Detecting and distinguishing cardiac-pacing artifacts

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When a heart patient with an implanted pacemaker undergoes electrocardiogram testing, the cardiologist must be able to detect the presence and effects of the pacemaker (see sidebar, “When the heart’s electrical subsystem malfunctions”). A simple implanted pacer’s activity is generally not perceptible on a normal ECG trace, because the very fast pulses—with typical widths of hundreds of microseconds—get filtered due to low-bandwidth display resolution (monitor/diagnostic 40-/150-Hz bandwidths). The pacer’s signal, however, can be inferred through the changed morphology of the ECG trace, which is representative of the heart’s own electrical activity as recorded at the skin surface via ECG leads.

It is important to be able to detect and identify pacing artifacts because they indicate the presence of the pacemaker and help in evaluating its interaction with the heart. But the artifacts’ small amplitude, narrow width, and varying waveshape make them difficult to detect, especially in the presence of electrical noise that can be many times their amplitude. At the same time, pacing therapy has become extremely advanced, with dozens of pacing modes available for single- to three-chamber pacing. Complicating the detection of pacing artifacts, pacemakers produce lead-integrity pulses, minute-ventilation (MV) pulses, telemetry signals, and other signals that can be incorrectly identified as pacing artifacts.

The use of real-time pacemaker telemetry has made the display of pacing artifacts on an ECG strip less important than it used to be. An individual skilled in pacing therapies can look at the strip and sometimes infer the type of pacing therapy being administered to the patient and determine whether the pacemaker is working properly.


How pacemakers pace
Implantable pacemakers (Figure 1) are typically lightweight and compact. They contain the circuitry necessary to monitor the heart’s electrical activity through implanted leads and to stimulate the heart muscle as necessary to ensure a regular heartbeat. Pacemakers must be low-power devices, as they operate with a small battery that typically has a 10-year lifespan. The National Academy of Engineering estimated in 2010 that more than 400,000 pacemakers are implanted in patients every year (Reference 1).

Figure 1 Pacemakers must be light, compact, low-power devices (Reference 2).

In unipolar pacing, the pacing leads consist of an electrode at the tip of a single pacing lead and the metal wall of the pacemaker housing itself. The pacing artifacts caused by this mode of pacing can be several hundred millivolts at the skin surface, with a width of up to 2 msec. Unipolar pacing is no longer commonly used, however.

In bipolar pacing, which today accounts for the bulk of pacing artifacts created, the heart is paced from the electrode at the tip of the pacing lead. The return electrode is a ring electrode located very close to the tip electrode. The artifacts that this type of lead produces are much smaller than those produced by unipolar pacing; pulses on the skin surface can be as small as a few hundred microvolts high and 25 μsec wide, with average artifacts measuring 1 mV high and 500 μsec wide. The amplitude of the artifact can be much smaller when the detection vector does not line up directly with the pacing lead vector.

Many pacemakers can be programmed for pulse widths as short as 25 μsec, but the short-pulse-width settings are typically used only in pacemaker threshold tests performed in an electrophysiology laboratory. Setting the lower limit to 100 μsec eliminates the problem of falsely detecting MV and lead-integrity (LV lead) pulses as valid pacing artifacts. These subthreshold pulses are usually programmed to be between 10 and 50 μsec.

Various types of pacemakers are available for pacing specific chambers of the heart. Single-chamber pacing delivers pacing therapy to either the right atrium or the right ventricle. Such a pacer can be either unipolar or bipolar. Dual-chamber pacing delivers pacing therapy to both the right atrium and the right ventricle. Biventricular pacing delivers pacing therapy to both the right ventricle and the left ventricle; in addition, the heart is usually paced in the right atrium.

The biventricular pacing mode can be difficult to display properly, for two main reasons. First, the two ventricle paces may occur at the same time, appearing as a single pulse at the skin surface. Second, the left-ventricle lead placement is generally not on the same vector as the right-ventricle...
lead and may actually be orthogonal to it. Usually, the right atrium is best displayed in lead aVF—one of the augmented limb leads—and the right ventricle is best displayed in lead II. Most ECG systems do not employ three simultaneous lead-detection circuits or algorithms, making the left ventricle the toughest lead to pick up. Thus, it is sometimes best detected in one of the V leads.

Artifact waveforms

Most pacing pulses have very fast rising edges. The rise time measured at the pacemaker output is generally about 100 nsec. When measured at the skin surface, the rise time will be slightly slower because of the inductance and capacitance of the pacing lead. Most pacing artifacts at the skin surface are on the order of 10 μsec or less. As complex devices with built-in protection, pacemakers can produce high-speed glitches that do not affect the heart but do affect pacemaker-detection circuits.

Figure 2 shows an example of an ideal pacing artifact. The positive pulse has a fast rising edge. After the pulse reaches its maximum amplitude, a capacitive droop follows, and then the trailing edge occurs. The artifact next changes polarity for the recharge portion of the pacing pulse. The recharge pulse is required so that the heart tissue is left with a net-zero charge; with a monophasic pulse, ions would build up around the electrodes, creating a dc charge that could lead to necropsy of the heart tissue.

Introducing cardiac-resynchronization devices adds another degree of complication in detecting and displaying pacing artifacts. These devices pace the patient in the right atrium and both ventricles. The pulses in the two ventricles can fall close together, overlap, or occur at exactly the same time; the left ventricle can even be paced before the right ventricle. Currently, most devices pace both ventricles at the same time, but studies have shown that adjusting the timing will benefit some patients by yielding a higher cardiac output.

Detecting and displaying both pulses separately is not always possible, and many times the pulses will appear as a single pulse on the ECG electrodes. If both pulses were to occur at the same time
with the leads oriented in opposite directions, the pulses could cancel each other out on the skin surface. The probability of such an occurrence is remote, but one can envision the appearance on the skin surface of two ventricle-pacing artifacts with opposite polarities. If the two pulses were offset by a small time interval, the resulting pulse shape might be very complex.

Figure 3 shows scope traces of a cardiac-resynchronization device pacing in a saline tank. This is a standard test environment for pacemaker validation, designed to mimic the conductivity of the human body. The proximity of the scope probes to the pacing leads causes the amplitudes to be much larger than what would be expected on the skin surface, however, and the low impedance that the saline solution presents to the ECG electrodes results in much less noise than would normally be seen in a skin-surface measurement.

The first, second, and third pulses shown in the figure (l to r) are the atrial, right-ventricle, and left-ventricle pulses, respectively. The leads were placed in the saline tank with vectors optimized to see the pulses clearly. The negative-going pulse is the pace; the positive-going pulse is the recharge. The amplitude of the atrial pulse is slightly larger than the two other pulse amplitudes because the lead was in a slightly better vector than the ventricle leads; in actuality, all three pacing outputs in the resynchronization device were programmed to have the same amplitude and width. With real patients, the amplitudes and widths are often different for each pacemaker lead.

Artifact detection

It is impossible to detect all pacing artifacts and reject all possible noise sources in a cost-effective manner. Among the challenges are the number of chambers that the pace detection must monitor, the interference signals encountered, and the wide variety of pacemakers in use. Solutions for detecting artifacts may range from hardware implementations to digital algorithms.

The pacing leads for cardiac-resynchronization devices will not all have the same vector. The right-atrium lead usually aligns with lead II, but it can sometimes point straight out of the chest, so a Vx (precordial lead) vector may be needed to see it. The right-ventricle lead is usually placed at the apex of the right ventricle, so it usually aligns well with lead II. The left-ventricle pacing lead, threaded through the coronary sinus, is actually on the outside of the left ventricle. This lead usually
aligns with lead II but may have a V-axis orientation.

The pacing leads of implantable defibrillators and resynchronization devices are sometimes placed in areas of the heart that have not had an infarction. Placing them around infarcts is the main reason that this system uses three vectors and requires a high-performance pacing-artifact detection function.

A major noise source is the H-field telemetry scheme used in most implantable heart devices. Other sources of noise are transthoracic-impedance measurements for respiration, electric cautery, and conducted noise from other medical devices connected to the patient.

Complicating the problem of acquiring pacing artifacts, each pacemaker manufacturer uses a different telemetry scheme. In some cases, a single manufacturer may use different telemetry systems for different implantable-device models. Many implantable devices can communicate using both H-field telemetry and either ISM- or Medical Implant Communication Service (MICS)-band telemetry. The variability of H-field telemetry from one model to the next makes filter design difficult. ECG devices have to be Class CF—the most stringent classification—as there is direct conductive contact with the heart, whereas other medical devices may be built to less stringent Class B or BF requirements, and their higher leakage currents may interfere with the performance of ECG-acquisition devices.

Artifact-detecting AFE

The ADAS1000 (Figure 4) is a five-channel analog front end designed to address some of the challenges facing designers of low-power, low-noise, high-performance, tethered or portable ECG systems. The AFE, designed for both monitor- and diagnostic-quality ECG measurements, comprises five electrode inputs and a dedicated right-leg-drive (RLD) output reference electrode. In addition to supporting the essential ECG signal-monitoring elements, the AFE enables such functions as respiration (thoracic impedance) measurement, lead/electrode connection status, internal calibration, and capabilities for pacing-artifact detection.
One ADAS1000 supports five electrode inputs, facilitating a traditional, six-lead ECG measurement. By cascading a companion ADAS1000-2 device, the system can be scaled up to a true 12-lead measurement; by cascading three or more devices, the system can be scaled to measurements with 15 leads and beyond.
The flowchart shows the digital-pacemaker decision process for the artifact-detection algorithm, which detects pacing artifacts with widths that range from 100 μsec to 2 msec and amplitudes that range from 400 μV to 1000 mV.

Detection algorithm

The device's front end includes a digital pacemaker artifact-detection algorithm that detects pacing artifacts with widths ranging from 100 μsec to 2 msec and amplitudes ranging from 400 μV to 1000 mV, to align with AAMI and IEC standards. Figure 5 is a flow diagram of the algorithm.

The pace-detection algorithm runs three instances of a digital algorithm on three of four possible leads (I, II, III, or aVF). It runs on the high-frequency ECG data, in parallel with the internal decimation and filtering, and returns a flag that indicates pacing was detected on one or more of the
leads, providing the measured height and width of the detected signal. For users who wish to run their own digital pace algorithm, the ADAS1000 supplies a high-speed pace interface that provides the ECG data at a 128-kHz data rate; the filtered and decimated ECG data remains unchanged on the standard interface.

A minute-ventilation filter is built into the ADAS1000 algorithm. MV pulses, which are conducted from the ring of a bipolar lead to the housing of the pacemaker, detect respiration rates to control the pacing rate. They're always less than 100 μsec wide, varying from about 15 to 100 μsec.

The simultaneous three-vector pacing-artifact system can detect pacing artifacts in noisy environments. Each of the three instances of the pace algorithm can be programmed to detect pace signals on different leads (I, II, III, or aVF). Programmable threshold levels tailor the algorithm to detect the range of pulse widths and heights presented, with internal digital filters designed to reject heartbeat, noise, and MV pulses. When a pace has been validated in an individual instance of the pace signal, the device outputs a flag so that the user can mark or identify the pace signal in the ECG capture strip.

The choice of sample rate for the pacing-artifact algorithm is significant because it cannot be exactly the same frequency as those used for the H-field telemetry carrier by the three pacing-systems companies (Boston Scientific, Medtronic, and St Jude). All three vendors use different frequencies, and each has many different telemetry systems. Analog Devices believes that the ADAS1000’s sampling frequency does not line up with that of any of the major telemetry systems.

References

When the heart's electrical subsystem malfunctions

The heart, a biochemical-electromechnical system, develops an electrical impulse that travels from the sinoatrial (SA) node in the upper right atrium to the atrioventricular (AV) node. The SA node acts as the pacemaker for the system (Figure 1).
This electrical impulse generates the P wave, which can be seen on the ECG capture in Figure 2. From the AV node, the electrical signal propagates, via the His-Purkinje system, to the ventricles, causing the ventricle muscles to contract. Their contraction (the R wave) moves oxygenated blood from the left ventricle into and through the body, and moves deoxygenated blood from the right ventricle to the lungs.

When the electrical system doesn’t work perfectly, different heart conditions can occur. For example, bradycardia occurs when the heart beats too slowly or misses beats. A typical surgical
intervention for this condition would be to implant a pacemaker device (pulse generator) just under the skin of the patient’s chest, with endocardial leads routed through the veins directly to the heart, as shown in **Figure 3**.

![Pacemaker Insertion Diagram]

**Figure 3** Pacemaker-lead insertions are shown for the various pacemaker types. (RA is right atrium, RV is the right ventricle; LV is the left ventricle).

In another class of arrhythmias, called tachycardia, the heart beats too fast. This very serious condition is treated with implantable cardiac defibrillators (ICDs). Modern ICDs can also treat many bradycardia arrhythmias.

Heart failure can occur when the heart becomes enlarged, lengthening its conduction paths and upsetting the timing of the ventricular contractions. This forms a positive feedback system, further aggravating the heart. Implantable cardiac resynchronization (ICR) devices resynchronize the ventricles by pacing both ventricles and usually one atrium. These devices improve cardiac output, allowing the heart to recover to a certain degree. Cardiac resynchronization therapy (CRT) devices include an ICD as part of the system.

**Figure 4a** is a fluoroscopic image showing an implanted CRT device. A layperson would find the image difficult to interpret, but physicians use such images to place the device leads. In the figure, you can see a light outline of the heart. In this typical lead placement, the black arrow points to the right-atrium lead; the dashed black arrow points to the right-ventricle lead. The partially seen lead, indicated by the red arrow, is the left-ventricle lead (the red arrow points to the tip of the electrode).

**Figure 4b** shows a fluoroscopic image of the typical lead placement for a dual-chamber pacemaker. The right-atrium lead is pointing up and is placed in the right atrium. The right-ventricle lead is positioned at the apex of the right ventricle.
Figure 4 Physicians use fluoroscopic images like these to aid in pacemaker lead placement (Reference 3). Arrangements for single-chamber (a) and dual-chamber (b) pacemakers are shown.

References
2. Sinus Rhythm Labels
3. (a) Cardiac resynchronisation therapy
   (b) Fluoroscopy pacemaker leads right atrium ventricle
4. St Jude Medical pacemaker with ruler

Authors’ biographies
John Kruse is a field applications engineer for Analog Devices in Minneapolis. He joined ADI in 2005 and specializes in medical applications. He has authored many articles and patents; several of the patents cover pacing-artifact acquisition. Kruse graduated with a bachelor of science degree in electronics engineering from the University of Minnesota in 1980. In 1997, he received a master of science degree in electronics engineering from the University of St Thomas (St Paul, MN), where he currently is an adjunct professor.

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