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Abstract
Continuous advancements in technology and software algorithms for pacemakers and implantable cardioverter-defibrillators (ICDs) have improved functional reliability and broadened their diagnostic capabilities. At the same time, understanding management and troubleshooting of modern devices has become increasingly complex for the device implanter. This chapter provides an overview of the underlying physics and basic principles important to pacemaker and ICD function. The second part of this chapter outlines common device problems encountered in patients with pacemakers and ICDs and provides solutions and tips for troubleshooting.

**Keywords:** signal processing, filters, pacemaker troubleshooting, ICD troubleshooting

1. Introduction: Device physics

1.1. Signal processing
Signal processing refers to the science of analyzing time-varying physical processes [1]. Signal processing is divided into two categories: analog signal processing and digital signal processing. An analog signal is continuous in time and can take on a continuous range of amplitude values. A discrete-time signal is an independent time variable that is quantized so that only the value of the signal at the discrete instant in time is known. This can be illustrated in the following example: a continuous sinewave with peak amplitude of 1 and frequency of $f$ is described in Eq. (1):

$$x(t) = \sin(2\pi ft)$$  \hspace{1cm} (1)

where the frequency $f$ is measured in Hertz (Hz).

By plotting Eq. (1) a continuous curve is obtained (**Figure 1a**). If the continuous waveform represents a continuous physical voltage sampling every $t_s$ seconds, using an analog-to-digital converter...
would result in a sinewave represented as a sequence of discrete values shown in Figure 1(b). Figure 1(b) represents the digitization of the continuous signal in Figure 1(a). Variable \( t \) in Eq. (1) and Figure 1(a) is a continuous and independent variable. Variable \( n \) in Figure 1(b) is a discrete and independent variable that can take only integer values. As a result, the index \( n \) identifies the elements of the digital signal in Figure 1(b). All naturally occurring intracardiac signals are continuous and all signals stored by pacemakers and defibrillators are digital.

1.2. Filtering

Filters are used for two general purposes: (1) separation of signals that have been combined and (2) restoration of signals that have been distorted in some form. Signal separation is needed when if the signal is contaminated by interference, noise or other signals. As an example, filtering is used to separate nonphysiologic high-frequency pulmonary vein potentials recorded during catheter ablation of atrial fibrillation (AF) from physiologic signals. Signal restoration is used

![Figure 1. A time-domain sinewave: (a) continuous waveform representation and (b) discrete sample representation.](image-url)
when a signal has been distorted in some form. For example, an audio recording obtained with poor equipment may be filtered to improve fidelity so the actual sound is better reproduced.

For raw signal data to be analyzed, information must be represented in either the time or frequency domain. The most commonly used filters applied in intracardiac devices are in the frequency domain. Figure 2 summarizes the four most common basic frequency responses. These filters allow unaltered passing of some frequencies, while other frequencies are completely blocked. Those frequencies that pass through are called “passband,” while frequencies that are blocked are referred to as “stopband.” The band in-between is called the “transition band.” A very narrow transition band is called “fast roll-off,” “The cut-off frequency” is the frequency that separates the “passband” from the “transition band,” Analog filters use a cut-off frequency that is decreased to 0.707 from the original amplitude. Digital filters are less strict, and usually the cut-offs used are 99, 90, 70.7, and 50% of the original amplitude levels.

The example shown in Figure 3 highlights the three parameters described above. An example of a “fast roll-off,” is shown in (a) and (b). A “passband ripple” example is shown in (c) and (d), and finally, “stopband attenuation” is shown in (e) and (f).

1.3. Chebyshev filters

Chebyshev filters are used to separate one band of frequencies from another. They are the most commonly used in cardiac electrophysiology applications. The primary attribute of Chebyshev filters is their speed. The Chebyshev response is a mathematical strategy for achieving a faster “roll-off” by allowing “ripple” in the frequency response.
Figure 4 shows three ripple values, 0, 0.5, and 20%, for a low-pass Chebyshev filter. If the ripple decreases (good) the roll-off becomes less sharp (bad). The Chebyshev filter design is an optimal balance between these two parameters. If the ripple is 0%, the filter is called “Butterworth filter.” A ripple of 0.5% is often a good choice for digital filters. This matches the typical precision and accuracy of the analog electronics that the signal has passed through.

Figure 3. The three parameters important for evaluating frequency domain performance: (1) roll-off sharpness, (a) and (b); (2) passband ripple, (c) and (d); and (3) stopband attenuation, (e) and (f).
1.4. Unipolar versus bipolar recordings

All electrical circuits must have a cathode (negative pole) and an anode (positive pole) [2]. In general, there are two types of electrical circuits used in pacing systems depending on the location of the anode. In a unipolar system, as shown in Figure 5(a), the metal can of the pacemaker is used as the anode (+), and the distal electrode of pacemaker lead as the cathode (−). In a unipolar system, the pacing lead has only one electrical pole. Figure 5(b) shows the other type, a BIPOLAR system where both the anode (+) and cathode (−) are located on the same pacing lead. In all pacing systems, the distal pole that is in direct contact with cardiac tissue is negative. All currently available ICDs are bipolar, however, based on the lead utilized, the system may be dedicated bipolar or integrated bipolar. In a dedicated bipolar design, the anode is separate from the shock coil. In an integrated design, the distal shock coil also serves as the anode for pacing and sensing. An integrated design allows for more simple lead construction, as the distal shock coil serves two purposes. A dedicated bipolar system may provide more reliable sensing than an integrated design with a shared coil, as the anode is not affected by the high-voltage shock. Unipolar pacing systems have the advantage of a simpler and more reliable single-coil lead construction. It is also much easier to appreciate the pacing artifact of a unipolar system due to the anatomic distance between lead and pulse generator with parts of the electrical circuit closer to the skin surface. In some instances, sensing and capture thresholds are better than those obtained from a bipolar system, although lower lead impedance may result in higher current drain from the battery. In order to reduce the risk of pacemaker stimulation of the pectoralis muscle and/or device oversensing of electrical signals generated by the pectoralis muscle, many of the older pacemaker models incorporated a layer of protective coating on the device side facing the muscular tissue.
Bipolar pacing systems offer several advantages that have made this polarity choice increasingly popular, especially as dual-chamber pacing has become more prevalent in clinical practice. Because the distance between the individual electrodes is small (short antenna) and since both are located deep within the body, bipolar devices are less susceptible than unipolar systems to electrical interference caused by skeletal muscle activity or electromagnetic interference (EMI). Also, higher output settings required for unipolar pacing may result in stimulation of the pocket around the pacemaker. This problem is virtually unknown in normally functioning bipolar systems. One downside to using bipolar pacing is that the pacing artifact is very small and often difficult to discern on the surface electrocardiogram. This makes determination of proper function and malfunction more difficult. For this reason, it is not uncommon to see a pacemaker programmed to unipolar pacing but bipolar sensing.

1.5. Sensing

Sensing is the ability of the device to detect the intrinsic cardiac activity [3]. This is measured in millivolts (mV). The larger the signal in mV, the easier it is for the device to sense the event as well as to discriminate normal intrinsic from spurious electrical signals. Setting the sensitivity of a pacemaker is often confusing. When programming this value, it must be understood that the value programmed is the smallest amplitude signal that will be sensed (Figure 6). There is an inverse relation between sensing and sensitivity. The higher the sensing value, the lower the sensitivity to detect the intrinsic electrical signal. Thus, a setting of 8 mV requires at least an 8 mV electrical signal for the pacemaker to detect. A 2 mV setting will allow any signal above 2 mV to be sensed by the pacemaker.

1.6. Slew rate

Measurement of the intrinsic electrical signal for sensing is not simple, as the pacemaker does not use the entire electrical signal that is present. This “raw” electrical signal is filtered to eliminate a majority of noncardiac signals as well as portions of the cardiac signals that are not needed. Because filtering allows only certain frequencies to pass through to the sensing circuit, the final “filtered” signal may be substantially different from the original signal.
One way of measuring the quality of a sensed signal is to look at the slew rate. The slew rate refers to the slope of the intrinsic signal (Figure 8) and is measured in volts/second. High slew rates (>1.0 V/s in the ventricle and >0.5 V/s in the atrium) are desirable for consistent sensing.

(Figure 7). One way of measuring the quality of a sensed signal is to look at the slew rate. The slew rate refers to the slope of the intrinsic signal (Figure 8) and is measured in volts/second. High slew rates (>1.0 V/s in the ventricle and >0.5 V/s in the atrium) are desirable for consistent sensing.
2.2.1. Failure to shock or deliver anti-tachycardia pacing

Failure of the ICD to deliver anti-tachycardia therapy may be lethal. The reasons for failure to shock are listed as follows [14]:

1. Undersensing
   a. Lead malposition
   b. Lead dislodgment
   c. Lead perforation
   d. Lead fracture
   e. Lead insulation failure
   f. Lead-to-device connector problem
   g. Sensitivity set too low (i.e. insensitive)
   h. Poor electrogram amplitude due to change in myocardial substrate
   i. Myocardial infarction
   j. Drug therapy
   k. Metabolic imbalance
   l. “Fine” ventricular fibrillation

2. Primary circuit failure
3. Battery failure
4. Shock therapy turned off (by programming or magnet)
5. Magnet placed over the device
6. Strong magnetic field present
7. Detection rate set too high
8. Failure to meet additional detection criteria
   a. Rate stability
   b. Sudden onset
   c. Morphology criteria
9. Slowing of tachycardia below detection rate
   a. Substrate changes
   b. Metabolic changes
c. Electrolyte changes
d. Drug therapy changes

10. Interaction with permanent pacemaker

Lead failure or programming the rate detection zone too high is the most common reason for failure of the ICD to deliver therapy. The cause for lead failure may be identified on fluoroscopy. As older transvenous ICD leads are substantially thicker than conventional pacing leads, they are exposed to higher forces below the clavicle when using a subclavian vein access. Lead fracture typically affects one of the inner conductors of a coaxial or triaxial lead. Sometimes an intact outer conductor shielding a fractured inner conductor complicates proper diagnosis on fluoroscopy. Fractures can result in two broken ends remaining in intermittent contact. Several fluoroscopic projections may be required to visualize conductor failure and a slightly over-penetrated fluoroscopic image with settings similar to a dedicated thoracic spine view should be used. Fractures and insulation failures are more likely to occur after 1 or more years. If undersensing develops within 30 days of ICD implant, lead malposition, lead dislodgment or lead perforation need to be considered. Rarely, a loose connection between a connector pin and a connector block is the cause for ICD failure. Although ICDs are generally very reliable, a number of alerts have been reported for different models. Circuit failure, software lock-up, and other problems do occur infrequently and proper device interrogation will usually not be possible if any of these situations are present. In some cases, a "system reset" may be able to resolve the problem. In other cases, a software patch downloaded to the device will correct the problem.

Patient noncompliance with routine device clinic follow-up may result in ICD failure due to battery depletion. The ICD may become nonfunctional or lack sufficient power to charge the capacitors to the required voltage for discharge. Most ICDs restrict the time allowed for the capacitor to charge. Should the battery reserve be too low or the capacitor be defective (a common problem in earlier devices), the charge time may exceed the maximum time allowed and the ICD will not deliver a shock.

Occasionally, the rate detection zone is set too high. This may result from inappropriate programming or more commonly initiation of antiarrhythmic drug therapy such as amiodarone or sotalol. Antiarrhythmic drugs may cause slowing of the ventricular tachycardia cycle length below the programmed detection rate [15]. Significant metabolic or electrolyte abnormalities can affect the tachycardia cycle length, but may also alter the signal amplitude resulting in undersensing or failure to detect. Use of additional detection criteria to enhance specificity may delay or prevent appropriate ICD therapy and should be applied cautiously. Tissue injury due to myocardial infarction may lead to significant changes in the intracardiac electrogram and failure to sense.

Asynchronous pacing can be seen if bradycardia backup-pacing is turned on. In the past, many patients requiring pacing support underwent additional pacemaker implantation to prevent early ICD battery depletion from frequent pacing. This is usually of no clinical consequence.
unless the ICD senses the pacing output delivered by the pacemaker. In a worst-case scenario, the pacemaker may misinterpret ventricular fibrillation for asystole and attempt to pace fibrillating myocardium. If the ICD were falsely interpret the pacing impulse from the pacemaker for a regular Waveforms of ventricular depolarization (QRS) complex, device therapy may be withheld indefinitely. For this reason, special care is exercised if a pacemaker patient undergoes additional ICD implantation or a dedicated pacemaker is indicated in an ICD patient. Be aware that, albeit less likely, oversensing of the atrial pacemaker impulse by the ICD may lead to similar grave consequences.

2.2.1.1. Corrective action

Defibrillator lead-related problems virtually always require surgical correction. Most physicians argue that lead failure requires lead removal due to the large size of the lead and potential interaction with a newly placed lead. A recently implanted ICD lead that has dislodged or demonstrated poor sensing performance may be repositioned if lead integrity can be verified. Immediate device replacement is indicated in the case of battery depletion or if a nonfunctional ICD fails software reset. Simple reprogramming of the ICD will resolve problems related to inappropriate tachycardia detection zones or if too many specificity criteria are applied to diagnose ventricular tachycardia causing delay or failure to deliver appropriate therapy. Interaction with a permanent pacemaker may be eliminated by reprogramming the pacemaker output and pulse width to lower values. Only a bipolar pacemaker should be implanted if an ICD is already present. Furthermore, the pacemaker should be a dedicated bipolar device or allow bipolar pacing as the “power-on-reset” polarity. The latter will prevent reset to unipolar polarity and guarantee pacing in the bipolar mode if power is temporarily interrupted. Since current ICDs integrate fullFeatured pacing capabilities, a separate pacemaker is rarely indicated. Noise due to lead fracture can cause oversensing with inhibition of output. Acute management includes changing to a unipolar configuration or sensing from a wider antenna, for example, lead tip to right ventricle (RV) coil, until the lead can be replaced.

2.2.2. Failure to convert ventricular arrhythmia

Despite proper detection and appropriate ICD therapy, some arrhythmic episodes may fail to convert to sinus rhythm with potentially lethal consequences for the patient. Below is a list of problems that may prevent restoration of sinus rhythm despite appropriate ICD therapy [15]:

- High defibrillation threshold
- Poor cardiac substrate (fibrosis, scar, etc.)
- Acute myocardial infarction
- Metabolic abnormality
- Electrolyte abnormality
- Drug therapy
- Drug proarrhythmia
- High-voltage lead fracture
• High-voltage lead insulation failure
• High-voltage lead migration
• Inappropriate device programming
• Low (inadequate) shock energy
• Ineffective polarity
• Sub-optimal “tilt”
• Ineffective pacing sequence
• Pacemaker polarity switch
• Atrial arrhythmias
• Sinus tachycardia
• “VT Storm”

Changes to the myocardial substrate following successful ICD implantation may result in delayed or unsuccessful antiarrhythmic therapy. Acute myocardial infarction, severe electrolyte or metabolic imbalance or initiation of antiarrhythmic drug therapy may increase the defibrillation threshold. Amiodarone is frequently utilized in patients presenting with life-threatening arrhythmias and may increase the defibrillation threshold. Some patients will require defibrillation threshold testing after amiodarone initiation to verify successful conversion with ICD shock delivery. Other drugs may act proarrhythmic to the effect that the arrhythmia fails to convert or resumes immediately after conversion. Lead fracture or insulation failure will reduce the actual amount of energy delivered to the heart and may impact the delivery of an effective ICD shock. Lead movement may alter the shock vector resulting in suboptimal current flow between anode and cathode.

Programming the shock energy below maximum output will conserve battery life, allow quicker shock delivery, and cause less pain to the patient. However, an insufficient safety margin between defibrillation threshold and applied energy reduces the probability of successful conversion. The shock duration (pulse width) is programmable on some devices and set automatically on others. If set too short or overly long, defibrillation will be unsuccessful. The optimal shock duration varies based on the resistance. The positive and negative phases of the shock wave may be programmable in duration and can significantly affect efficiency of therapy. Furthermore, anti-tachycardia pacing or low-energy shock delivery may accelerate ventricular tachycardia or cause degeneration into ventricular fibrillation.

2.2.2.1. Corrective action

Immediately correct reversible metabolic, drug or electrolyte abnormalities. Lead or device problems will often require surgical revision. Reprogram ICD to a different rate detection zone and/or reassess additional criteria applied for tachycardia recognition. Atrial arrhythmias may require drug therapy, catheter ablation to definitive treatment of the clinical arrhythmia or ablation of the AV node. Appropriate pacemaker selection and programming are mandatory if separate devices are used in the same patient. Strongly consider replacement for a single device.
2.2.3. Inappropriate ICD therapy

Inappropriate ICD shocks are far more common than failure to convert or failure to deliver therapy. Patients may think an ICD shock was delivered inappropriately, while thorough evaluation of telemetry data and stored electrograms confirms proper device therapy. If the ICD shock was determined inappropriate, the triggering event needs to be elucidated and corrected quickly. Repeat ICD shocks are poorly tolerated by the conscious patient because of pain encountered and fear of future episodes. The patient may voice anger and frustration or demand device removal. Although inappropriate shocks are less likely to result in patient death, immediate diagnosis and correction of the underlying cause are warranted. Causes for inappropriate ICD therapy are as follows [16]:

1. Oversensing
   a. Electromagnetic interference
   b. Interaction with another implanted device
   c. Lead fracture
   d. Lead insulation failure
   e. Loose connections
   f. Myopotentials
   g. T-Wave oversensing
   h. Pacing impulse from permanent pacemaker
   i. “Y” adapted biventricular adapters and connectors

2. Detection rate set too low

3. Supraventricular arrhythmias
   a. Paroxysmal supraventricular tachycardia
   b. Atrial fibrillation
   c. Atrial flutter
   d. Sinus tachycardia

Inappropriate shocks are most commonly encountered in the presence of atrial fibrillation. Many patients who undergo ICD implantation demonstrate enlarged hearts predisposing them to atrial tachyarrhythmias. Patients with a history of slow ventricular tachycardia may experience overlap with sinus tachycardia at the lower rate limit of the detection zone. This may occur during exercise, sexual intercourse or emotional stress and result in ICD shock.
Oversensing may lead to inappropriate detection as detailed above. Interactions may result from separate pacemaker and ICD implantation in the same patient. In the presence of a unipolar and some bipolar pacemakers, the ICD may sense the ventricular and/or atrial pacing spike resulting in double-counting of the ventricular rate during VVI pacing or triple-counting of the ventricular rate during DDD pacing. Double-sensing may also be seen with some biventricular devices if the right and left ventricles are wired into the same sensing circuit, for example, when using a “Y” adapter on the pacing lead to connect to a single ventricular connector on the device. It may also be the result of an older ICD design where, despite separate connectors available for the RV and left ventricle (LV) lead, the leads are interconnected within the device and run through a single pace/sense circuit. The net result of both of these configurations is the same, with the RV and LV lead being sensed on the same channel. Double-counting may occur due to the long conduction delay between RV and LV if the patient has a heart rate in excess of the URL, or one of the leads fails to capture.

2.2.3.1. Corrective action

The ICD detection rate should be increased if the sinus rate overlaps with the lower rate limit of the detection zone. Beta-blocker therapy should be initiated or uptitrated to reduce the sinus rate. Furthermore, additional discrimination criteria such as sudden onset, rate stability, and QRS morphology should be activated. Catheter ablation to treat the clinical atrial arrhythmia or ablation of the AV node may be an option in select patients. Interaction between pacemaker and ICD will require reprogramming to a lower output and pulse width, using bipolar polarity or upgrading to an integrated pacemaker and ICD system. The latter is often necessary if double-sensing occurs while using retained older leads or ICD connector designs. In some situations, the pacing lead may require repositioning. Lead failure and connection problems will often require urgent surgical correction. If EMI is detected, the patient should be advised to avoid the source of interference. For some patients, this may involve reassignment of duties at work or even a change in employment. Most ICD malfunctions and pseudo-malfunctions are readily diagnosed after obtaining a careful patient history, use of fluoroscopy, and device interrogation. Unnecessary replacement of the ICD will be avoided and patient safety and comfort assured if competent personnel addresses the device problem in a consistent manner.

3. Conclusion

In order to troubleshoot implantable cardiac devices, the clinician should have a thorough understanding of the underlying physics and signal processing techniques. Device implantation and follow-up requires knowledge of the most common causes for device malfunction. While device reprogramming may offer a permanent solution for some pacemaker or ICD malfunctions, others will require surgical correction as appropriate first-line therapy.
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