Elevations in Ventricular Pacing Threshold with the Use of the Y Adaptor: Implications for Biventricular Pacing

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RHO, R.W., ET AL.: Elevations in Ventricular Pacing Threshold with the Use of the Y Adaptor: Implications for Biventricular Pacing. *Cardiac resynchronization therapy (CRT) is a new and promising therapeutic option for patients with severe heart failure and intraventricular conduction delay. Patients who are candidates for CRT and have a previously implanted device may utilize a "Y" IS 1 connector to accommodate the coronary sinus lead. This modification has the potential to alter biventricular pacing thresholds. During an 18 month period, successful biventricular pacemaker implantation was performed in 72 patients (age: 67 ± 11 years, left ventricular ejection fraction: 20.5 ± 5.6%). All of these patients had severe symptomatic congestive heart failure (NYHA Class III and IV). In 20 patients a special "Y" adaptor that bifurcates the ventricular IS 1 bipolar output to two bipolar outputs or one unipolar and one bipolar output was utilized. During initial implantation, LV thresholds obtained in a unipolar configuration prior to connecting to the "Y" adaptor were significantly lower than thresholds obtained after connecting to the "Y" adaptor (1.7 ± 1.11 V at 0.5 ms pulse width versus 2.8 ± 1.5 V at 0.5 ms pulse width [P = 0.01]). Two patients (10%) required left ventricular lead revisions due to unacceptably high left ventricular thresholds during device follow-up. The difference in measured left ventricular thresholds between the two configurations is best explained by a resistive element that is added to the circuit when performing threshold measurement of the LV lead through the "Y" adaptor (combined tip to RV ring configuration) versus measurement of the LV lead in a unipolar configuration. This resistive element represents multiple factors including anode surface area, resistive polarization at the tissue-electrode interface, and transmyocardial resistance. LV thresholds should be measured in an LV tip to RV ring configuration or ideally in a combined tip (LV and RV) to shared ring configuration in order to accurately assess LV thresholds. This observation has significant clinical implications as loss of capture may occur as a result of improper measurement of left ventricular thresholds at the time of implantation. (PACE 2003; 26:747–751)*

cardiac resynchronization, biventricular pacing, unipolar, bipolar, anode surface area, resistance, threshold, congestive heart failure, intraventricular conduction delay

Introduction

Patients with advanced heart failure suffer significant morbidity and mortality despite optimal medical therapy. Conduction abnormalities including left bundle branch block, right bundle branch block, and nonspecific intraventricular conduction delays occur in up to 53% of patients with dilated cardiomyopathy.[1] These conduction abnormalities are associated with impaired left ventricular systolic function, diastolic dysfunction, and mitral regurgitation.[2,3] Intraventricular conduction delay and resultant ventricular dysnchrony is an independent risk factor for increased mortality in patients with heart failure.[4]

In 1994, Cazeau et al. reported significant hemodynamic and functional improvement in a patient with refractory heart failure who received the first implantation of a 4-chamber cardiac pacing system.[5] Since then multiple studies were performed demonstrating improved hemodynamics (increased cardiac index, decreased pulmonary capillary wedge pressure, decreased systemic vascular resistance), improved left ventricular function, and improved functional capacity. Recently two prospective, multicenter, randomized, controlled studies were completed assessing the benefits of cardiac resynchronization therapy (CRT) in patients with drug refractory NYHA Class II-IV heart failure and a QRS duration of $\geq$130 ms. A significant improvement in functional capacity,

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quality of life score, and decreased hospitalizations for decompensated heart failure was observed in patients randomized to CRT.[6,7]

Many patients with heart failure have had previously implanted pacemakers for symptomatic bradycardia due to sick sinus syndrome or high grade AV block. In patients who are candidates for upgrades to biventricular pacing, the ventricular output of the pacemaker generator is divided via a "Y" connector (Medtronic, Inc, Minneapolis, MN, USA) from one bipolar output to two separate outputs (usually a unipolar left ventricle (LV) and a bipolar right ventricle (RV) or a bipolar LV and a bipolar RV) to accommodate the LV lead. This modification has the potential for altering LV pacing thresholds depending on the configuration the LV threshold is measured in at the time of implant. We report our experience in the degree to which LV thresholds are altered, and the clinical implications of connecting LV and RV leads in parallel through a Y connector.

Methods

From June 1999 to January 2001 at the Hospital of the University of Pennsylvania, successful CS lead implantation for CRT was performed in 72 patients. In 20 patients (study group), biventricular pacing was performed using a "Y" adaptor to accommodate the CS and RV leads to the single ventricular output of a previously implanted pacemaker. The risk and benefits of coronary sinus lead implantation was explained and informed consent was obtained in all patients. The 20 patients in the study group were implanted utilizing a "Y" connector that divides one IS-1 bipolar output to two outputs (unipolar LV, bipolar RV or bipolar LV, bipolar RV) to accommodate the coronary sinus lead. During the implantation procedure, left ventricular lead thresholds were prospectively measured in two configurations. The first was in an LV unipolar configuration where the LV capture threshold was measured from the distal LV lead electrode to the subcutaneous tissue of the open incision connected to a small Wietlander. The second was in a shared ring configuration where the LV capture threshold was measured from the distal LV lead electrode to the proximal RV lead electrode while both ventricular leads were connected to the "Y" connector. LV thresholds were assessed through the device at 1 month and 3 month follow-up.

Results

Seventy two patients (67 ± 11 years of age, ejection fraction was 21 ± 6%) had successful upgrade of their preexisting devices to a biventricular pacemaker. All patients had severe congestive heart failure (NYHA Class III and IV). Of the 20 patients in the study group, 12 patients had unipolar LV leads implanted (Medtronic model: 4023) and 8 patients had bipolar LV leads (Medtronic model: 2188) implanted. The average unipolar LV threshold at implant was 1.7 ± 1.11 V at 0.5 ms pulse width (n = 20). The average LV threshold at 1 month follow-up (combined LV and RV tips to shared ring measured through the generator across the "Y" adaptor) was 3.1 ± 1.8 V at 0.5 ms pulse width (n = 17), while the average LV threshold at 3 month follow-up was 3.0 ± 1.2 V at 0.5 ms pulse width (n = 17). Two patients required coronary sinus lead revision due to an unacceptably high LV threshold during follow-up. Neither of these two patients had radiographic evidence of lead dislodgement.

The acute LV unipolar threshold versus the acute LV threshold via the "Y" adaptor were significantly different (1.7 ± 1.11 V vs 2.8 ± 1.5 V, $P = 0.01$). The difference in the LV threshold at 1 month versus the LV threshold at 3 months was not significantly different (3.1 ± 1.8 V vs 3.0 ± 1.7 V, P = NS). The difference in the LV thresholds at implant versus at 1 month follow-up were compared separately for the unipolar and bipolar LV lead configurations. The LV threshold of the bipolar 2188 lead at implant (via the "Y" adaptor) versus at 1 month was not significantly different (2.4 ± 1.2 V vs 2.8 ± 1.7 V, P = NS). The LV threshold of the unipolar 4023 lead at implant (via the "Y" adaptor) versus at 1 month was also not significantly different (3.1 ± 1.7 V versus 3.3 ± 1.9 V, P = NS).

Discussion

Many factors influence the pacing capture threshold. These include the size of the stimulating electrode, the anode surface area, the electrode-tissue interface, the inter-electrode spacing, the conduction properties of tissue separating the electrodes, and resistive polarization (leading edge resistance) at the cathode. All of these factors differ according to the configuration in which the capture threshold and whether pacing is performed endovascularly (in a cardiac vein) or endomyocardially.[8]

The difference in LV thresholds measured during implantation between an LV unipolar measurement versus through a Y connector with RV and LV leads in parallel is not due to a low resistance RV lead "shunting" current away from the LV lead. The effect of "shunting" current into a relatively low resistance RV lead does not mathematically alter the electromotive force (EMF) necessary to maintain a given (threshold) current into the LV limb of the circuit. When the RV lead resistance is less than the LV lead resistance, the fraction of current that travels down the LV limb is proportional

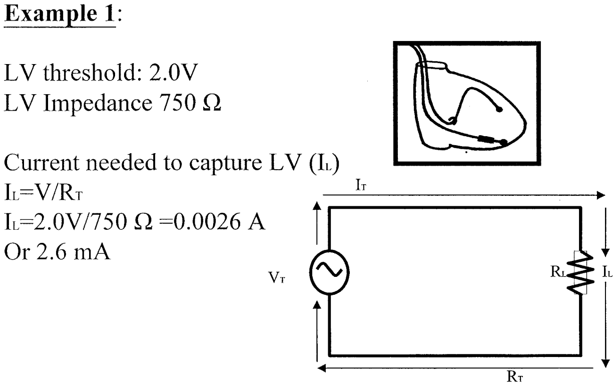


Figure 1. *Example 1. Left ventricular capture threshold measured via the left ventricular lead alone. Assuming an LV threshold of 2.0 V and an LV lead impedance of 750 ohms the current needed to capture the LV is 2.6 mA.*

to the RV resistance/(RV resistance + LV resistance). The smaller fraction of current that travels across the LV limb of the circuit when RV resistance << LV resistance is offset by the increase in total current because the total resistance is lower when the RV and LV leads are connected in parallel.

The concept is illustrated in Figure 1. In Example 1, we assume the LV capture threshold is 2.0 V. The capture threshold in the LV is dependent on current density and therefore the current needed to capture and depolarize the LV in a unipolar configuration is equal to V total ÷ R total which equals 2.0 V ÷ 750 ohms or 2.6 mA. A schematic representation of the LV threshold measured through the "Y" connector with the RV lead is shown in Example 2. The following example illustrates the effect of changes in the RV lead resistance on the EMF necessary to drive 2.6 mA of current into the LV limb and thus capture the left ventricle. In Example 2A the RV and LV resistances are equal (750 ohms) and the total resistance (R Total) is calculated in step 1. In step 2 the total current (I total) is calculated and the current in the LV limb will be the ratio of the RV resistance ÷ (RV resistance + LV resistance). The total current is calculated from this equation using 2.6 mA as the threshold current in the LV limb. In step 3 the EMF (V total) is calculated by multiplying I total X R total which equals 1.95 V. Therefore, 1.95 V is necessary to drive 2.6 mA of current into the LV limb of the circuit when the two leads are of equal impedance and connected in parallel. In Example 2B, the same calculation is performed with an RV resistance of 500 ohms and an LV resistance of 750 ohms. In Example 2C, the same calculation is performed with an RV resistance of 1000 ohms and an LV resistance of 750 ohms. Despite a range of RV resistances (500–1000 ohms) for a fixed LV resistance, the EMF necessary to drive the same amount of current in the LV limb remains constant (1.95 V in our example). This illustrates that the difference in the LV threshold measured via a "Y" connector is not due to a low resistance RV lead "shunting" current away from the LV lead.

In reality, the difference in measurement of the LV threshold in a unipolar configuration versus via the "Y" adaptor is more closely represented in Example 3. The LV and RV leads are in parallel but there is an additional resistive element that is schematically represented in series with the LV resistance. This resistive element represents the differences in multiple factors such as the anode surface area, resistive polarization at the tissue-electrode interface, and transmyocardial resistance between the two configurations. If this resistance element (Rx) = 150 ohms, the calculated EMF necessary to "push" 2.6 mA of current through the LV limb calculates to 2.3 V (a 15% increase in the threshold). We have measured differences in the range of 25–262 ohms (122.4 ± 79.1 ohms, n = 10) between an LV tip to RV ring measurements versus LV unipolar measurements.

Many factors are involved in determining the stimulation threshold in cardiac pacing. The critical factor to successfully induce a wavefront of depolarization in myocardial tissue is the current density delivered to excitable myocardium between the stimulating electrodes. The impedance of the pacing circuit plays a large role in the current density applied to the excitable myocardium. Pacing impedance is determined by lead resistance (resistance in the conducting wire), resistive polarization at the tissue-electrode interface, ohmic polarization at the electrode-tissue interface, and transmyocardial resistance (resistance of the tissue between the electrodes). The relative size and geometric surface area of the cathode and anode also plays a large role in determining current density at the stimulating electrode-tissue interface.[8]

Clinically, the anode surface area contributes significantly to LV stimulation threshold. In the unipolar configuration the cathode is the tip of the LV lead and the anode is the surface area of the surgical instrument in contact with the body. The measurement of thresholds via the "Y" adaptor is performed in a combined LV and RV tip to shared RV ring configuration (anode: RV ring, cathode: combined tips of the LV and RV leads). Worley et al.[9] assessed LV capture thresholds in 18 consecutive patients who had their implantable defibrillators modified for biventricular pacing. Cathodal LV unipolar pacing thresholds were assessed with three different sized RV anodes: (1) RV screwed tip

Example 2A:

$R_R = R_L = 750\ \Omega$

Step 1:

$R_T = R_R R_L/(R_R + R_L)$

$= 562{,}500\ \Omega / 1500\ \Omega$

$= 375\ \Omega$

Step 2:

$I_L = R_R/(R_L + R_R) \times I_T$

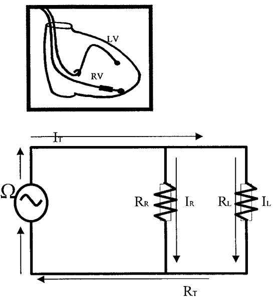
$I_T = (R_L + R_R) \times I_L / R_R$

$= (750\ \Omega + 750\ \Omega) \times 0.0026\ A/750V\ \Omega$

$= 0.0052A$

Step 3:

$V_T = I_T \times R_T = 0.0052\ A \times 375\ \Omega = 1.95V$



Example 2B:

$R_R = 500\ \Omega$

$R_L = 750\ \Omega$

Step 1:

$R_T = R_R \times R_L / (R_R + R_L)$

$R_T = 500\ \Omega \times 750\ \Omega / (500\ \Omega + 750\ \Omega)$

$R_T = 300\ \Omega$

Step 2:

$I_T = (R_L + R_R) x I_L / R_R$

$I_T = 0.0065A$

Step 3:

$V_T = I_T \times R_T = 0.0065\ A \times 300\ \Omega = 1.95V$

Example 2C:

$R_R = 1000\ \Omega$

$R_L = 750\ \Omega$

Step 1:

$R_T = R_R \times R_L / (R_R + R_L)$

$R_T = 1000\ \Omega \times 750\ \Omega / (1000\ \Omega + 750\ \Omega)$

$R_T = 428.57\ \Omega$

Step 2:

$I_T = (R_R + R_L) x I_L / R_R$

$I_T = 0.00455\ A$

Step 3:

$V_T = 0.00455\ A \times 428.57\ \Omega = 1.95V$

Figure 2. *Example 2A. Schematic representation of LV and RV leads connected in parallel via the "Y" adaptor. The current necessary to capture the LV lead is 2.6 mA. When the RV resistance and LV resistance are equal (750 ohms), the electromotive force necessary to drive 2.6 mA of current into the LV limb and thus capture the LV, is 1.95 V. Example 2B. Schematic representation of LV and RV leads connected in parallel via the "Y" adaptor. In this illustration the RV resistance is significantly less than the LV resistance (500 ohms and 750 ohms respectively). Despite the difference, the electromotive force (EMF) necessary to drive 2.6 mA of current into the LV limb is 1.95. Although the fraction of total current contributing to the LV limb is lower than the RV limb, this difference is offset by the increase in total current (6.5 mA versus 5.2 mA in Example 2A). Example 2C. Schematic representation of LV and RV leads connected in parallel via the "Y" adaptor. In this illustration the RV resistance is significantly more than the LV resistance (1000 ohms versus 750 ohms). The calculated electromotive force (EMF) necessary to drive 2.6 mA of current into the LV limb of the circuit remains at 1.95 V. Example 2A, B, and C illustrate that when the LV and RV are in parallel and the LV resistance remains the same, the electromotive force (EMF) necessary to drive a given current in the LV limb remains the same through a wide range of RV impedances.*

electrode, (2) RV ring electrode, and (3) RV distal defibrillator coil electrode. The LV capture thresholds were (1) 2.76 V, (2) 1.97 V, (3) 1.19 V respectively.[9] The size of the anode in the acute measurement of LV thresholds in a unipolar configuration can be highly variable depending on the effective surface area of the anode's (alligator clip or surgical instrument) contact to the patient.

It is well known that stimulation thresholds increase and peak several weeks after initial implantation and then plateau at a threshold above the acute threshold measurement.[10] This is due to

Example 3

R_X =Resistive element representing:
1) Difference in anode surface area comparing measurements in LV unipolar configuration vs. LV/RV tip to shared ring configuration.
2) To a lesser degree: Resistive polarization at electrode tissue interface and myocardial resistance.

If RL =750 Ohms; RR = 1000 Ohms; and RX = 150 Ohms

IL = 0.0026A (current needed to capture LV)

$$R_T = R_R x[R_L + R_X] / (R_R + [R_L + R_X])$$
$$= 1000\ \Omega \text{ x } [900\ \Omega] / 1000\ \Omega + [900\ \Omega]$$
$$= 473.68\ \Omega$$

$$I_L = I_T\ (R_R/R_R + R_L + R_X)$$
$$I_T = I_L / (R_R/R_R + R_L + R_X)$$
$$I_T = 0.0026 \text{ A}/(1000\ \Omega / 1900\ \Omega)$$
$$= 0.00494 \text{ A}$$

$$V_T = I_T \text{ X } R_T = 0.00494 \text{ A x } 473.68\ \Omega = \underline{\mathbf{2.3\ V}}$$

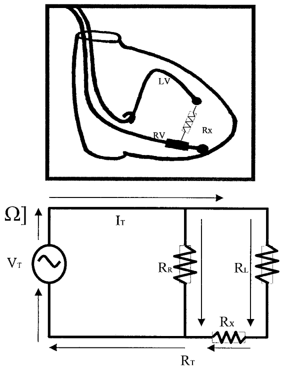


Figure 3. *Example 3. Schematic representation illustrating the difference in measured LV thresholds comparing a unipolar LV configuration versus through a "Y" connector. A resistance element that represents a difference in anode surface area between the two configurations and other factors such as resistive polarization at the electrode-tissue interface and myocardial resistance. When this resistive element is considered, a significant difference in electromotive force (EMF) is now necessary to drive the same amount of current in the LV limb.*

an inflammatory reaction to the lead forming a fibrous capsule at the electrode-tissue interface. The significance and degree of threshold changes as a function of time with coronary sinus leads has not been reported. We have observed no significant increase in threshold at 1 month and 3 month follow-up suggesting that there is minimal biologic reaction to the electrode within the cardiac vein. Larger studies need to be performed to profile the changes in thresholds of leads positioned in cardiac veins with time.

Conclusion

We have observed a significant difference in LV lead thresholds when measured in a unipolar configuration versus via a "Y" adaptor. This has significant clinical implications because LV thresholds measured prior to connecting to the "Y" adaptor may underestimate the true LV threshold. In our study, 2 patients required left ventricular lead revisions due to excessive elevations in the LV thresholds during follow-up. When "Y" adaptors are used, LV thresholds should be assessed in an LV tip to RV ring configuration or ideally via the "Y" adaptor in order to avoid this pitfall.

Upgrading permanent pacemakers to biventricular pacing systems via a "Y" adaptor remains an option to patients with severe symptomatic heart failure and intraventricular conduction delay. Accurate assessment of the true LV threshold can only be performed when the LV threshold is assessed through the "Y" adaptor at the time of implant. Most first generation biventricular pacemaker generators are wired with "Y connectors" internally within the header to accommodate the LV lead (i.e., single ventricular output divided into two ventricular ouputs within the header). Our findings remain relevant in these newer devices.

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