and/or antiarrhythmic drug therapy or
- when patients are not willing to take long-term drugs the efficacy of which cannot be predicted beforehand (level of evidence: C)

Class IIb: Ablation may be considered as the sole procedure, i.e., without an ICD, in patients after myocardial infarction who have relatively well-preserved LV function (> 35–40%) and
- in whom VT is monomorphic, relatively slow and well tolerated
- who are considered to have a good long-term prognosis and
- who are either drug-resistant, do not tolerate an antiarrhythmic drug, or do not accept long-term therapy (level of evidence: C)

Class IIb: Ablation may be considered in patients after myocardial infarction who present with frequent self-terminating monomorphic VTs that may cause shock intervention by the ICD that potentially cannot be avoided by changing the intervention rate of the ICD (level of evidence: C)

Class IIb: Ablation of VT may be considered in patients with markedly reduced longevity and comorbidities (e.g., heart failure, reduced renal function) where VT can either not be prevented by antiarrhythmic drug therapy or drugs have not been tolerated and where an ICD would not be indicated due to the overall conditions of the patient. VT ablation may be an option provided that access to the LV is not prevented by major vascular changes where a transseptal approach may be considered

Class IIb: Catheter ablation may be considered in patients with more than one intervention of the ICD by a shock
- that is causing severe anxiety and psychological distress

With the increase in complexity of catheter technology and the recent appearance of very sophisticated "modern" or "new" computerized mapping techniques, the classic endocardial electrogram recording via a relatively small number of strategically positioned catheters now appears almost old-fash-

ioned. However, the experienced electrophysiologist identifies the substrate of an arrhythmia as well as the ideal ablation site with classic mapping techniques and only uses additional "modern" technology when the old one fails.

Activation Sequence Mapping

Activation sequence mapping compares the timing of electrograms recorded from the roving catheter during tachycardia with the timing of a reference signal in order to either identify the earliest possible signal or a progression of activation around a macro-reentrant circuit. This technique is ideal for focal VTs arising in structurally normal hearts such as idiopathic outflow tract VT.

Pace Mapping

Pace mapping is especially helpful in identifying the source of a focal tachycardia. The principle of the technique is that the cardiac activation sequence generated by a particular arrhythmia can be reproduced by pacing at its origin at a similar cycle length. In the case of VTs arising in structurally normal hearts such as idiopathic outflow tract VT or fascicular VT, comparison of surface QRS morphologies at pacing sites can be seen to exactly match the QRS morphology generated by the tachycardia. However, the area with excellent pace map criteria may be relatively large, so that additional criteria for a successful ablation site are often required.

Entrainment Mapping

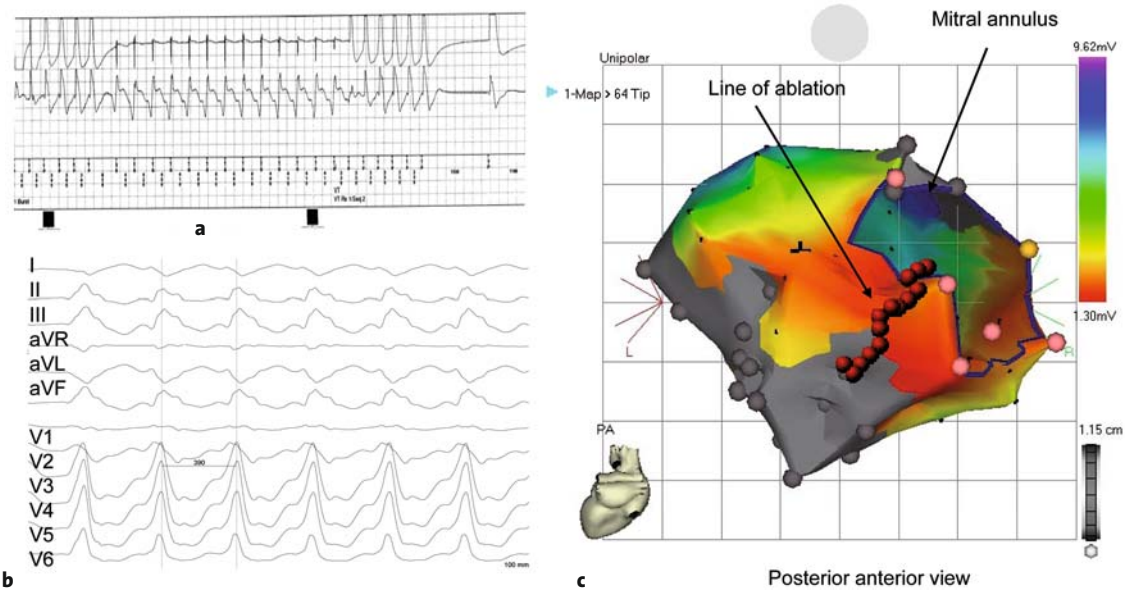
This technique may be used to map macro-reentrant circuits that have an excitable gap. The ability to entrain a tachycardia by pacing confirms a reentrant mechanism. Since an excitable gap is a prerequisite for reentry, it is possible to induce stimuli from sites within or outside the reentrant circuit that capture myocardium. If pacing is performed within the reentrant circuit, two wave fronts are produced, one traveling antidromically and colliding with the returning orthodromic wave front, whereas the other travels orthodromically within the circuit resetting the tachycardia. If pacing is successfully performed outside the circuit, the wave front propagates through the intervening myocardium, reaches the circuit and propagates in both, orthodromic and antidromic directions again resetting the tachycardia. If a train of stimuli is applied at a cycle length just below the tachycardia rate, it is possible to continuously reset, or entrain, the tachycardia [6]. To confirm that pacing has occurred within the tachycardia circuit, the result is examined for the following criteria: (1) the activation sequence of the chambers paced should be identical to that seen during tachycardia (concealed entrainment); (2) the interval between the pacing stimulus and a fixed reference point should be identical to the interval present during tachycardia between the electrogram recorded at the pacing site and the same reference point; (3) the return cycle at the pacing site should be ≤ 30 ms to the tachycardia cycle length.

Additional Mapping Characteristics

Mapping of the reentrant circuit with the described conventional techniques in infarct-related VT is often difficult because it is usually not possible to identify complete VT circuits. The areas of slow conduction have been shown to be desirable targets of ablation. Slowly conducting tissue may be identified during endocardial catheter mapping by fractionated and/or mid-diastolic electrograms, continuous electrical activity or a long delay between a stimulus and the resulting QRS complex. Pacing from within the diastolic pathway during VT will generate QRS complexes of identical morphology to those seen in VT and the interval between the pacing stimulus and QRS will be identical to that between the diastolic potential during VT and the onset of the VT QRS. Moreover, pacing at sites within the reentrant circuit or near its exit site can entrain the tachycardia, which appears to be accelerated to the pacing rate, without a change in QRS morphology [7]. The postpacing interval is within 30 ms of the VT cycle length when pacing is performed within the circuit, but it increases progressively with increasing distance between the pacing site and the circuit [8]. The described pacing results can be particularly helpful when used in combination. A combination of three criteria such as an exact QRS match during tachycardia, a return cycle within 30 ms of the VT cycle length, and the presence of diastolic potentials has been reported to terminate a VT with a single radiofrequency (RF) lesion [9].

"Novel" Mapping Technologies

Classic catheter mapping methods rely on electrical information from a relatively small number of electrodes of catheters and from anatomic information gathered from fluoroscopic images, in which the endocardial contours cannot actually be visualized. Activation sequence mapping with the classic catheter technology is time-consuming, technically difficult, not perfectly reproducible, and not suitable for hemodynamically unstable patients or spontaneous arrhythmias of short duration. The limitations of catheter ablation have been reduced by the development of complex computerized mapping systems, which have also



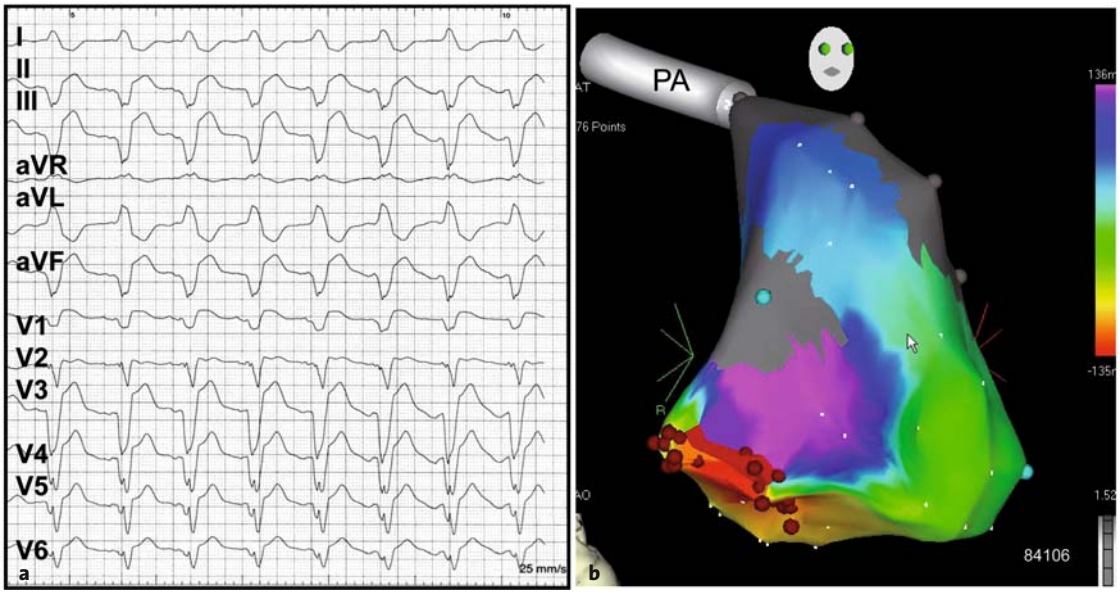
Figures 1a to 1c. Episode of ventricular tachycardia (cycle length ~ 400 ms) detected and terminated by an implanted cardioverter defibrillator in a patient with a remote inferior myocardial infarction who experienced recurrent VT episodes (a). Twelve-lead ECG of the VT in the same patient (b). Posterior view of an electroanatomic voltage map (CARTO) of the left ventricle. Electroanatomic mapping can be used to define isthmus boundaries and thus guide successful ablation. The color range represents the voltage amplitude. Gray denotes dense scar tissue. A linear ablation lesion was placed from the mitral annulus to the edge of the scar tissue to prevent mitral "isthmus" reentrant tachycardias around the mitral valve and/or around the posterior scar (c).

Abbildungen 1a bis 1c. Episode einer ventrikulären Tachykardie (Zykluslänge ~ 400 ms), die durch einen implantierbaren Kardioverter-Defibrillator regelrecht detektiert und therapiert wurde, bei einem Patienten mit einige Jahre zurückliegendem Myokardinfarkt und wiederholten VT-Episoden (a). VT-EKG-Dokumentation desselben Patienten (b). Posteriore Ansicht eines elektroanatomischen Maps (CARTO) des linken Ventrikels. Die Farbkodierung stellt die Spannungsamplituden dar (sog. „voltage map"). Graue Farbe zeigt Narbengewebe an. Eine lineare Ablationslinie wurde in der kritischen Zone des Reentrys der VT zwischen Mitralklappenanulus und Narbengewebe gesetzt, so dass die klinische VT nicht mehr auslösbar war (c).

increased our understanding and successful treatment of complex arrhythmias. A new method for nonfluoroscopic catheter-based endocardial mapping that enables the generation of 3-D electroanatomic maps of the heart chambers was introduced in 1997 [10]. Novel mapping technologies generally provide electrical information from a large number of sources, thus markedly increasing mapping resolution. Most systems can localize catheters or electrodes in 3-D space. They are capable of reconstructing 3-D endocardial activation maps as well as accurately localizing and guiding mapping catheters to sites that are suitable for ablation. The accuracy of the systems has recently been enhanced by the computerized incorporation of previously acquired computed tomography (CT) or magnetic resonance (MR) images of cardiac structures acquired prior to the mapping session to guide catheter navigation with further precision. The combination of precise 3-D CT or MRI guidance based on actual anatomy may have tremendous potential in optimizing efficacy and safety of ablation.

Although the "novel" systems may be better in confirming that a chosen target is, indeed, an appropriate site for ablation with reduced fluoroscopy and often but not always reduced procedure time, use of these systems is cost-intensive, relies on a stable position of the reference catheter, may be time-consuming, and requires a lot of operator experience.

The "novel" mapping technologies can be subdivided into methods that combine electrophysiological data with anatomic information, which mainly include CARTO (Biosence-Webster, Baldwin Park, CA, USA; Figures 1 and 2) and, more recently, CARTOMerge (Biosence-Webster) and NavX (St Jude Medical, Saint Paul, MN, USA), and methods that provide continuous and complete data of all electrophysiological events within a cardiac chamber, including basket maps (Cardiac pathways, EP Technologies, Sunnyvale, CA, USA) and noncontact mapping (EnSite 3000, St Jude Medical; Figure 3). Noncontact mapping also combines anatomic and electrophysiological information.

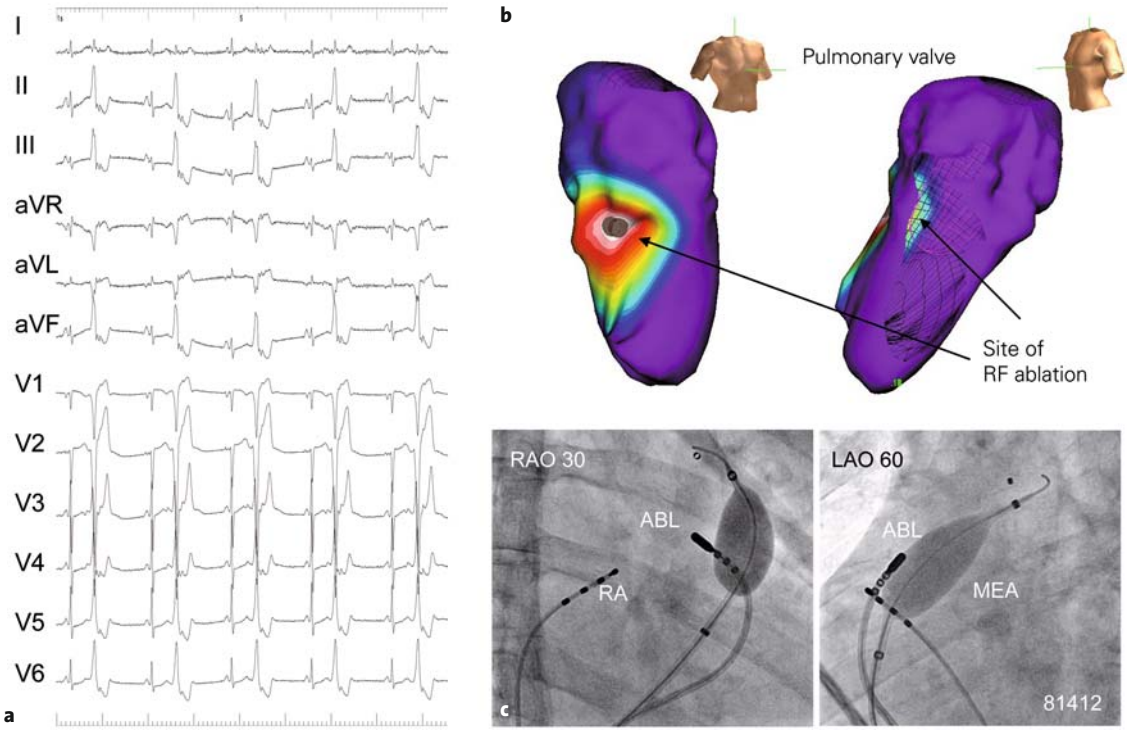


Figures 2a and 2b. Slow right ventricular tachycardia with left bundle branch block/superior axis (cycle length = 660 ms) in a patient with severe arrhythmogenic right ventricular tachycardia with chronic amiodarone treatment (a). Right anterior oblique view of an electroanatomic activation map of the VT (CARTO). Red color represents earliest depolarization. A zone of slow conduction was mapped close to the exit of the VT where a short line of ablation terminated the VT (b).

Abbildungen 2a und 2b. Langsame rechtsventrikuläre Tachykardie mit Linksschenkelblock/LAH-Konfiguration (Zykluslänge = 660 ms) bei einem Patienten mit arrhythmogener rechtsventrikulärer Kardiomyopathie (ARVD) und Amiodarontherapie (a). Elektroanatomisches Map der VT (CARTO). Rote Farbe zeigt frühe Depolarisation an. Eine Zone langsamer Leitung wurde in unmittelbarer Nähe zum Exit der VT identifiziert. Hier konnte die VT durch eine kurze Ablationslinie erfolgreich abladiert werden (b).

The first two techniques localize catheter position in space by sensing changes in its position within a magnetic field (CARTO, see below), or by sensing impedance changes between the catheter and reference points (NavX, see below). In the cases of CARTO, this information is allied to the electrograms at each catheter site. The system requires specific catheters, whereas NavX data can be obtained with any catheter and the data applied to any rhythm. With all these systems, a picture of the rhythm is built up from sequentially acquired points. By contrast, the second group of methods acquires global data so that a rhythm can be characterized from only one single beat. The accuracy of the maps created by a basket system depends on the number of splines on the basket, the number of electrodes on each spline, and the percentage of both that achieve endocardial contact. The noncontact system (see below) is based around a midcavity sensor (a special multielectrode array [MEA]) that detects far-field endocardial activity. This far-field information is transformed via inverse solution mathematically into computed equivalents of over 3,300 contact "near-field" points on a "virtual" endocardium. The definition of the map is thus influenced by the size of the chamber and the distance between the MEA and the endocardium. All of the various mapping methods have successfully created maps of all four cardiac chambers, guiding successful ablation in each.

The *CARTO system* serves as an endocardial mapping system that allows the creation of 3-D electroanatomic maps of cardiac chambers and can help navigate the roving catheter, reducing the need for fluoroscopy, and guiding it to target sites suitable for ablation, e.g., in order to create linear ablation lines (Figure 1). This method is based on using a special catheter connected to an endocardial mapping and navigation system. The system comprises a miniature passive magnetic field sensor located at the tip of the catheter, an external ultralow magnetic field, and a processing unit. The system uses the magnetic technology to accurately determine the location and orientation of a catheter in space. It simultaneously records intracardiac local electrograms from the catheter tip. The 3-D geometry of the chamber is reconstructed in real time with the electrophysiological information, which is color-coded with red representing the earliest and purple the latest points of activation and superimposed on the reconstructed 3-D geometry of the chamber. Besides activation maps,



Figures 3a to 3c. Noncontact mapping of ventricular bigeminus with left bundle branch block/inferior axis morphology originating from the right ventricular outflow tract in a highly symptomatic patient (a). The multielectrode array catheter (MEA) is part of the noncontact mapping system (EnSite 3000). The system permits mapping of a single QRS complex. The MEA, which is filled with a contrast-saline medium, is positioned in the right ventricular outflow tract (RAO/LAO: right/left anterior oblique views). The system calculates electrograms from 3,000 endocardial points simultaneously by reconstructing far-field signals. Nondepolarized myocardium is shown in purple in this three-dimensional isopotential map (b). The map also shows the site of earliest depolarization (white circle). At this site the extrasystoles were successfully ablated using radiofrequency ablation. The ablation catheter (ABL) is located at the successful ablation site. RA: diagnostic catheter in the right atrium (c).

Abbildungen 3a bis 3c. Sogenanntes „noncontact map" eines ventrikulären Bigeminus aus dem rechtsventrikulären Ausflusstrakt (a). Der sog. „multielectrode array catheter" (MEA) ist als wesentlicher Teil des EnSite-Systems im rechtsventrikulären Ausflusstrakt platziert. Das System erlaubt es, den Ursprung einzelner QRS-Komplexe zu lokalisieren. Der MEA wird mit Kontrastmittel gefüllt, nachdem er zuvor in der entsprechenden Herzkammer von femoral oder jugular positioniert wurde (RAO/LAO: rechts/links schräge Ansichten). Das System berechnet simultan Elektrogramme aus 3 000 endokardialen Punkten durch Rekonstruktion entfernter Potentiale (sog. „far-field signals"). Nichtdepolarisiertes Myokard erscheint in diesem dreidimensionalen Isopotentialmap violett (b). Das Map zeigt den frühesten Punkt der ventrikulären Depolarisation an (weißer Kreis). An diesem Punkt konnten die Extrasystolen erfolgreich abladiert werden. Der Ablationskatheter (ABL) ist an der erfolgreich abladierten Stelle lokalisiert. RA: diagnostischer Katheter im rechten Vorhof (c).

the voltage of the electrograms can be displayed in a color-coded fashion, which enables the 3-D visualization of areas with high-amplitude signals (i.e., normal myocardium) and of those with reduced or loss of amplitude (i.e., fibrosis, scarring; Figure 2) [11]. The resolution of the map depends on the number of contact points. We generally take at least 100 mapping points. For activation mapping, at each endocardial point, the local activation time is calculated as the interval between a reference point (e.g., fixed point on a surface ECG or intracardiac electrogram) and the unipolar electrogram recorded from the mapping catheter. For ventricular arrhythmias, we routinely use a right ventricular apex catheter as reference. The system has become a useful tool for mapping VT or areas of scarring and guiding the formation of linear lesions (Figure 1). More recently, fusion of 3-D CT or MR images with an electroanatomic map has been developed (CARTOMerge) [12]. This technique seems particular valuable in complex anatomic structures.

The *NavX* (former LocaLisa) system is also a nonfluoroscopic catheter-positioning system that allows localization of a catheter in 3-D space. The system has the significant advantage that no special catheters or arrays need to be used. It measures the volt-

age drop that occurs between electrodes placed on opposite sites of the chest wall and the catheter in three orthogonal planes. Three low-current (1 mA) fields, each with a characteristic frequency of approximately 30 kHz, are applied at right angles to each other through pairs of skin electrodes. Electrode position is determined by dividing each of the three amplitudes by the corresponding electrical field strength and is averaged over 1–2 s. The resulting voltage is recorded via standard catheter electrodes and is used to determine electrode position [13]. Additionally, the system has been shown to be helpful in reducing patient and operator exposure to radiation during mapping [14].

The nonsustained character and the poor hemodynamic tolerability of VT significantly reduce the number of patients with structural heart disease and reentrant VT suitable for catheter ablation by use of conventional techniques. In such a situation, the 3-D mapping systems and specifically the *noncontact mapping system* may be of particular value (Figure 3). It uses an MEA, which is positioned in the chamber being mapped. This array consists of a 9-F catheter with a 7.5-ml ellipsoid balloon. The balloon is surrounded by 64 electrically insulated wires, each with one small laser-etched break in insulation, allowing them to function as unipolar electrodes. Far-field electrocardiographic data from the array are fed into an amplifier system. A ring electrode on the proximal shaft of the array catheter is used as a reference for unipolar electrogram recordings. Since the far-field electrogram recordings detected by the array are of low amplitude and frequency, the potentials are enhanced and resolved mathematically [15]. A low-current locator signal is used to locate the mapping catheter in space. By moving a catheter, the system records the position in 3-D space by recording a number of points on the endocardial surface. These points are used to reconstruct the endocardium of any chamber. The geometry matrix defines the relationship between the location of the 64 electrodes on the array and more than 3,000 points on the endocardium where the reconstruction is computed, thus allowing the reconstruction of high-resolution endocardial isopotential and isochronal maps. Using the same locator signal, the system can also guide the mapping catheter without the need for X-ray. In contrast to the CARTO system, NavX, and RPM, the noncontact system can analyze the pattern of endocardial activation from a single beat of tachycardia [16]. Information can be displayed as reconstructed virtual electrograms, series of isopotential maps, or isochronal maps. Validation of the accuracy of the reconstructed electrogram has been published for all heart chambers [17–19]. The system has been used to map macro-reentrant VT complicating ischemic heart disease, where it has proven valuable in identifying and guiding ablation to the region of the diastolic pathway [20], as well as other VTs [21]. In right ventricular outflow tract (RVOT) VT, noncontact mapping may assist in differentiating pericardial and endocardial sites as well as ablation of single extra beats [16] (Figure 3).

The need to simultaneously map a high number of endocardial sites in 3-D space has prompted introduction of the *basket catheters*. They are constituted of flexible, elliptic, basket-shaped recording catheters incorporating five to eight splines, on which up to ten electrodes are arranged as bipolar pairs. The most commonly used catheter has 64 electrodes on eight highly flexible splines and is capable of acquiring electrophysiological data from multiple sites simultaneously. Electrograms and color-coded activation maps are reconstructed online and are displayed on a monitor. Thus, tachycardia mapping is improved, although with relatively limited resolution. The system has been successfully used to aid mapping of VT [22].

Which Technique for Which Patient?

In many patients, mapping of VT remains challenging because of a combination of factors that include the frequent presence of multiple VT morphologies, the hemodynamic instability of the VT, especially in patients with impaired ventricular function, and, in the case of ischemic heart disease-related VT, the frequent existence of functional as well as anatomic areas of block that make mapping during sinus rhythm unreliable – although regions of low-amplitude potentials and fractionated electrograms indicate sites more likely to be critical to generating VT [23]. Because of the complexity of the reentrant circuit of VT in ischemic heart disease and the lack of reliable diagnostic mapping criteria for identifying the circuit, multiple mapping techniques are often required to identify critical parts of the macro reentry, which can subsequently be targeted for ablation. In patients with hemodynamically tolerated stable VT, we perform conventional mapping with the described pacing techniques. The combination with a 3-D system often helps identifying the critical isthmus and facilitates linear ablation by a combined electrical and anatomic approach.

Full delineation of the reentrant circuit may not be possible during endocardial mapping because parts of, or occasionally the complete circuit, may have an intramural or epicardial location. A technique that allows access to the pericardial space for mapping of epicardial VT circuits has been described for patients with Chagas' disease [24] but also for patients with VT related to previous myocardial infarc-

tion [25]. Epicardial identification of the circuit is based on techniques described above for endocardial mapping. Epicardial mapping can also be performed through the coronary sinus tributaries. Using standard mapping techniques, including activation sequence-mapping and pace-mapping techniques, the location of pericardial electrodes can help guide roving endocardial catheters to sites of successful ablation [26].

For hemodynamically unstable VT, we predominantly perform an anatomic approach using the CARTO or NavX system. We almost always obtain a left ventricular angiogram before ablation – not necessarily during the ablation study. This procedure involves defining areas of scarring by means of left ventricular angiography and the presence of low-frequency, low-amplitude, and fragmented electrograms. Thereafter, we create linear ablation lesions with serial energy applications, which aim to connect the presumed exit regions to scars or anatomic structures, such as the mitral annulus [27] (Figure 1). In a report of postischemic VT in 20 patients, the noncontact mapping system has proven usefulness in showing exit sites in 99% of the studied VTs with complete VT circuits traced in about 20%. Successful ablation was achieved by 77% of RF applications to relevant diastolic activity identified by the system and was significantly more likely than at the VT exit or remote from diastolic activation [20]. 3-D mapping is also extremely helpful in the relatively rare situation of an electrical storm and/or repetitive episodes of VF that sometimes arise from triggers in the Purkinje network.

The term idiopathic VT refers to tachycardias that arise from ventricles without apparent structural abnormalities. The group consists of several distinct entities, including the most common form originating from the RVOT which accounts for up to 80% of cases of idiopathic VTs. Other idiopathic VTs include idiopathic left VT, which often arises from the region of the left posterior fascicle, and an autonomic form that may originate from either ventricle [28]. Activation sequence and pace mapping during tachycardia are used to identify the origin of the tachycardia. However, if these VTs are only poorly inducible, the use of 3-D mapping systems such as the noncontact system is extremely valuable (Figure 3). Basket catheters have also been used in a small series [22].

Conclusion

The typical patient with structural heart disease considered for VT ablation has frequent VT episodes resulting in ICD shocks due to rapid VT or ineffective antitachycardia pacing or has severe symptoms (e.g., presyncope) despite effective antitachycardia pacing therapy. In many cases, several reentrant circuits may coexist making ablation of a single form of VT a palliative procedure which does not obviate the risk of sudden death. During recent years, numerous advances in cardiac mapping have been obtained due to the introduction of complex recording technology and of algorithms for presentation and evaluation of the multitude of signals. The introduction of 3-D technology which combines anatomic and electrical information has contributed to a more and more complete understanding of cardiac electrophysiology and high success rates of catheter ablation of VT.

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