Defibrillation Threshold Testing: A Primer

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ABSTRACT. Implantable cardioverter-defibrillators lower mortality in appropriately selected patients. Defibrillation threshold (DFT) testing has traditionally been an inherent part of the implant procedure. Emerging data have begun to question the safety, benefits, and necessity of routine DFT testing. In this review we discuss defibrillation, outline the risks and benefits of DFT testing and outline an algorithm for treating patients with an elevated DFT.

KEYWORDS. Defibrillation threshold, implantable cardioverter-defibrillator, right ventricular, superior vena cava.

Introduction

The implantable cardioverter-defibrillator (ICD) has been proven to reduce the risk of sudden cardiac death through the termination of ventricular fibrillation and life-threatening ventricular tachycardia. Inherent to the mortality reduction is the expectation that the ICD is successful in terminating these arrhythmias. For this reason, defibrillation threshold (DFT) testing has traditionally been an integral component of ICD implantation. Historically, DFT testing was critical to ensure that the device was functioning appropriately, that sensing was adequate, and that the system could reliably deliver enough energy to terminate ventricular tachyarrhythmias. Past studies have demonstrated that elevated DFTs occur in between 6% and 12% of patients undergoing ICD implantation, upgrade, or revision. DFT testing is, however, not without risk. As a result of improvements in technology and increasing concern about possible short-term and long-term adverse events associated with testing, debate has increased regarding the necessity and appropriateness of DFT testing. Regardless of whether DFT testing is performed, it is evident from previous studies that some patients will have an elevated defibrillation threshold. In this review we discuss defibrillation, the risks and benefits of DFT testing, and outline a management strategy for treating patients with an elevated DFT.

Defibrillation

The mechanism of defibrillation is not completely understood. During ventricular fibrillation, the ventricular myocardium is overrun by numerous dynamic eddy currents. While fibrillation at first blush seems to be a chaotic electrical storm, it is increasingly believed that it follows a more organized pattern. The mother rotor hypothesis and restitution hypothesis have both been proposed to explain this organization and are well-described elsewhere.

It is believed that during a successful defibrillation shock an adequate voltage gradient, measured in volts per centimeter of tissue, is created though the myocardium and the extracellular space of the heart. This gradient drives current into cardiac cells facilitating defibrillation through alteration of the cellular transmembrane potential. Factors that determine the adequacy of the created voltage gradient include the shock strength and the waveform morphology, i.e. biphasic waveforms generally more efficiently create a voltage gradient than monophasic waveforms. If the voltage gradient created falls below the appropriate threshold, all of the fibrillating eddy currents may not terminate or new currents may be initiated leading to redevelopment of fibrillation. Inherent to the success of defibrillation, therefore, is the delivery of a large enough current in the appropriate waveform through a large enough amount of myocardial tissue to disrupt these eddy currents and restore unified depolarization.

Ideally the defibrillation threshold would exist as a fixed point above which it would always be successful and below which it would likely fail, similar to the threshold for pacing. Unfortunately, defibrillation is inherently a probabilistic phenomenon meaning that the same energy cannot be counted on to always defibrillate the patient. A variety of factors including ischemia, metabolic or electrolyte derangements, autonomic tone, and medications can affect the success of defibrillation. The mechanisms by which these factors affect defibrillation are not well understood, but likely...
they have an impact on the number and size of the eddy currents existing during fibrillation and the voltage gradient necessary to terminate them. The defibrillation threshold has been loosely defined as the shock amplitude at which there is roughly a 50% success rate in terminating ventricular fibrillation. The hope is that an ICD at implant will have enough of a safety margin between the defibrillation threshold and its maximum output so as to expect that it will reliably defibrillate the patient when clinically necessary.

Defibrillation testing

Defibrillation testing is typically performed at the completion of the implant procedure, often before or during closure of the ICD pocket. Some physicians repeat DFT testing at a later time, i.e. 3 months post implant, annually, following antiarrhythmic drug initiation, or at the time of generator replacement or device upgrade to ensure continued defibrillation success. Because of the probabilistic nature of the defibrillation, a single defibrillation shock near or at the maximum output of the device is inadequate to ensure clinical success. Early studies in defibrillation revealed that a tested and confirmed safety margin at implantation of >10 J (i.e. 10 J below the maximum output of the device) was adequate to ensure success in the event of a “real-life” arrhythmic episode. A number of defibrillation testing protocols have been used in the past, including a step-down or step-up procedure in which sequential systematic defibrillation testing is performed to assess the exact defibrillation threshold at implant. Presently it is more common to ensure a repeated successful defibrillation 10 J or more below the maximum output of the device or at least once 15–20 J or more below the maximum output of the device. This testing protocol does not determine the actual defibrillation threshold but does establish defibrillation efficacy.

No exact definition of a high defibrillation threshold exists. However, practically speaking a threshold falling <10 J below the maximum output of the device is considered to be elevated. Reprogramming or revision should be considered in these circumstances.

Necessity of DFT testing

With advancement in technology including higher output devices, use of biphasic waveforms, and use of an active can configuration it has been argued that DFT testing is no longer necessary. Several arguments exist to support this contention. The first is the observation that most spontaneously occurring arrhythmias tend to be ventricular tachycardia, a more organized rhythm that requires less energy for conversion than the energy required for defibrillation of ventricular fibrillation. Second, evidence supports that successive sub-DFT shocks during ventricular arrhythmias will ultimately lead to conversion. Lastly, it has been reported that high DFTs at implantation may decrease with time, though other studies demonstrate progressive increases or no change in DFT over time.

Proponents of continued DFT testing also have numerous arguments. First they contend that predictors of elevated DFT are notoriously unreliable for an individual patient, preventing selective use of DFT testing (see below). In addition, despite the frequency of ventricular tachycardia as a common presenting arrhythmia, cardioversion of monomorphic ventricular tachycardia can be proarrhythmic, degenerating into ventricular fibrillation requiring defibrillation. Therefore, low-voltage shocks cannot be depended on to be successful. Additionally, confirmation of defibrillation at a relatively low shock output allows the implantor to program the device to deliver initial shocks at or near threshold, allowing for shorter capacitor charge times and therefore shorter time to delivery of the first shock. This shorter time and lower shock strength could have a favorable impact in avoiding loss of consciousness or other adverse events such as hemodynamic compromise and myocardial injury, as has been shown in experimental animal models. Third, some studies have supported a progressive rise in defibrillation threshold over time, both acute and chronic, suggesting that the lower the threshold at implant, the better for long-term success, especially if repeated defibrillation tests are not performed later in the patient’s life. The final, and possibly most important, argument centers around the observation that a significant percentage of patients with defibrillators and high DFTs die of sudden cardiac death apparently due to inadequate defibrillation energy or inadequate sensing. Presumably these events could be avoided by appropriate DFT testing, although this remains unproven.

Safety of defibrillation testing

Despite having been an integral part of the ICD implantation procedure for many years, DFT testing is not without risk. First, routine DFT testing requires the use of additional anesthetics during the implant procedure that can lead to airway compromise, hypotension, and left ventricular dysfunction. Second, prolonged DFT testing with repeated inductions of ventricular fibrillation and subsequent shocks may lead to hemodynamic compromise and further deterioration of left ventricular function as well as transient cerebral dysfunction. Furthermore, it appears that testing at increased energy levels can lead to more acute myocardial dysfunction than testing at lower energy levels. On a cellular level it has been suggested that ICD shocks can lead to tissue necrosis and an adverse cascade of events including apoptosis. Most implanters would agree that DFT testing should be, at the minimum, withheld in patients with hemodynamic instability, active ischemia, or the presence of intracavitary thrombus without appropriate anticoagulation.

In lieu of increasing concerns about the safety of DFT testing, it is appropriate to question whether the reassurance the patient and physician receive from DFT
testing translate into better long-term outcomes. Unfortunately, the answer to this question remains controversial. In the past it has been shown that an elevated DFT with an inadequate safety margin was associated with a worse outcome.\(^4\) Implantation without testing has also been shown to portend a worse survival, though this was not prospectively evaluated in a randomized fashion.\(^4\) Analysis of the multicenter Sudden Cardiac Death in Heart Failure Trial demonstrated generally low DFT overall with no difference in long-term outcomes between those tested at baseline and those that were not. In addition, the study showed that a low DFT (<10 J) does not portend a better prognosis than a higher DFT.\(^4\) A recently published decision analysis and Monte Carlo simulation found that DFT testing may have a small favorable, but likely negligible, impact on 5-year survival.\(^4\) It appears that emerging data on the safety and benefits of DFT testing is having an impact, as a recent study demonstrated that two-thirds of patients undergoing implantation in the cohort did not undergo DFT testing.\(^4\) Given these controversies, DFT testing should be performed at the careful discretion of the implanting or following physician.

**Predicting high DFT at the time of implant**

Many studies have tried to identify predictors of high DFTs with mixed results. The presence of a non-ischemic cardiomyopathy, dilated heart, younger age have been shown to be independent predictors of high DFTs requiring system modification.\(^4\) In addition, chronic oral amiodarone use appears to lead to a three times higher likelihood to have elevated defibrillation thresholds.\(^4\) In at least one study, gender, QRS width, and presence of a right-sided or abdominal implant did not appear to have a significant role, but other studies have found the opposite.\(^3,4,9,50\) A large multicenter trial of 1946 patients with ICDs, 90 of whom had elevated defibrillation thresholds (≥25 J) found that elevated thresholds were more likely to be found in those taking an antiarrhythmic medication, particularly amiodarone, but did not find differences regarding age, incidence of coronary artery disease, and degree of myocardial dysfunction.\(^5\) Despite the numerous investigations in this area, no sufficient predictive model exists to reliably help the implanter predict an elevated DFT or confirm an adequate safety margin with an individual patient.

**Treatment options for an elevated DFT**

In the event that an elevated defibrillation threshold is found at implant testing or during follow-up, the implanting or following physician should have a systemic approach to address this problem. This approach should systematically consider potential external, reversible factors that may have led to the elevated DFT followed by a focus on non-invasive programming options and finally invasive treatment options. In patients with high DFTs, it has been demonstrated that >85% of patients can undergo device modifications that provide adequate (>10 J) safety margins.\(^4\)

**Non-invasive strategies of managing high DFTs**

Following an assessment of potential reversible causes of an elevated DFT, non-invasive options for management should be explored.

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**Reversible causes of a high DFT**

When faced with a high DFT at the time of implant physicians should look for various reversible causes of high DFTs, which include:

- **Medications:** A number of medications are known to influence the defibrillation threshold. Lidocaine, mexiletine, moracizine, verapamil, venlafaxine, anesthetic agents, cocaine, and sildenafil are reported to increase DFTs.\(^51-55\) Sotalol and dofetilide have been reported to decrease the DFTs in a single randomized controlled trial each.\(^56\) Amiodarone is unique. Acute intravenous use of amiodarone may have a favorable impact on the defibrillation threshold while long-term oral use appears to raise the threshold.\(^57,58\) Various anesthetic agents can influence the DFTs at the time of implant. Propofol, a commonly used agent for induction during ICD implantations, has been reported to induce a dose-dependent rise in DFTs.\(^54\) In the event that an antiarrhythmic drug can be discontinued, it is recommended to attempt this first and consider retesting of the defibrillation threshold following an appropriate washout period.

- **Pneumothorax:** Pneumothorax, which is a known complication of device implantation can be an unrecognized cause of high DFTs. A high DFT with high impedance should prompt a careful evaluation to rule out pneumothorax, even if traumatic vein cannulation was not observed. Whether DFT elevation is proportional to the size or location of the pneumothorax is unclear. In addition to the standard post-procedure chest x-ray film, inspection of the thorax with fluoroscopy during the procedure (helped with slight chest elevation) may help early detection of this complication.

- **Prolonged procedural time and DFT testing:** In patients with reduced left ventricular function, prolonged procedural time and DFT testing can lead to unsuccessful defibrillation with an energy that would otherwise be effective. The etiology of this failure can be due to the development of cardiac stunning from the prolonged procedure time, accumulation of anesthetic agents, and/or previous induction of ventricular fibrillation and shocks. Other issues are the development of acidemia, electrolyte derangements, worsening heart failure, hypoxia, hypercarbia, and ischemia. Repeat testing on a different day may be appropriate.
• Change of polarity: Changes in the shock vector (which describes the path that the defibrillation energy takes) can sometimes be helpful by increasing the effectiveness of defibrillation (thus lowering DFTs) without an increase in the delivered energy. Most right ventricular (RV) pacing is performed using the ventricular tip electrode as the cathode, and at least two major manufacturers maintain this designation for defibrillation. Using the RV coil as anode results in a 16% reduction in DFTs compared with a cathodal RV coil. A meta-analysis of several defibrillation studies has demonstrated that 88% of patients had equivalent or superior defibrillation thresholds with the RV tip maintained as the anode. The nominal configuration using the RV or distal coil as cathode may be adequate for most patients. Polarity reversal is warranted in patients in whom the initial testing was performed using an anodal RV configuration. Repeated testing should be considered given that the reduction in DFTs that occur with polarity change may not be reliably reproduced when retested.59

• Tilt modification: One major ICD manufacturer allows the adjustment of waveform tilt. Tilt can be defined as the percent fall in voltage on the capacitor from the beginning (leading edge) to the end of each phase (trailing edge) over the entire pulse waveform. Adjustment to the tilt of the biphasic waveform is a viable option for managing high DFTs in some patients. A concept of fixed tilt in this regard appears appealing. In a fixed tilt configuration a constant energy is delivered to the patient automatically adjusting the pulse width based on lead impedance. When the impedance is high the tilt is smaller, and conversely the impedance is low the tilt is larger. The pulse width adjusts automatically based on fixed tilt setting and shock impedance of the system. There is no optimal tilt value that applies to all patients. There are published tables which help estimation of the optimal second phase duration, and thus assisting alteration of tilt. These tables are available from the manufacturer for the implanting physicians.60

• Removal of the superior vena cava (SVC) coil: Addition of an SVC coil to an active or hot can configuration may help decrease DFTs but increases the peak current, which is suggestive of a worsened vector with an SVC coil. Fortunately, this effect is to a large extent offset by a large reduction in lead impedance. Electronic removal of the SVC coil in

Figure 1: Left subclavian venous defibrillation lead placement in a patient with a right-sided implantable cardioverter-defibrillator with hypertrophic cardiomyopathy and high defibrillation threshold. Repeated defibrillation testing using the right ventricular coil as the cathode and left subclavian lead as the anode repeatedly provided an adequate safety margin for defibrillation. Used with permission from Mainigi SK, Callans DJ. How to manage the patient with a high defibrillation threshold. Heart Rhythm 2006; 3:492–495.
patients with low impedance (less than 40 ohms) may help reduce high DFTs in these patients. In one study, this strategy was found to be effective in 15% of patients presenting with high DFTs. The success of this maneuver coupled with the increased difficulty with dual-coil RV lead extraction versus single-coil lead extraction has led implanters to increasingly use single-coil RV leads during implantation.

- Medication: Sotalol has been reported to lower the DFTs, hence it can be used in patients with high DFTs. Doses of 40–320 mg twice a day have been used. Dofetilide has also been shown to reduce DFT and prevent the need for more complex invasive device modification strategies. Given the potential proarhythmic nature of these drugs, this strategy should only be employed under careful observation. Repeat defibrillation testing several weeks after initiation is recommended to ensure success.

**Invasive strategies**

- Use of a high output device at the time of initial implant: A simple solution to a problem of high DFTs or inadequate safety margin is to replace a standard generator with a high-output generator. Some centers empirically implant a high-output generator whenever DFT testing is not performed at the time of implant or in patients who may have an elevated DFT (patients receiving chronic amiodarone therapy, with hypertrophic cardiomyopathy, older age, lower ejection fraction, dilated cardiomyopathy, worse New York heart Association class, or right-sided pectoral pre-pectoral implant). However, 48% of patients still required additional modification(s). Use of a high-output device is a solution when it provides an adequate defibrillation safety margin (10 J); however, it is not recommended as an empiric substitute for

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**Figure 2:** Coronary sinus defibrillation lead placement in a patient with a high defibrillation threshold. The patient did not undergo defibrillation threshold testing at implantation but presented with spontaneous ventricular fibrillation that failed defibrillation with an adequate safety margin. Non-invasive programming changes proved unsuccessful and the patient required an additional lead to be placed. Repeated defibrillation testing using the right ventricular coil as the cathode and coronary sinus lead and active can in combination as the anode repeatedly provided an adequate safety margin for defibrillation.
DFT testing unless testing cannot be safely performed. Manufacturers are continuing to increase the energy delivered from their ICDs, potentially decreasing the incidence of elevated DFTs in the future.

- RV lead position: Successful defibrillation occurs when the shock vector contains within it enough ventricular myocardium to disrupt the numerous eddy currents consuming the heart. Inherently, an endocardial RV location is not an attractive place to implant a defibrillation lead. The right ventricle contains less myocardial mass than the left ventricle and is a relatively anterior structure. In order to be effective, the RV lead generally needs to be apically located to maximize the intervening myocardium between the lead and the can. A proximal location (either intentional or as a result of dislodgement) results in higher DFTs. Other locations have been considered, including placement in the anterior interventricular septum of the outflow tract, which demonstrated reduced DFTs without late RV lead dislodgement. If the current lead position is unsuccessful in achieving an adequate defibrillation, a more apical or anterior interventricular location should be considered.

- Addition of a new lead: If repositioning of the RV lead or upgrade to a higher output proves unsuccessful, incorporation of an additional defibrillation coil into the vector may be appropriate. Numerous locations have been tried, including placement of a posterior subcutaneous (SQ) array, addition of a separate proximally placed coil, and placement of a coil in the coronary sinus or azygous vein.

- Placement of a separate proximal coil: Single-lead, dual-coil systems have effectively replaced dual-lead systems in standard practice. However, one of the limitations of the single-lead system is the fixed interelectrode distance between the distal and proximal coils. A two-lead system offers the advantage of an independent proximal electrode that can be

![Figure 3: Defibrillation lead placed in the azygous vein. The patient failed to defibrillate at maximum device output during implantation. Non-invasive programming changes proved unsuccessful and the patient required an additional lead to be placed. Repeated defibrillation testing using the right ventricular coil as the cathode and azygous lead and active can in combination as the anode repeatedly provided an adequate safety margin for defibrillation.](image-url)
Figure 4: Subcutaneous array in a patient with a high defibrillation threshold. The patient failed at the maximum output of the device. Implantation of the subcutaneous array provided a repeated 15-J safety margin for defibrillation.

Figure 5: Suggested management algorithm for the patient with a high defibrillation threshold and failure of the initial shock with successful rescue shock at maximum output. After ruling out pneumothorax, the implanter is advised to attempt modifications as outlined, with frequent retesting to assess success. RV: right ventricular; RVOT: right ventricular outflow tract; SQ: subcutaneous; SVC: superior vena cava. Used with permission from Mainigi SK, Callans DJ. How to manage the patient with a high defibrillation threshold. Heart Rhythm 2006; 3:492–495.
variably positioned in the SVC or other structure. In a right-sided implant, an effective strategy would be to consider placement of a passive fixation defibrillation lead in the left subclavian vein.64–67 (Figure 1).

- Placement of a coronary sinus lead: Studies have shown that placement of coil in the posterior or lateral branch of the coronary sinus (CS) can result in substantial (up to 45%) reductions in mean DFT (Figure 2). Whether an anterior left ventricular location is acceptable is unclear. Placing a defibrillation lead in the CS appears promising; however, a current barrier is the limited number of models of defibrillation leads with sufficiently small diameters to successfully navigate the CS and its branches. Long-term stability of the coil in the CS has also been questioned.

- Placement of a coil in the azygous vein: The azygous vein runs to the right of the thoracic vertebral column returning blood from the posterior walls of the thorax and abdomen into the SVC. Because of its location it is often ideally suited to be an alternative to the proximal coil in the defibrillation vector. Probing with a guidewire or angled catheter at or near the junction of the left subclavian vein and SVC, typically accompanied by small puffs of contrast, usually identifies the vein. In our experience, most azygous veins are suitable for placement of a passive defibrillation coil (Figure 3).

- Placement of a SQ array: Typically, after placing the RV lead and confirming a high DFT, a curved tunneling rod introducer is advanced through the standard infraclavicular incision into the SQ tissue until the tip rests inferior to the scapula and just lateral to the spine. Then the SQ array is advanced to this position through the introducer. In an alternate technique, a separate small incision can be made several inches inferior to the infraclavicular pocket along the mid or anterior axillary line. This access point can be used to tunnel the SQ array into a similar posterior position, often in a more direct fashion. The lead should then be secured in this pocket and then tunneled up to the infraclavicular pocket for attachment to the generator. With this technique the DFT can be lowered to an adequate level in 14% patients.16 The improvement in DFT is driven by 1) an impedance drop which will allow an increased current delivery assuming a constant voltage; and 2) a switch to a more posteriorly directed current from the RV coil allowing improved voltage gradient in the left ventricular myocardium. In the event of improvement but still inadequate DFTs after SQ array placement, there may be a success with a second SQ array inferior to the SQ array in position.

Figure 6: Suggested management algorithm for the patient with a high defibrillation threshold and failure of the initial and maximal output shocks. After ruling out pneumothorax, the implanter is advised to attempt modifications as outlined, with frequent retesting to assess success. RV: right ventricular; RVOT: right ventricular outflow tract; SQ: subcutaneous; SVC: superior vena cava. Used with permission from Mainigi SK, Callans DJ. How to manage the patient with a high defibrillation threshold. Heart Rhythm 2006; 3:492–495.
to the first array connected with a Y-connector. Implantation of the SQ array is often painful and typically requires deeper sedation (Figure 4).

**Approach to the patient with an elevated DFT**

There has been a substantial growth in the number of ICDs implanted in recent years. Although the incidence of high DFTs is likely to decrease with improvements in technology, the prevalence will likely remain significant. All implanters should have a systematic approach to dealing with a patient with an elevated DFT. Below we outline two algorithms based on two typical scenarios. In the first algorithm (Figure 5) we outline an approach for patients who fail initial defibrillation at a lower output but who are successful at or near the maximum output of the device. In this group an initial non-invasive approach focusing on programming changes may prove successful before proceeding with invasive options. In the second algorithm (Figure 6) we outline an approach for patients who fail defibrillation even at the maximum output of the device. In this group, significant device revisions are likely necessary.

**Considerations for DF-4 Systems**

Recently three major device manufacturers have introduced ICDs with a DF4 connector in which the pace/sense, distal coil, and (if applicable) proximal coil are combined into a single connector attaching to the header. This new standard has multiple potential benefits including decreased bulk in the pocket, improved reliability, and avoidance of improper connections due to physician error. Unfortunately the consolidated design also limits the hardware adaptations that can be performed. Because the proximal coil cannot be individually disconnected from the header and replaced with a SQ array or additional coil in the coronary sinus, azygous vein, subclavian vein or other location, this type of modification to the system would require replacement of the right ventricular defibrillation lead and ICD generator in addition to the placement of the additional lead or array. Clearly because of the additional time, risk, and cost associated with these changes, the physician is advised to consider all available reversible or noninvasive options first. It is expected that one or more of the manufacturers or a third party will be offering a variety of adaptors in the future to address these connection issues.

**Conclusion**

Successful defibrillation is inherent to the mortality reduction expected with ICD implantation. Defibrillation testing has traditionally been performed at or following ICD implantation to reassure the physician that the device is functioning appropriately and will deliver needed therapy in the future. Emerging data have begun to question the safety and benefits of this practice. Regardless of the utility of DFT testing, the implantner needs to have a systematic approach to dealing with the patient with an elevated DFT.

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