

Cardiac Arrhythmia 3

Ventricular arrhythmias and sudden cardiac death

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This is the third in a Series of three papers about cardiac arrhythmia

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Management strategies for ventricular arrhythmias are guided by the risk of sudden death and severity of symptoms. Patients with a substantial risk of sudden death usually need an implantable cardioverter defibrillator (ICD). Although ICDs effectively end most episodes of ventricular tachycardia or ventricular fibrillation and decrease mortality in specific populations of patients, they have inherent risks and limitations. Generally, antiarrhythmic drugs do not provide sufficient protection from sudden death, but do have a role in reducing arrhythmias that cause symptoms. Catheter ablation is likewise important for reducing the frequency of spontaneous arrhythmias and is curative for some patients, usually those with idiopathic arrhythmias and no heart disease. Arrhythmia surgery is now infrequent, offered by only a few specialised centres for refractory arrhythmias. Advances in understanding of genetic arrhythmia syndromes and in technology for mapping and ablation of ventricular arrhythmias, and enhanced algorithms in implantable devices for rhythm management, have contributed to improved outcomes.

Introduction

Ventricular arrhythmias are an important cause of morbidity and sudden death in almost all forms of heart disease. Assessment of the risk of sudden death and effective prevention are the main issues in patients with these arrhythmias. Presence of structural heart disease or genetic arrhythmia syndromes frequently impart a clinically significant risk, and in these cases an implantable cardioverter defibrillator (ICD) should be considered. ICDs effectively end most episodes of ventricular tachycardia or ventricular fibrillation and reduce total mortality in high-risk groups of patients who have not yet had a ventricular arrhythmia. Antiarrhythmic drugs and catheter ablation have important roles in reduction of symptomatic arrhythmias and shocks from ICDs. In this Series paper, we address common causes of ventricular arrhythmias and arrhythmic sudden death and approaches to management that are based on patient characteristics.

Sudden cardiac death

In Europe and North America, 50–100 sudden unexpected cardiac deaths occur per 100 000 population every year.^{1,2} The incidence decreases from 1 per 1000 population for adults older than 35 years to 1 per 100 000 for those younger than 35 years.³ About half these events are attributable to ventricular tachycardia or ventricular fibrillation. For unclear reasons, the proportion of patients with pulseless electrical activity or asystole has increased over the past two decades.⁴ Overall, less than 5% of people with an out-of-hospital cardiac arrest survive.^{1,5} Most victims have structural heart disease, most often coronary artery disease. Unfortunately, the underlying disease is often unrecognised before death, such that sudden death is the first manifestation of heart disease.^{1,2}

For the clinician assessing the risk of sudden death in an individual patient, age, underlying heart disease, and presenting symptoms are important considerations. In children and young adults, the most frequent causes of

sudden cardiac death are hypertrophic and arrhythmogenic cardiomyopathies, myocarditis, coronary artery malformations, and genetic arrhythmia syndromes.^{1,2} With increasing age, atherosclerotic coronary artery disease is the main cause of sudden death. In adults with cardiac disease, the severity of ventricular dysfunction is the most consistent marker of risk.¹

Ventricular arrhythmias

Features identified by electrocardiogram (ECG) often suggest the mechanism and cardiac site of origin of ventricular tachycardia (figure 1).⁶ Ventricular tachycardia is often defined as sustained if it lasts longer than 30 s, produces syncope or cardiac arrest, or needs cardioversion or pacing from an ICD for cessation.

Polymorphic ventricular tachycardia has a continually changing QRS axis, suggesting a varying ventricular activation sequence (figure 1). A fixed anatomic substrate is not needed. Acute myocardial ischaemia and genetic arrhythmia syndromes are important causes of polymorphic ventricular tachycardia.⁷ This tachycardia, known as torsade de pointes, is associated with QT prolongation and often has a characteristic waxing and waning QRS amplitude.⁷

Search strategy and selection criteria

We searched PubMed for articles published between Jan 1, 2005, and Dec 31, 2011, and the Cochrane library for those published between Jan 1, 2007, and Dec 31, 2011, with the search terms "Ventricular Tachycardia", "Ventricular Arrhythmias", or "Sudden Death" cross-referenced with "catheter ablation", "implantable defibrillators", and "specific diseases" for each section of the Series paper. We reviewed the reference lists of articles identified by the search and selected those deemed relevant. We cited review articles to provide readers with more details.

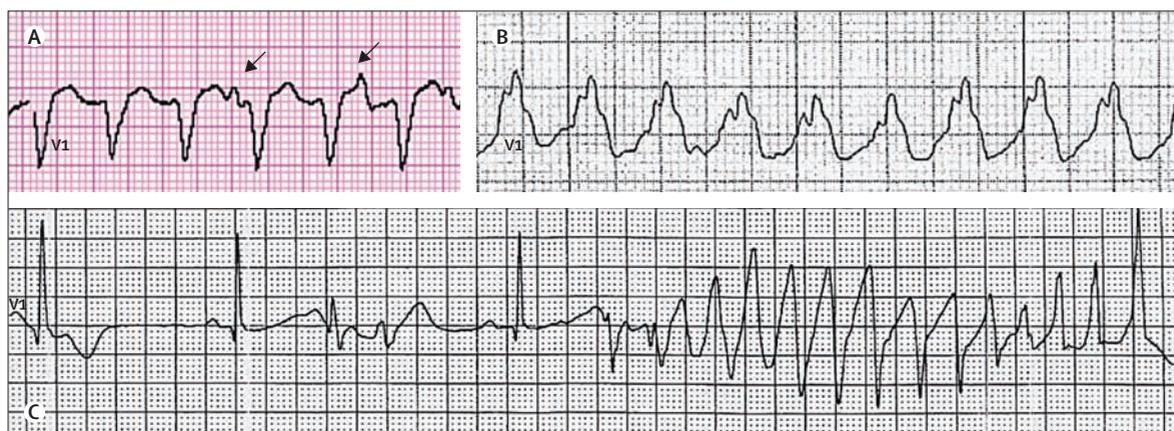


Figure 1: Electrocardiographical features of different types of ventricular tachycardia

(A and B) Lead V1 from two patients with sustained monomorphic ventricular tachycardia. (A) Ventricular tachycardia has a left bundle branch block-like configuration in V1, consistent with an origin in the right ventricle or septum. Dissociated P waves (arrows) are present, supporting a diagnosis of ventricular tachycardia. (B) Ventricular tachycardia has a right bundle branch block-like configuration, with a dominant R wave in V1, suggesting a probable left ventricular origin. (C) Polymorphic ventricular tachycardia associated with marked QT prolongation (torsade de pointes ventricular tachycardia).

Monomorphic ventricular tachycardia has the same QRS configuration from beat to beat (figure 1), suggesting a stable origin of tachycardia from a focus or structural substrate. ECG morphology suggests the ventricular origin.⁶ A left bundle branch block-like configuration, defined by a dominant S wave in lead V1, suggests that the arrhythmia originates in the right ventricle or interventricular septum (figure 1). A right configuration, defined by a dominant R wave in V1, typically originates from the left ventricle (figure 1). In structural heart disease, sustained monomorphic ventricular tachycardia is usually caused by re-entry, involving a region of ventricular scar that might be a result of previous myocardial infarction, cardiomyopathy, or ventricular surgery—eg, repair of tetralogy of Fallot.⁶ Less frequent causes of monomorphic ventricular tachycardia are re-entry or automaticity in diseased Purkinje tissue.⁶

Ventricular tachycardia without structural heart disease is often referred to as idiopathic tachycardia.⁶ Most cases of the idiopathic disorder are due to an automatic focus along the pulmonic, aortic, mitral, or tricuspid valve annulus, or less often, re-entry in or near the fascicles of the left bundle branch.⁶

Genetic arrhythmia syndromes

General characteristics

Many single gene mutations have been identified that cause either arrhythmias and sudden death by disruption of cardiac ion channel function (channelopathies), or cardiomyopathy. Most mutations are uncommon, but when an otherwise healthy individual develops arrhythmia symptoms or after the sudden cardiac death of a relative, the first point of medical contact is often the family physician. The ECG is an important screening method, but abnormalities can be subtle and vary from day to day in some disorders.³ Family screening is also

complicated by substantial variability in penetrance, such that the same mutation can cause frequent arrhythmias in one individual, but be asymptomatic in another. Genotyping is increasingly used to confirm the type of disorder, identify affected relatives of the first diagnosed patient, and in some, but not all disorders, help to assess risk of sudden death.⁸ Diagnosis of genetic arrhythmia syndromes can be challenging, and management is difficult; referral to a specialist is usually warranted when such syndromes are identified or suspected.

Abnormalities of repolarisation and the QT interval

In long QT (LQT) syndrome, prolonged repolarisation typically extends the corrected QT interval to more than 440 ms in men and 460 ms in women. Syncope or cardiac arrest due to torsade de pointes ventricular tachycardia is the presenting symptom. At least 13 different forms of congenital LQT syndrome have been identified and are caused by variations in genes encoding cardiac ion channels or their supporting proteins; however, three groups of mutations that lead to LQT-1, LQT-2, or LQT-3 syndromes account for 90% of cases.^{8,9} Several genotype-phenotype correlations have been made. Depending on the mutation, other clinical features can include bradycardia, dysmorphic features, and deafness.¹⁰ The most common mutations—LQT-1 and LQT-2—are attributable to loss-of-function mutations in genes encoding potassium channels (*KCNQ1* and *KCNH2*). In LQT-1, arrhythmias typically occur during exertion, notably swimming. In LQT-2, arrhythmias are often triggered by a surprise, such as a sudden loud noise. LQT-3 syndrome is caused by a mutation that increases the sodium current in cardiac cells; sudden death during sleep is a notable feature. The appearance of T waves often suggests LQT syndrome: broad-based T waves show LQT-1, notched T waves show LQT-2, and narrow-based T waves show

LQT-3.¹⁰ Markers of increased risk include prolonged QT intervals (particularly >0.5 s), female sex, and a history of syncope or cardiac arrest. Genotyping has clinical relevance

for risk assessment and treatment, and is recommended.⁸⁻¹⁰ β -blocker therapy is protective in LQT-1 and LQT-2, particularly when symptoms are adrenergically mediated, but an adequate dose and ensured compliance is crucial.^{11,12} Recurrent syncope despite β -blocker therapy, or high-risk profiles, merits consideration of an ICD.^{9,10,13} Avoidance of drugs that prolong the QT interval is important for all individuals, including those who are genotype positive but have normal QT intervals.

Short QT syndrome is a rare cause of polymorphic ventricular tachycardia and sudden death.¹⁰ This disease is genetically heterogeneous because of mutations that either increase outward potassium currents or reduce inward depolarising currents, such as the calcium current. The corrected QT interval is shorter than 0.36 s, and usually less than 0.30 s.

Brugada syndrome, characterised by syncope or sudden death, is associated with a characteristic ECG appearance with ST segment elevation in at least two of leads V1–V3 with a typical coved morphology (referred to as type I Brugada ECG), which either arises spontaneously or is induced by administration of a sodium-channel blocking drug (figure 2A).¹⁰ Gene mutations are identified in less than 30% of patients, and most include the cardiac sodium-channel gene *SCN5A*.⁸ Inheritance is typically autosomal dominant. Abnormal conduction and fibrosis in the right ventricular outflow tract and overlap with arrhythmogenic right ventricular cardiomyopathy has been described, suggesting that the syndrome might have several causes.¹⁴ A predominance in men has been noted. Cardiac arrest is caused by polymorphic ventricular tachycardia, which often occurs during sleep or fever. An ICD is warranted for individuals who have had syncope or been resuscitated from cardiac arrest.^{9,13}

Early repolarisation syndrome consists of J-point elevation with a notching of the terminal QRS. This pattern has been associated with ventricular fibrillation without structural heart disease, often referred to as idiopathic ventricular fibrillation (figure 2B).^{15,16} The family history of sudden death that is present in some patients suggests a potential genetic basis. An ICD is generally considered for patients with polymorphic ventricular tachycardia or previous cardiac arrest. J-point elevation is often a normal variant in patients with no history of arrhythmia.

Catecholaminergic polymorphic ventricular tachycardia

Catecholaminergic polymorphic ventricular tachycardia presents with syncope or cardiac arrest during exertion or emotional upset.⁹ Causative mutations in the genes encoding ryanodine receptor or calsequestrin result in abnormal calcium handling and ventricular arrhythmias that can resemble those of digitalis toxicity. ICDs, restriction of physical activity, and β blockers have been mainstays of treatment.¹³ The sodium-channel blockers flecainide and propafenone might be effective.⁹ Surgical sympathectomy can be helpful in refractory cases.¹⁷

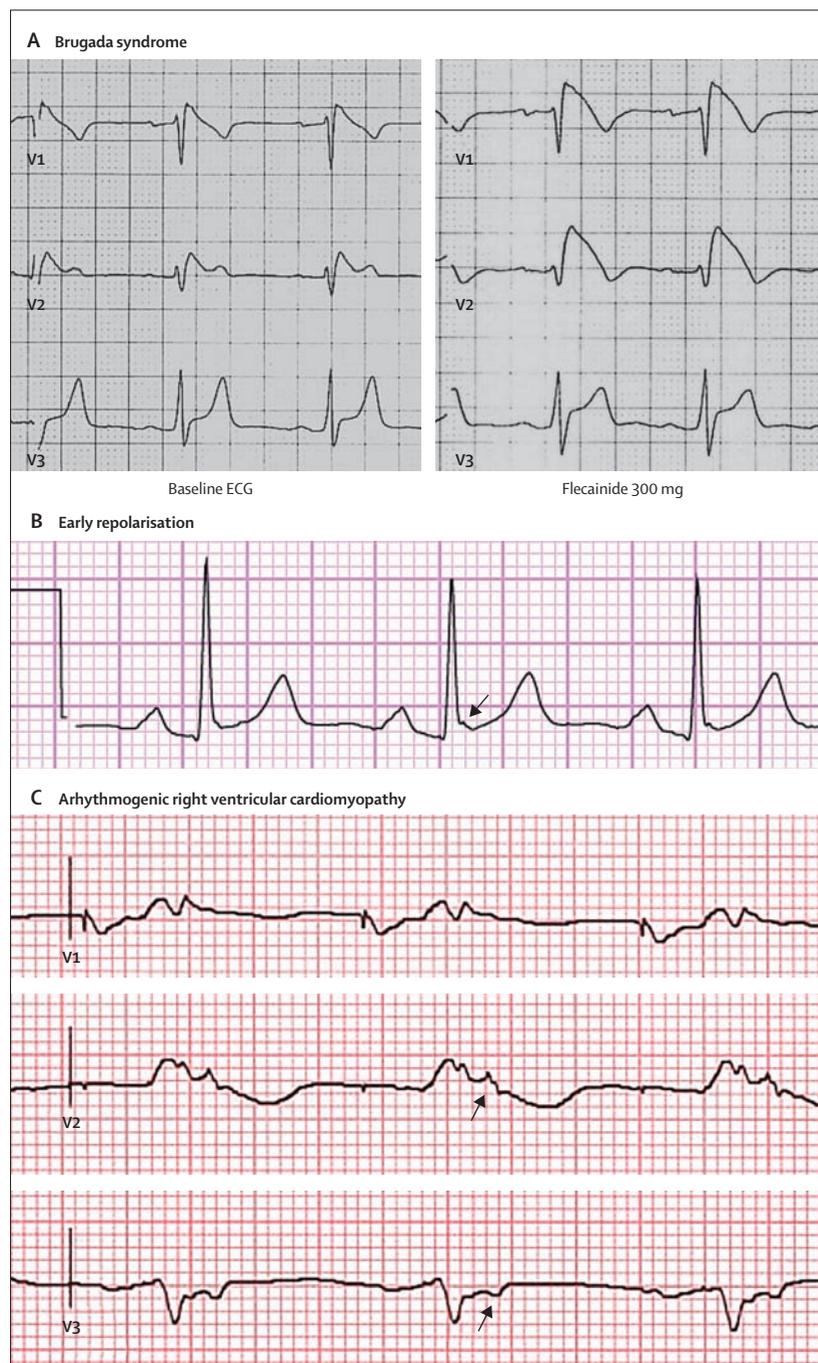


Figure 2: Typical electrocardiographical features of genetically mediated arrhythmic disorders
(A) Precordial leads V1–V3 of a patient with Brugada syndrome. At baseline, concave upward ST elevation in V2 is recorded. After oral administration of flecainide 300 mg, convex upward ST elevation (type I pattern) becomes apparent. (B) Lead II of a 20-year-old man resuscitated from an arrhythmic cardiac arrest. Typical ST elevation with notching in the terminal QRS is evident (arrow). (C) Precordial leads V1–V3 of a patient with arrhythmogenic right ventricular cardiomyopathy. Wide right bundle branch block with delayed activation manifests as a late epsilon wave (arrows), and T inversion is present.

Inherited cardiomyopathies

Hypertrophic cardiomyopathy is the most common genetic cardiovascular disorder, occurring in 1 in 500 individuals, and is a prominent cause of sudden death before the age of 35 years.¹⁸ Most occurrences of this disorder are due to mutations in genes encoding sarcomeric proteins, but once diagnosis is made, genotyping has not been helpful for assessment of sudden death risk. Sudden death is usually due to polymorphic ventricular tachycardia or fibrillation. Risk factors include young age, non-sustained ventricular tachycardia, failure of blood pressure to increase during exercise, recent (within 6 months) syncope, ventricular wall thickness of greater than 3 cm, and possibly the severity of left ventricular outflow obstruction.¹⁹ Whether fibrosis detected as delayed gadolinium enhancement on MRI will prove to be another marker of risk remains to be established.²⁰ An ICD is recommended for patients at high risk, but the specific risk profile warranting an ICD continues to be debated.^{13,19} Surgical myectomy has been associated with a sudden death rate of less than 1% per year.^{21,22} The reported yearly rate of sustained ventricular tachycardia or sudden death after transcatheter ethanol septal ablation ranges from 1% to as high as 5%.^{21,22}

Arrhythmogenic right ventricular cardiomyopathy, or just arrhythmogenic cardiomyopathy, is a group of genetic disorders characterised by fatty replacement of ventricular myocardium or ventricular tachycardia arising in regions of fibrosis.^{23,24} Most types of this disorder are due to mutations in genes encoding proteins involved in cell-to-cell adhesion in desmosomes, such as plakoglobin and plakophilin. Left ventricular involvement occurs in about a third of cases and can predominate. Inheritance is typically autosomal dominant. The sinus rhythm ECG displays inverted T waves in the anterior precordial leads in more than 75% of patients (figure 2C).²³ An ICD is usually warranted.^{13,25} Cardiac sarcoidosis can mimic arrhythmogenic right ventricular cardiomyopathy.

Non-ischaemic dilated cardiomyopathies have a genetic basis in more than 40% of cases,²⁴ and several are associated with concomitant conduction disease. Sudden death can occur from ventricular arrhythmias or bradyarrhythmias.

Management according to clinical presentation

Symptomatic arrhythmia

Ventricular arrhythmias might present with palpitations, presyncope, syncope, or cardiac arrest. Prognosis and risk of sudden death are largely determined by the nature of the underlying heart disease (figure 3). History and

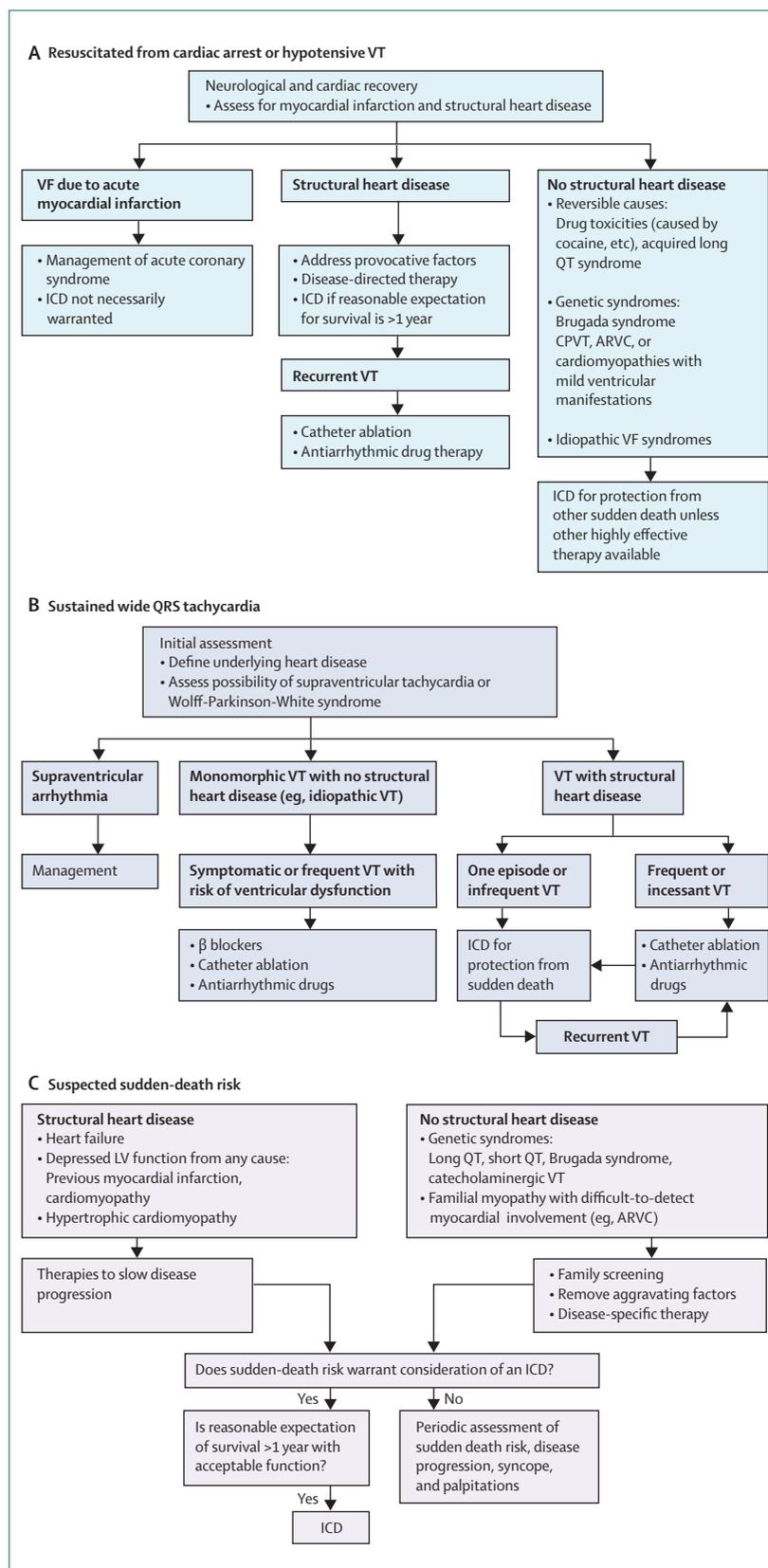


Figure 3: Management algorithms

General approach to management of patients who: (A) have been resuscitated from cardiac arrest; (B) have sustained wide QRS tachycardia; and (C) are suspected as having a risk of sudden death on the basis of detected heart disease or a family history of sudden death. VT=ventricular tachycardia. ICD=implantable cardioverter defibrillator. CPVT=catecholaminergic polymorphic ventricular tachycardia. ARVC=arrhythmogenic right ventricular cardiomyopathy. VF=ventricular fibrillation. LV=left ventricular.

physical examination should focus on identification of heart disease. Potential aggravating factors should be sought and addressed, including electrolyte imbalances, stimulants such as caffeine and amphetamine analogues, and other drugs. An ECG often provides the first indication of underlying heart disease or a genetic arrhythmia syndrome. Assessment for coronary artery disease is the first major consideration in adults. Ventricular imaging, usually with an ECG, is needed to detect myopathies and assess ventricular function. Cardiac MRI can be helpful to assess the presence of scar, which is the most common substrate for sustained monomorphic ventricular tachycardia.²⁰ The specific arrhythmia can often direct specific assessment and management.

Sustained wide QRS tachycardia

Sustained monomorphic ventricular tachycardia should be distinguished from supraventricular tachycardia with aberrancy or pre-excitation over an accessory pathway (figure 3); ECG criteria are good but not perfect at accurately distinguishing the two disorders.²⁶ The presence of structural heart disease favours ventricular tachycardia. Because a definitive diagnosis is mandatory to assess risk and guide therapy, an electrophysiology study is occasionally needed. ECG artifacts can mimic ventricular tachycardia, and inappropriate treatments have been administered when tachycardia has not been recognised.²⁷ The 12-lead ECG morphology of ventricular tachycardia suggests the probable ventricular origin and can point to the type of structural disease that needs to be excluded. For example, ventricular tachycardia of right ventricular origin should alert the physician to the possibility of arrhythmogenic right ventricular cardiomyopathy.

When structural heart disease is present, monomorphic ventricular tachycardia is usually a result of scar-related re-entry. Although myocardial ischaemia can act as a trigger for such ventricular tachycardia, revascularisation therapies alone are unlikely to prevent recurrences. More than 40% of patients have recurrent arrhythmia within 2 years and all have a risk of sudden death.^{28,29} An ICD should be considered.¹³ However, even with an ICD, recurrent ventricular tachycardia is associated with increased mortality and hospital admissions and reduced quality of life after ICD shocks.^{6,30,31} Antiarrhythmic drugs or catheter ablation are used to reduce recurrences and control incessant ventricular tachycardia or electrical storms (defined as more than three ventricular tachycardia or fibrillation episodes in 24 h).^{6,28,31,32}

Idiopathic ventricular tachycardia in the absence of structural heart disease most often originates from the right ventricular outflow tract. Diseases such as arrhythmogenic right ventricular cardiomyopathy and sarcoidosis often need to be excluded before a diagnosis is made. Idiopathic ventricular tachycardia must be distinguished from ventricular tachycardia with structural heart disease, because the latter often warrants an

ICD. Detection of ventricular scar on cardiac imaging can be helpful.³³ Although idiopathic monomorphic ventricular tachycardia can cause syncope, sudden death is rare.³⁴ β blockers, calcium-channel blockers, or catheter ablation are often effective.

Polymorphic ventricular tachycardia and resuscitated ventricular fibrillation

Polymorphic ventricular tachycardia generally suggests the presence of clinically significant heart disease caused by acute myocardial ischaemia, cardiomyopathies, or a genetic arrhythmia syndrome. Drugs causing QT prolongation and metabolic derangements are other causes.⁷ Unless a clear precipitant can be identified and corrected, an ICD is often warranted.¹³ Polymorphic ventricular tachycardia or fibrillation complicating the first 48 h of acute myocardial infarction is associated with greater in-hospital mortality, but not greater long-term mortality for patients who survive to hospital discharge, and an ICD is not usually beneficial.³⁵ Patients who present with ventricular fibrillation who are resuscitated might have had sustained monomorphic ventricular tachycardia or polymorphic ventricular tachycardia as the initial arrhythmia, which necessitates a broader assessment.

Syncope

Ventricular arrhythmias might present as syncope. Assessment for structural heart disease and genetic arrhythmia syndromes is essential. Unexplained syncope in association with impaired ventricular function is associated with a risk of sudden death, and an ICD should be considered.¹³

Premature ventricular contractions and non-sustained ventricular tachycardia

Premature ventricular contractions are common, and are reported in up to 27% of healthy individuals during exercise testing.³⁶ Their prevalence increases with age and with the presence and severity of heart disease. Exercise-induced and recovery-phase premature ventricular contractions or non-sustained ventricular tachycardia are associated with increased mortality, probably because they are markers for underlying heart disease.³⁷ When structural heart disease is absent and an underlying genetic arrhythmia syndrome is not evident, the risk is low and therapy is not needed unless for treatment of symptoms.

Very frequent premature ventricular contractions—particularly more than 24% of total heart beats per 24 h—or incessant repetitive monomorphic ventricular tachycardia occasionally causes depressed ventricular function.^{6,38} Apparent ventricular dysfunction can also be due to impaired ability to measure ventricular function during the arrhythmia, or to an underlying cardiomyopathy. Often, only reassessment of ventricular function after ablation of the arrhythmia clarifies the cause.

Increased risk of sudden death without arrhythmia symptoms

Various cardiac diseases carry a risk of sudden arrhythmic death, even in the absence of detected arrhythmias or arrhythmia symptoms (figure 3). The severity of left ventricular dysfunction is a major factor, guiding selection of patients for ICDs.^{1,2,13} Other non-invasive markers of arrhythmia risk, such as non-sustained ventricular tachycardia on ambulatory monitoring, blunted baroreflex sensitivity, a reduction in heart rate variability, presence of late myocardial activation (late potentials), T-wave alternans, and extent of myocardial scar have not yet been shown to be routinely useful for selection of ICD therapy.^{1,2,20}

Cardiac arrest and sudden death are most frequent within the first hours of an acute myocardial infarction. For survivors of an acute myocardial infarction, the risk declines from a rate of 1·4% in the first month to 0·14% per month after 2 years, but is greater (at 2·3% per month) for those with a left ventricular ejection fraction (LVEF) of 30% or less.³⁹ Inducible ventricular tachycardia 5 days to 4 weeks after myocardial infarction was associated with a 25% risk of spontaneous ventricular tachycardia within 2 years, but an invasive electrophysiology study is needed to identify this risk, which is not routine in most centres.⁴⁰ Acute reperfusion of the infarct artery, β blockers, angiotensin-converting enzyme inhibitors, and aldosterone antagonists reduce sudden death.^{1,41}

Despite the early risk of sudden death, ICD implantation within 5–40 days of myocardial infarction does not improve mortality.^{42,43} Cardiac rupture and recurrent ischaemia probably contribute to early mortality that is not prevented by an ICD.^{43,44} For patients with previous myocardial infarction and LVEF of 30% or less at least 40 days after myocardial infarction or 90 days after revascularisation, ICDs reduced mortality from 19·8% to 14·2% over a mean 20 month follow-up.⁴⁵ In patients with stable functional class II or III heart failure and LVEF of less than 35% due to coronary artery disease or non-ischaemic cardiomyopathy, ICDs reduced mortality from 28% to 22% over a median follow-up of 45 months.⁴⁶ ICDs also reduced mortality in patients with LVEF of 40% or less who had inducible sustained ventricular tachycardia.¹³

For patients with non-ischaemic cardiomyopathies, the risk of sudden death is roughly 2% per year for those with stable heart failure.^{47,48} Syncope and the severity of ventricular dysfunction are risk factors.⁴⁹ Because ventricular function often improves after initial presentation, reassessment is generally warranted after 3 months of stable medical therapy. ICDs are recommended for those with heart failure and LVEF that remains persistently at 35% or less.¹³

Drug therapy for ventricular arrhythmias

Pharmacological therapies have an important role in the reduction of recurrent symptomatic arrhythmias.²⁸ Many

arrhythmias are provoked by exertion or aggravated by sympathetic stimulation, and respond favourably to β blockers. The favourable safety profile of these drugs makes them a first-line therapy for most symptomatic ventricular arrhythmias, despite reduced efficacy for arrhythmias associated with heart disease.

Membrane-active antiarrhythmic drugs that block cardiac ion channels have little role in the prevention of sudden death in patients with structural heart disease, but are useful for reduction of symptomatic arrhythmias.⁵⁰ However, they should be used cautiously, because they are associated with toxicities and can aggravate arrhythmias. The sodium channel blocking drugs flecainide and propafenone are occasionally considered for idiopathic ventricular tachycardias, but these agents should be avoided in patients with heart disease because they have negative inotropic effects, and flecainide increased mortality when given to survivors of myocardial infarction.⁵⁰ Drugs that prominently block potassium channels (eg, sotalol, dofetilide, quinidine) prolong repolarisation, with a risk of causing torsade de pointes ventricular tachycardia. Careful monitoring for excessive QT prolongation during initiation is needed.

Both oral amiodarone and sotalol reduce ventricular and atrial arrhythmias that can lead to ICD shocks.²⁸ Amiodarone is most effective, but toxicities (eg, prominently thyroid, lung, liver, and neurological effects) restrict long-term use in more than 20% of patients.²⁸ In patients with LVEF of 35% or less, amiodarone had no effect on mortality in class II heart failure, but was associated with increased mortality in class III heart failure.⁴⁶ Amiodarone is a reasonable consideration for patients who have had sustained ventricular tachycardia or fibrillation, but who have a contraindication to or refuse an ICD.⁵⁰

ICDs

ICDs improve mortality in cardiac arrest survivors and in patients at risk for sudden death due to structural heart diseases.^{13,50,51} In all cases, ICDs are recommended only if the patient is expected to survive for at least 1 year with acceptable functional capacity.¹³ An ICD is appropriate, however, for patients with end-stage heart disease who are awaiting cardiac transplantation and are not in hospital, or who have left bundle branch block QRS prolongation such that they are likely to have improvement in ventricular function with cardiac resynchronisation therapy from a biventricular ICD.^{13,52}

ICD implantation has a 3% risk of complications, including pneumothorax, perforation, bleeding, and heart failure decompensation, but the procedure-related mortality is less than 1%.^{53,54} After implantation, care must be taken to program the ICD to avoid unnecessary right ventricular pacing, which can aggravate ventricular dysfunction.⁵⁵ Inappropriate shocks due to sinus tachycardia, atrial fibrillation, non-sustained ventricular tachycardia, or lead malfunction occur at a yearly rate of

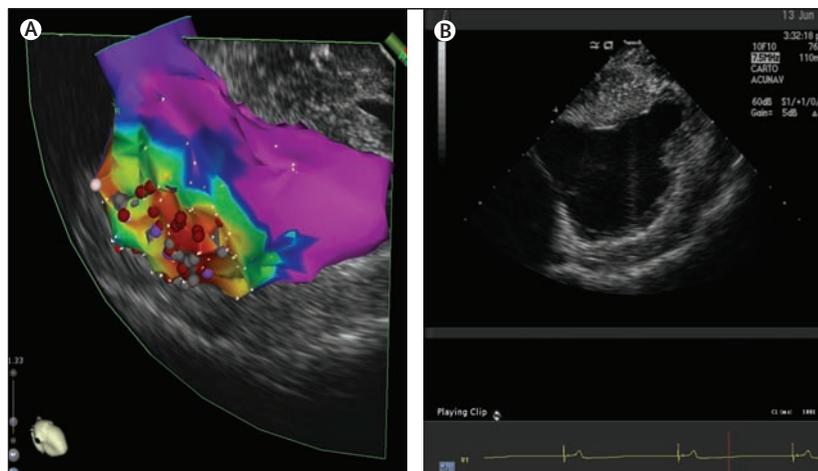


Figure 4: Mapping and ablation of ventricular tachycardia with electroanatomic and intracardiac echocardiographical imaging

Images obtained during substrate mapping of the left ventricle in a patient with ventricular tachycardia caused by an old inferior wall infarction. (A) Voltage map of the left ventricle viewed from the posterior-inferior aspect of the ventricle; the plane of the ultrasound image is shown. Colours represent electrogram voltage: purple is normal (>1.5 mV) and blue, green, yellow, and red are progressively lower amplitude regions consistent with the infarct scar, present as an inferior wall aneurysm. Dark red circular tags are sites of ablation lesions placed in the scar. Grey circular tags are electrically unexcitable to pacing, suggesting dense fibrosis. (B) Image of the left ventricle obtained from an ultrasound catheter in the right ventricle.

about 3.5%.^{56,57} ICD shocks reduce quality of life and have been associated with increased mortality, possibly related to adverse effects of the high voltage shock itself.⁵⁸ Strategic programming of ICD arrhythmia detection criteria and antitachycardia pacing therapy can reduce the chance of necessary and unnecessary shocks without compromising safety. The ICD and its leads should be removed if a patient has an ICD-related infection; ICD removal-related mortality is 0.25%.⁵⁹

Patients receiving ICDs should to be carefully followed up to detect arrhythmias, which are a harbinger of heart failure deterioration and reduce quality of life, and to monitor device malfunction and battery life. Remote monitoring systems that allow patients to transmit ICD recordings from home to a central station have simplified follow-up and enhanced early detection of arrhythmias and malfunctions.^{60,61}

Catheter ablation for ventricular tachycardia

Better understanding and definitions of cardiac anatomy from use of electroanatomic mapping systems, intracardiac echocardiography, and preacquired MRI or CT images incorporated into mapping systems (figure 4) are improving ablation therapy.^{6,62} Percutaneous epicardial mapping and ablation achieved by insertion of a sheath and mapping catheter into the pericardial space is now possible.^{6,63} Efficacy and risk of complications depends on the location of the ventricular tachycardia origin and associated heart disease, which, along with the availability of an experienced ablation programme, are important considerations during risk-benefit assessment of this therapy.

Procedural complications occur in about 3% of patients with idiopathic ventricular tachycardia, and 6% of patients with structural heart disease, including tamponade, stroke, heart block, and, most frequently, vascular access complications.^{6,64} Procedural mortality is rare in idiopathic ventricular tachycardia, but ranges from 1% to 3% in patients with structural heart disease.^{64,65} Percutaneous epicardial access and ablation has a 5% risk of major complications, including coronary artery injury and pericardial bleeding that is usually self-limited, but deaths have been reported.⁶⁶⁻⁶⁸

Catheter ablation is a reasonable first-line therapy for many symptomatic idiopathic ventricular tachycardias.⁶ Success rates approach 80–90% in experienced centres.⁶ Most idiopathic ventricular tachycardias originate from a focus in the right ventricular outflow tract. Success rates are lower than average for those arising in less common locations such as along the aortic annulus, within the aortic sinuses, within the great cardiac vein, or from the epicardium. Failure of ablation is usually due to inability to induce the arrhythmia for precise localisation, or ventricular tachycardia origin in a location that is inaccessible or in close proximity to a coronary artery, which precludes safe ablation.⁶⁹

In patients with structural heart disease, catheter ablation of ventricular tachycardia is used to reduce the frequency of symptomatic ventricular tachycardia that triggers ICD shocks, or to control incessant or very frequent ventricular tachycardia.^{6,32,65} These are usually scar-related re-entrant ventricular tachycardias that can cause haemodynamic collapse, which prevents extensive mapping during ventricular tachycardia. To avoid haemodynamic compromise, substrate mapping during stable sinus rhythm is often used to identify the area of scar and probable arrhythmia origin from electrogram characteristics (figure 4).⁶ This region can then be targeted for ablation without inducing ventricular tachycardia. This approach can also be combined with limited mapping during ventricular tachycardia for more focal targeting of re-entry circuits.

Ablation can be life saving for patients with very frequent or incessant ventricular tachycardia.³² Ablation abolishes recurrent, drug-refractory ventricular tachycardia due to previous myocardial infarction in roughly 50% of patients, and reduces the frequency of ventricular tachycardia in an additional 20%.^{6,65} More than one procedure is necessary in up to 30% of patients.⁷⁰ Outcomes are less well defined in other heart diseases, but case series show control of recurrent monomorphic ventricular tachycardia due to non-ischaemic cardiomyopathy, repaired congenital heart disease,⁷¹ arrhythmogenic right ventricular cardiomyopathy,^{63,72} hypertrophic cardiomyopathy,⁷³ or valve surgery or ventricular aneurysmectomy,^{74,75} and in patients with left ventricular assist devices.⁷⁶ Epicardial ablation is often needed for patients with non-ischaemic cardiomyopathy.^{6,63}

Catheter ablation can also be life saving for patients with recurrent polymorphic ventricular tachycardia and

ventricular fibrillation that is repeatedly initiated by an index premature ventricular contraction.⁷⁷ The initiating ectopic beat often originates from the Purkinje system or the right ventricular outflow tract and can be targeted for ablation. Epicardial ablation at abnormal sites in the right ventricular outflow tract was successful in controlling recurrent ventricular fibrillation in Brugada syndrome in one small series.¹⁴

When catheter ablation fails, or is not an option, surgical cryoablation, often combined with aneurysmectomy, can be effective therapy for recurrent ventricular tachycardia due to previous myocardial infarction and has also been successful in a few patients with non-ischaemic heart disease.^{78,79} However, few centres have physicians with the correct skills to undertake this approach. Transcatheter ethanol ablation has also been used in a few patients for whom catheter ablation and drugs have not been successful, but risks are probably greater than for other forms of catheter ablation.⁸⁰

Future directions and conclusions

The primary focus of ventricular arrhythmia management is the assessment of subsequent risk of sudden death and its prevention, followed by management of symptomatic arrhythmias. Effective interventions have been defined for many common cardiac disorders, but assessment of risk in the rarer genetic syndromes is a challenge. Findings from ongoing studies continue to improve arrhythmia management and prevention of sudden death, and many advances are on the horizon. Treatments that specifically target arrhythmias caused by specific gene mutations are being realised.^{9,11,81} Registries of LQT syndrome, hypertrophic cardiomyopathy, and rare genetic syndromes continue to provide insights that will guide management of disorders for which large clinical trials are not feasible. Although antiarrhythmic drug development has been disappointing, with limited translation of advances from basic science into the clinic, new drugs are in investigation, such as carvedilol analogues that have activity against arrhythmias triggered by calcium overload, and that might theoretically be useful in catecholaminergic polymorphic ventricular tachycardia and heart failure.⁸² Arrhythmia management devices will continue to evolve, with improving safety and efficacy. Future devices will incorporate sensors that measure intracardiac pressures, which might help to detect deterioration of heart failure earlier, and allow therapy to be based on the haemodynamic effect of an arrhythmia—eg, withholding a shock for arrhythmias that are well tolerated. Technologies for mapping, ablation, and imaging continue to improve, enhancing the ablation of complex arrhythmias, with techniques including hybrid surgical and catheter-based ablation.^{62,83–85}

Contributors

RMJ wrote the summary and the section on management according to clinical presentation, and created figure 2. UBT and CMA wrote the sections on genetic arrhythmia syndromes. BAK and MOS wrote the section about implantable cardioverter defibrillators. LME, GFM, and

WGS wrote the section on catheter ablation for ventricular tachycardia. ALM wrote the section about drug therapy for ventricular arrhythmias. WGS wrote the outline of the review and the section on ventricular arrhythmias, and created figures 1, 3, and 4. RMJ and WGS were responsible for the overall compilation and editing of the report.

Conflicts of interest

RMJ has done industry sponsored research for Biosense Webster and Thermedical and received consultant and speaking honoraria from St Jude Medical. UBT has done industry sponsored research for St Jude Medical and Biosense Webster and has been a consultant for St Jude Medical and Boston Scientific. BAK has done industry sponsored research for Medtronic, Boston Scientific, St Jude Medical, and Zoll Medical and has been a consultant for St Jude Medical. CMA has received research grants from St Jude Medical; the American Heart Association; and the National Heart, Lung, and Blood Institute. LME has received consultant and speaking honoraria from Medtronic, St Jude Medical, Boston Scientific, Biosense Webster, and Sanofi Aventis and has done industry sponsored research for Medtronic and Boston Scientific. MOS (and the Brigham and Women's Hospital) own and have received royalties for intellectual property, including US patents, for electrical device therapy. GFM has been a consultant for Medtronic, St Jude Medical, and Boston Scientific. WGS is a holder of a US patent for needle ablation consigned to the Brigham and Women's Hospital. ALM declares that she has no conflicts of interest.

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