A Comparison of Unipolar and Bipolar Electrograms for Cardiac Pacemaker Sensing

VINCENT DECAPRIO, PH.D., PHILIP HURZELER, PH.D., AND SEYMOUR FURMAN, M.D.

SUMMARY Simultaneous unipolar and bipolar electrograms were recorded and compared from 49 pacemaker patients with bipolar endocardial electrodes. Average bipolar depolarization signal voltage equaled that of unipolar but showed greater variation. Bipolar and unipolar slew rates were equal in both mean and variance. The proximal pole voltage had little effect on the bipolar result in 8% of the cases, tended to cancel the tip voltage in 49% of the cases and augmented the tip voltage in 43% of the electrograms.

FROM THE FIRST DAYS of cardiac pacing, two varieties of stimulating electrodes have been used: unipolar and bipolar. The unipolar electrode has one pole (cathode or negative stimulating pole) in contact with cardiac tissue, and the other (anode or positive pole) outside of the heart, either in subcutaneous tissue or on the surface of the body. The bipolar electrode has both the cathode (sometimes called its distal or tip pole) and the anode (proximal or ring pole) at the cardiac tissue being stimulated.

The same electrodes are used to sense cardiac activity as well as to stimulate the heart. Bipolar and unipolar electrodes are not equivalent in transmitting the cardiac electrogram to the pacemaker. Only the electrical events at the tip pole describe the unipolar electrogram; the remote anode contributes negligible voltage, since its location is extracardiac. The bipolar electrode exhibits a large anodal voltage (ring signal), similar in magnitude to the tip signal, but the resulting electrogram is also dependent upon the orientation of the electrode within the heart. It has long been demonstrated that unfavorable electrode orientation can produce low voltage bipolar signals, even in the presence of high voltage tip and ring signals.

The average bipolar R wave duration was 28% less, the T wave amplitude 34% less, and the ST-segment elevation 37% less than the unipolar values.

By consistently attenuating the undesirable T waves and ST elevations, while leaving the depolarization signal unaffected, the bipolar electrode offered the advantage of a superior signal-to-noise ratio for sensing depolarization. In one case, however, the bipolar signal was so small as to cause a clinical sensing failure.

Methods

Right ventricular, high fidelity (0.1Hz – 2kHz) endocardial electrograms from bipolar pacemaker electrodes were measured in 49 patients. Twenty-one electrodes were acute and 28 were chronic (in service 2–83 months). A three-channel lead selector and high impedance isolated preamplifier of
custom design* allowed simultaneous bipolar and unipolar tracings to be recorded with a peripheral lead II ECG (fig. 1). A Hewlett-Packard Model 3960A instrumentation grade tape recorder stored the data for later playback to Models DR-8 and DR-12 Electronics for Medicine multichannel, high speed photographic recorders. Readings from the tracings were then statistically analyzed by a General Electric computer time sharing network.

Those parameters of the ventricular electrogram that most affect pacer sensing have been described elsewhere and in this study were similarly measured for both unipolar and bipolar signals, viz., peak-to-peak voltage and maximum slew rate (slope, or dy/dt) of the QRS complex, the ST-segment elevation and the peak-to-peak voltage and maximum slew rate of the T wave. The duration of the intrinsic deflection was taken as the width of the intracardiac R wave measured between crossings of the isoelectric line; however, the durations of some irregularly shaped curves could not be determined without extrapolation (e.g. fig. 2, middle) and are, therefore, estimates. Parameter values were averaged over one or two respiratory cycles before tabulation.

The electrograms were recorded from electrodes with a low, stable, and clinically useful stimulation threshold and impedance, and satisfactory radiographic visualization. The electrode surface areas and bipole separations are shown in table 1. Only complexes from the most prominent focus, either conducted or idioventricular, were analyzed. All recordings were free from pacemaker stimuli and artifacts.

Our recording arrangement causes a positive voltage at the tip electrode to register as an upward deflection. Unipolar signals were recorded with the negative input of a high impedance bioelectric amplifier connected to a large surface area metallic plate, temporarily inserted in the subcutaneous pulse generator site. Bipolar signals were measured with the tip electrode connected to the positive input and the ring electrode connected to the negative input.

Early results showed that the interpretation of some

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*Courtesy of Medtronic, Inc.
bipolar signals was facilitated by simultaneously observing the unipolar ring signal. Therefore, in the last 30 instances unipolar ring signals were also recorded by moving the positive input terminal from the tip to the ring electrode, and continuing the simultaneous recording. At the conclusion of the recording, simultaneous tip and bipolar electrograms, and simultaneous proximal and bipolar electrograms were available for analysis.

Signals which vary with time and may be displayed as a plot of amplitude as a function of time (e.g., electrograms) are said to be in the "time domain" in the mathematic terminology of waveform analysis. Such signals, by means of the "Fourier Transform" can be recast into the mathematically equivalent "frequency domain" and be visualized as a spectrum or plot of amplitude versus sinusoidal frequency. Both representations are equally accurate and precise although each offers specific conveniences. The frequency domain form is especially useful to designers of electronic circuitry, but as the time domain form preserves the morphologic features of the waveform, it permits correlation of physiologic events with pacemaker sensing circuit response. Since the frequency domain offers no further insights into the electrophysiologic process, it was not used in this study.

Results

One-third (16 of 49) of the bipolar depolarization signals resembled the bottom curve of figure 2 with a narrow triangular deflection crossing the isoelectric line more than once. Of these, the peak was positive, indicating propagation from ring to tip in 11 cases, and negative, indicating propagation from tip to ring, in five cases. The remaining 33 bipolar waveforms could not be classified into unique morphological subgroups.

The bipolar depolarization signal voltage (measured within 0.1 mV) was greater than its unipolar mate in 21 cases (43%), equal in four cases (8%) and less in 24 cases (49%). In one of the latter 24 cases the bipolar voltage was too small to be sensed by the pacemaker; the matching unipolar tip electrogram was larger and sensed. The maximum slew rate always occurred during an intrinsic deflection, which was usually a downward slope, virtually a straight line segment. The maximum bipolar slew rates, measured within 0.2 V/sec, were greater than their unipolar mates in 15 cases (31%), equal in 22 cases (45%) and less in 12 cases (24%). The unipolar tip signals always showed a larger slew rate than the corresponding unipolar ring signal.

Statistical evaluation of the unipolar and bipolar electrograms as independent groups revealed that average unipolar and bipolar voltages and slew rates are equal. The average bipolar R wave duration is 28% less, the T wave voltage 34%, and the ST-segment elevation 37% less than the average unipolar parameter (table 2). In the bar graphs of the bipolar and unipolar voltage distributions (fig. 3) the bipolar signals appear to show a larger variance, which is not significant according to an F test with 90% confidence.

By comparing the amplitudes of the unipolar tip and ring signals for each electrode, a ring-to-tip voltage ratio was computed. If the ring electrogram is small in comparison to the tip electrogram a large voltage difference exists and the bipolar signal then approximates the unipolar tip signal; it is a quasi-unipolar signal (fig. 4-1). Twenty-two cases with a ratio greater than 0.5 (a ring signal amplitude at least half the tip) were considered true bipolar signals, the result of tip and ring contributions of similar magnitude. The true bipolar signals exhibited a standard deviation of ± 6.8 mV with a mean amplitude of 11.3 mV and a greater variance than the unipolar group at the 90% level of the F test.

Data from each bipolar electrogram were then subtracted from the values of its unipolar mate, and the individual changes in voltage, slew rate, and duration were computed for all 49 cases and averaged. As six of the 21 acute bipolar electrograms had no discernible T wave, and the ST segment of chronic electrograms is isoelectric, in neither instance could a change be calculated. Therefore, for the T wave voltage and slew rate, and ST displacement, the mean values of the independent groups (table 2) were used to compute the percentage change (table 3). The probability (P) that the unipolar value may be equal to the bipolar value, based on Student's t-test, is included in the righthand column. Any P, value less than 0.05 indicates a significant change (table 3).

Bipolar R wave amplitudes were an average 3.03% less than unipolar ones. This difference, however, is not supported at any reasonable level of significance. The R wave duration, T wave amplitude, T wave slew rate, and ST-segment elevation are all significantly reduced with bipolar sensing (table 3).

Finally, the unipolar-bipolar pairs were further divided into acute and chronic subgroups. A comparison of the unpaired (not from the same electrode) acute and chronic values revealed similar changes for both unipolar and bipolar signals; amplitude is maintained, though only with marginal confidence; and slew rate is decreased by about 40% (table 4). Here, P is the probability that no acute-to-chronic difference exists. Values less than .05 indicate significance.

Table 1. Bipolar Electrode Specifications

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Manufacturer, model</th>
<th>Cathodal surface area</th>
<th>Bipole separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>Medtronic 6001</td>
<td>11 sq mm</td>
<td>28 mm</td>
</tr>
<tr>
<td>8</td>
<td>Medtronic 5810</td>
<td>87 sq mm</td>
<td>15 mm</td>
</tr>
<tr>
<td>6</td>
<td>G. E. bipolar</td>
<td>12 sq mm</td>
<td>20 mm</td>
</tr>
<tr>
<td>2</td>
<td>Pacemaker systems</td>
<td>12.2 sq mm</td>
<td>29 mm</td>
</tr>
</tbody>
</table>

Table 2. Unipolar and Bipolar Parameters

<table>
<thead>
<tr>
<th></th>
<th>Unipolar</th>
<th>Bipolar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Range</td>
</tr>
<tr>
<td>Amplitude (mV)</td>
<td>12.2 (5.2)</td>
<td>4.0-29.2</td>
</tr>
<tr>
<td>Slew rate (V/sec)</td>
<td>2.8 (1.7)</td>
<td>0.6-7.0</td>
</tr>
<tr>
<td>Duration (msec)</td>
<td>38.3 (30.3)</td>
<td>25.0-150.0</td>
</tr>
</tbody>
</table>
Discussion

Ventricular electrograms may be resolved into four bioelectric events: the intrinsic deflection (the intracardiac R wave), repolarization (the T wave), far-field phenomena (distant electrical activity) and the injury current (ST-segment elevation). The most important event for pacer sensing is the intrinsic deflection, the rapid, nearly straightline downward deflection of the unipolar electrogram, which occurs when the muscle adjacent to the electrode becomes electronegative as the depolarization wave passes. With bipolar electrodes, the waveform appears first at one pole, then travels to the other. An exception is the quasi-unipolar signal where the waveform does not produce similar intrinsic deflections at each pole. The bipolar voltage, i.e., the potential difference between the two poles at any time, is a function of three variables, tip voltage, ring voltage and travel time between poles, against only one (tip voltage) for the unipolar electrogram. Because of the increased number of variables, the greater variance in bipolar amplitude is not surprising. Further evidence for inconsistency in bipolar amplitude is found in the large signal variation associated with normal respiration.

The interelectrode distance (bipole separation), the velocity of the spreading depolarization wave and especially the direction of the depolarization pathway through the ventricle determine the timing of the tip and ring intrinsic deflections. In an idealized model of myocardial tissue activation (fig. 5) identical signals appear on both poles of a bipolar electrode. In the two extreme cases the bipole may be oriented either normal (N) (at a 90° angle) or parallel (P) to the path of the depolarization wave, here considered a

Table 3. Percent Change from Unipolar

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Pr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>-3.03</td>
<td>30.30</td>
<td>.32</td>
</tr>
<tr>
<td>Slew rate</td>
<td>.32</td>
<td>26.54</td>
<td>.98</td>
</tr>
<tr>
<td>Duration</td>
<td>-27.64</td>
<td>30.13</td>
<td>&lt;10^4</td>
</tr>
<tr>
<td>Mean T voltage</td>
<td>-33.00</td>
<td></td>
<td>.007</td>
</tr>
<tr>
<td>Mean T slew rate</td>
<td>-29.17</td>
<td></td>
<td>.045</td>
</tr>
<tr>
<td>Mean ST displacement</td>
<td>-37.40</td>
<td></td>
<td>&lt;10^-4</td>
</tr>
</tbody>
</table>
sheet of charge extending the full width of a strip of cardiac muscle. For the N orientation, the wavefront strikes both poles simultaneously and no bipolar potential results (fig. 4-3).

Alternatively, the P orientation causes a difference in arrival times at the two poles resulting in an additive bipolar signal (fig. 4-2). The amplitude of the bipolar signal is also influenced by the distances from each pole to the active tissue and the width of the depolarization wavefront.9

A parallel (P) orientation, with a bipolar signal larger than either ring or tip, occurred in 10 of the 30 cases in which the ring signal was explicitly recorded. In two of the 10, the bipolar was larger than the tip signal because of the ring contribution. In the other eight, the cause was a timing difference between the two smaller unipolar signals.

In the 21 cases in which the bipolar signal amplitude was greater than the associated tip signal, the tip signal alone was always large enough for clinically satisfactory sensing. No bipolar signal of sufficient amplitude and slew rate to trigger a pacemaker has been formed from two insufficient unipolar signals. The probability of such an occurrence is extremely small since the small, wide intrinsic deflections associated with poor electrode position or an infarcted myo-cardium10 arrive nearly simultaneously at both poles and tend to be attenuated rather than enhanced with bipolar sensing. (However, since only clinically satisfactory signals were recorded, and a unipolar tip signal greater than 2 mV was a criterion, such bipolar signals were not demonstrated in this study.) Thus, the clinical practice of unipolarizing a bipolar electrode with an N orientation to improve its sensing performance,6 does not have a useful converse: bipolarizing a pair of poorly performing unipolar electrodes will not help.

The purpose of a pacemaker's sensing amplifier is to respond selectively to cardiac electrical activity. An adequate signal, returning via the electrode, triggers the sensing circuit into modifying the pacemaker's output. Adequacy depends on the signal's amplitude and frequency content, which can be characterized by its voltage, rate of change (slew rate),2,9 and duration (the time between isoelectric crossings of the depolarization signal). Signals of very short duration tend to be rejected by the sensing circuit as spurious high frequency noise, and will trigger the circuit only if amplitude is high. The precise effect of signal duration on sensing is determined by the circuit's high frequency filter characteristics, and varies among designs. Pacemakers are tested with a haversine test signal to simulate an intracardiac R wave.† A typical sensing amplifier is most sensitive to a 25 msec duration haversine pulse and requires only a 2 mV amplitude to trigger at that duration. As the duration is decreased to 6 msec, a 4 mV haversine is required (personal communication, J. Hartlaub, Medtronic, Inc.).

Because tip and ring voltage is nearly equal throughout most of the R wave, a substantial voltage difference exists only when the depolarization wavefront is between poles. Usually, a bipolar signal of shorter duration and dissimilar morphology from either tip or ring is produced (fig. 4-4). Even if the amplitude of the ring signal is significantly less than the tip, a bipolar signal morphologically similar to the tip is generated, but again, with a shorter duration (fig. 4-1). Forty-four of the 49 cases had bipolar durations shorter than unipolar tip (mean decrease 28%), but as signal durations never fell below 10 msec (mean 75 msec) it is unlikely that a signal from a bipolar electrode would be rejected as noise.

The remaining three contributors to the electrogram (T wave, ST elevation and far-field activity) are physiologic noise to a sensing system and should be rejected. The myo-cardial repolarization wavefront is wide11 and appears nearly simultaneously on both poles of the bipolar system. It is, therefore, significantly attenuated. The bipolar T waves of this study were reduced an average of 34% compared to those of the simultaneous bipolar (figs. 4-3 and 4-4). The acute ST-segment elevation is believed due to a local current of injury caused by pressure of the electrode tip against the endocardium. The electrogram from the ring, which is distant from the injury, also displays an ST elevation.

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TABLE 4. **Acute-to-Chronic R Wave Change**

<table>
<thead>
<tr>
<th></th>
<th>Acute</th>
<th></th>
<th>Chronic</th>
<th></th>
<th></th>
<th>Pr.</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>sd</td>
<td>Mean</td>
<td>sd</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Unipolar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage (mV)</td>
<td>12.4</td>
<td>5.2</td>
<td>12.1</td>
<td>5.3</td>
<td>.025</td>
<td></td>
</tr>
<tr>
<td>Slew rate (V/sec)</td>
<td>3.5</td>
<td>1.7</td>
<td>2.3</td>
<td>1.6</td>
<td>.012</td>
<td></td>
</tr>
<tr>
<td><strong>Bipolar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage (mV)</td>
<td>13.4</td>
<td>6.1</td>
<td>10.5</td>
<td>5.8</td>
<td>.094</td>
<td></td>
</tr>
<tr>
<td>Slew rate (V/sec)</td>
<td>3.6</td>
<td>1.7</td>
<td>2.2</td>
<td>1.7</td>
<td>.008</td>
<td></td>
</tr>
</tbody>
</table>

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*In this instance good signals on tip and ring cancel each other to form an attenuated bipolar signal. Elimination of one leaves a good signal fully available.

†A haversine pulse is one half cycle of a sine wave, squared. It may be electronically generated and its amplitude and duration independently varied to test pacemaker sensitivity. See Pacemaker Standard (proposed), August, 1975, Para. 4.1.4.1., Association for the Advancement of Medical Instrumentation, 1901 Fort Meyers Drive, Arlington, Va. 22209.
(though smaller than the tip electrogram) and the bipolar signals therefore display lower ST elevations than the unipolar signals. Far-field potentials from distant electrical activity, (e.g., activation of the opposite ventricle, skeletal muscle potentials, atrial activity, nonphysiologic signals, etc.), if large enough, can falsely trigger the pacemaker. Unipolar signal amplitude is inversely proportional to the distance between the electrode and the signal source. Bipolar signal amplitude is inversely proportional to the square of the distance from a point midway between the two poles and the signal source.\textsuperscript{18} The smaller lead-field of the bipolar electrode renders it superior in rejecting electromagnetic interference and distant physiologic activity.\textsuperscript{18}

By the attenuation or enhancement of select events the bipolar electrode can provide a signal-to-noise ratio superior to that of a unipolar electrode. It attenuates not only electrical noise\textsuperscript{19} but also the physiologic signals which should be treated as noise. T waves, ST-segment elevations and potentials from areas of the heart far from the electrode are reduced before they enter the pacemaker’s sensing amplifier (where they may be further attenuated by filtering). At times, however, the price of low noise can be R wave attenuation unable to trigger a pacemaker in 2% of our cases. Often a small but artifact-free signal may be an advantage over one larger but noisier (better signal-to-noise ratio).\textsuperscript{14} If the T waves are considered noise, the signal (R wave)-to-noise ratio was greater for bipolar electrodes in 33 of our 49 cases (67%).

Conclusions

Bipolar and tip unipolar signals, simultaneously derived from the same catheter electrode, are usually unequal in amplitude, yet the averages of the two groups are equal. The probability of obtaining a signal much larger or much smaller than average is greater with bipolar sensing. The orientation of a bipolar electrode within the heart determines the amplitude and slew rate of the electrogram. The orientation can cause either a subtraction or an addition of the two unipolar amplitudes at each pole. The addition of two smaller unipolar signals, and not a large ring signal, accounted for the majority of the cases having a bipolar signal larger than the unipolar tip signal.

The depolarization signal of bipolar electrograms is shorter in duration than unipolar, yet not so short as to be mistaken for electrical noise by the sensing amplifier.

Bipolar sensing reduces both the physiologic (T waves, ST elevations and far-field) and nonphysiologic (electromagnetic interference) noise in sensing systems providing a signal-to-noise ratio superior to unipolar.

References

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\textsuperscript{*}A unipolar electrode is equivalent to a monopole and the bipolar electrode to a dipole in electric field theory.
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V DeCaprio, P Hurzeler and S Furman

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