Understanding capture detection

Willem G. de Voogt\textsuperscript{a,}\textsuperscript{*}, Ben F.M. Vonk\textsuperscript{b}, Bert A. Albers\textsuperscript{b}, Florian Hintringer\textsuperscript{c}

\textsuperscript{a}Department of Cardiology, St. Lucas Andreas Ziekenhuis, Jan Tooropstraat 164, 1061 AE Amsterdam, The Netherlands
\textsuperscript{b}Vitatron B.V., Meander 1051, 6825 MJ Arnhem, The Netherlands
\textsuperscript{c}Universitätsklinik Innsbruck, Ansichstrasse 35, 6020 Innsbruck, Austria

Submitted 5 March 2004; accepted after revision 1 August 2004

\textbf{Abstract}  Automatic capture detection systems are currently available in several cardiac pacing devices. All current systems use low-polarization electrodes and no beat to beat detection system is available for all types of electrodes. In addition the success ratio for currently available systems is not always 100%. Failure to detect capture reliably is often related to the behaviour of the electrode–tissue interface under different circumstances.

Pacemaker electrodes can be considered electrochemical cells with complicated characteristics depending on time, temperature and electrical charge. This electrochemical cell is disturbed when a charge is transferred across the electrode–tissue interface during pacing. Several measures can be taken in order to minimise this disturbance or pace polarization artefact (PPA) including the use of high active surface area electrodes and application of tri-phasic pacing pulses.

Another factor influencing detection of evoked potentials is the input circuit of the pacemaker affecting the PPA and the evoked response. Positive PPAs can be falsely interpreted as evoked potentials due to the undershoot of the second order filters applied in modern cardiac pacemakers.

This paper explains the behaviour of the interface between the electrode and the cardiac tissue in combination with the pacemaker output circuits and input amplifiers under different circumstances.

\textcopyright{} 2004 The European Society of Cardiology. Published by Elsevier Ltd. All rights reserved.
Introduction

Device based capture detection enables continuous adjustment of the stimulation parameters in the ambulatory situation. This allows the use of smaller safety margins and will benefit the longevity of the device. Furthermore, pacemaker follow up may become easier by using a stimulation threshold test performed by the device during follow up. In this perspective automatic capture detection is an essential step towards device supported automated pacemaker follow up and, moreover, safety.

Systems for the automatic detection of ventricular capture and ventricular pacing thresholds have been the subject of study [3]. In addition, systems for the detection of atrial evoked responses have also been studied [4]. Understanding the results of these studies requires in-depth knowledge of the electrode—tissue interface, the influence of the pacing pulse and of the electrical characteristics of the input circuits of the pacemaker.

A major requirement in achieving reliable detection of an evoked response is the appropriate reduction of the electrode polarization resulting from the pacing pulse, defined as the pace polarization artefact (PPA). The characteristics of this PPA are influenced by several aspects related to the electrode as well as the pacing pulse. In addition the input circuit and the sense amplifier of the pacemaker will modify the PPA as it travels through the device hardware and thereby influence the impact of the PPA on the detection of evoked responses.

When atrial capture detection is addressed, the small amplitude of the atrial evoked response, relative to the PPA amplitude, requires an even more effective reduction of the PPA than in the ventricle.

The electrode—tissue interface can be considered as an electrochemical cell, the characteristics of which depend on the applied electrode materials, electrode macrosurface and microstructure. Low-polarization electrodes using titanium-nitride (TiN) or iridium (Ir) coatings have been shown to reduce the polarization resulting from the pacing pulse [1].

The PPA resulting from the interaction between the electrode—tissue interface and the pacing pulse is influenced by the pacing amplitude and pulse duration. A tri-phasic pacing pulse, balancing the total charge delivered to the electrode—tissue interface, will reduce the PPA [2].

Besides the pacing pulse and the physical characteristics of the electrode, the characteristics of the input amplifiers and filters will influence the reliability of the detection of evoked responses.

Physical background of polarization

When a metal electrode is immersed into an ionic solution, an electrochemical process occurs between the conductor and the solution. In the conductor the electrical energy or charge is transported by electrons and in the ionic solution the transport of charge occurs by positively and negatively charged ions. When the electrode is implanted into the heart the ionic solution is a complex mixture of tissue fluids. The boundary between the metal and the ionic solution is called the phase boundary. In 1879 Helmholtz postulated the formation of a so-called double layer at the phase boundary, i.e. a layer of metal ions at the solid surface and a rigidly held layer of oppositely charged ions in the solution. Later his model was modified and perfected by Goüy (1910), Chapman (1913), Debye and Hückel (1923) and Stern (1924) [5]. The metal conductor becomes negatively charged and attracts positive ions from the solution. As a result of this exchange of electrical charge a voltage difference exists between the electrode and the ionic solution, which is called the half-cell potential. This voltage depends on the nature of the electrode material, the temperature (which can be considered a constant in a human situation) and the composition of the ionic solution. Due to the shift in electrical charge, a thin layer of water molecules and a second layer of hydrated ions are created between the electrode and the ionic bulk solution. This double layer behaves as an insulator and has the properties of the dielectric layer of a capacitor, as shown in Fig. 1. The value of the half-cell potential can be calculated using the Nernst equation [5]. To be able to measure the half-cell potential a second electrode has to be immersed into the solution. Normally a reference electrode (i.e. a standard hydrogen electrode) would be used to measure pure half-cell potentials. By the Stockholm Convention (1953) the half-cell potential of a platinum/hydrogen electrode was defined as 0 V. Consequently, half-cell potentials are always relative electrode potentials. It should be noted that in a pacing system either the ring of a bipolar electrode or the pacemaker can be the second half-cell of a total electrochemical cell. This complete electrochemical cell has a resting potential ranging from zero to several hundreds of millivolts Direct Current [DC].
Behaviour of the electrode–tissue interface during pacing

Electrical current is the transport of charge. In the metal parts of the pacing circuit this transport of charge is caused by the movement of electrons; in the ionic phase charge is transported by the movement of positively and negatively charged ions. Due to the transported charge a shift occurs in the double layer of the dielectric barrier (Fig. 1). Ions do not travel through the double layer but the spatial distribution of the different charge carriers changes and the half-cell potential is disturbed. This disturbance in the half-cell potential due to the transport of charges during delivery of a pacing pulse is called the pace polarization artefact (PPA) as illustrated in Fig. 1.

It should be noted that the change in charge carriers occurs at the tip as well as at the electrode ring or the pulse generator can. However, the surface of the interface included in the return path of the current is substantially larger than the tip surface. As the magnitude of the PPA decreases with increasing surface of the interface, the contribution of this interface in the total PPA amplitude is relatively low and is usually ignored [6].

Polarization and evoked response detection

The PPA voltage depends on the properties of the electrode–tissue interface and the amount of charge transported during the pacing pulse. As shown in Fig. 2 the PPA is present immediately after delivery of the pacing pulse and its amplitude decreases towards the initial cell potential. The evoked response can be considered as a moving wavefront, travelling away from the electrode, and as a result it has an initial negative downslope. Since the evoked response is present at the same time, the signal measured on the tip of the...
electrode is a summation of the evoked response and the PPA (see Fig. 2).

One of the challenges of a capture detection system is detection of the evoked response with minimal disturbance due to polarization. Therefore, the polarization should ideally be zero or low compared with the amplitude of the evoked response. This can be achieved by the use of low-polarization electrodes or applying an optimally adjusted tri-phasic output pulse.

**Reduction of the pace polarization artefact**

A capture detection system is usually designed to detect a negative evoked response amplitude. Reduction of the PPA should therefore be aimed at achieving a small positive residual PPA to avoid a negative residual PPA being erroneously detected as an evoked response.

Almost all modern pacemakers make use of a fast recharge pulse to reduce the PPA voltage. This positive pulse is applied shortly after the negative pacing pulse and recharges the output capacitor of the device. By balancing the positive charge delivered by the recharge pulse and the negative charge delivered by the pacing pulse the net charge transferred across the phase boundary is zero. Empirically, it was found that a tri-phasic pulse with a positive pre-stimulus and post-stimulus pulse and a negative stimulation pulse is most effective in eliminating the PPA (Fig. 3). Technically speaking recharging is performed immediately after the stimulation pulse (post-stimulus) and the final small part of the recharge is made immediately prior to the stimulation pulse (pre-stimulus). This means that a complete discharge—recharge cycle starts at the stimulation pulse is then followed by the post-stimulus pulse and is completed by the pre-stimulus pulse of the next beat. This principle is currently applied in pacemakers using the QT-interval as a rate responsive indicator [7]. The technical implementation of this principle uses a fixed duration for the pre-stimulus and post-stimulus pulses. This implementation allows for sufficient reduction of the polarization voltage with respect to the evoked T-wave amplitude and reliable T-wave sensing and measurement of the QT-interval [8].

Although based on the same principle the reduction of the pace polarization artefact to enable detection of an evoked P or R complex is a technologically more demanding challenge than detecting...
the evoked T-wave. The reason for this is that in a capture detection system the evoked response has to be sensed within milliseconds of the stimulus when the polarization artefact has the maximum amplitude. Unlike the implementation for evoked T-wave sensing, the tri-phasic stimulation pulse may require adaptation to the electrode and tissue characteristics, to enable detection of the evoked response.

The CADET study [11] was conducted to investigate the ability of reducing the PPA by optimal adjustment of the post-stimulus pulse duration. In this study dedicated functionality was downloaded into implanted devices enabling adjustment of the post-stimulus pulse duration and measurement of the PPA amplitude. Results from this study showed that a sufficient reduction of the PPA amplitude can be achieved by adjusting the duration of the post-stimulus pulse with a fixed duration of the pre-stimulus pulse (Fig. 4).

**Input filtering and blanking**

Pacemakers with inhibited pacing modes require a number of measures to reduce the probability of false inhibition due to sensing artefacts and extracardiac signals. These measures are usually implemented in the device hardware and include the application of input filters and blanking of the input signal.

Many pacemakers use second order band-pass filters to filter the input signal [9]. In addition, by means of the blanking switches the input amplifiers are disconnected from the lead, shortly before, during and after the stimulus to avoid major distortion of the input amplifiers and the input filters. The combination of a blanking period and a second order input filter may result in an additional impeding effect with regard to reliable detection of evoked responses. To explain this effect the typical step response of a second order band-pass filter, as displayed in Fig. 5, should be considered. This response is observed for any stepwise increase in the input signal, for instance when the filter is connected to a positive PPA at the end of the blanking period (Figs. 6 and 7).

As explained earlier, reduction of the PPA is aimed at obtaining a small positive residual PPA in order to differentiate the PPA from the negative evoked response. However, due to the characteristics of a second order input filter a positive residual polarization voltage may still result in a negative undershoot. Especially when the evoked response amplitude is relatively small and a high detection sensitivity is therefore required, false positive capture detection may easily occur.

**Dynamic response**

The electrode–tissue interface is often simplified by a single capacitor, charged by a pacing pulse and a resistance, allowing for a discharge current. However, the actual electrical characteristics of this interface are more complex and include time-dependent and voltage-dependent elements. Due to these characteristics a change in the stimulation output voltage from a situation with an optimally adjusted post-stimulus pulse duration does not immediately result in a minimised polarization artefact. Usually, a steady state in which the

---

**Figure 4** The summation of the PPA and the evoked response at various durations of the post-stimulus pulse. The durations of the pre-stimulus and stimulus pulse remain constant. Decreasing the post-stimulus pulse duration attenuates the PPA and as a result the observed signal shows a better resemblance to the true evoked response. It should be noted that this figure shows steady state signals, i.e. signals observed after several stimuli with identical durations of the three phases have been applied.

**Figure 5** The response of a second order band-pass filter to a positive step wave shows a negative undershoot.
polarization artefact is again minimised after one or two stimuli. The implementation of an automatic threshold test, in which the amplitude or duration of the pacing pulse is gradually reduced and loss of capture is detected by the pacemaker, should account for this dynamic response [10].

Fig. 8 shows an example of the dynamic response as observed during a ventricular pulse duration threshold test. Immediately after reduction of the pulse duration the ventricular signal, which is a summation of the true evoked response and the PPA, has a smaller negative deflection. This is caused by a higher positive PPA as a result of the change in ventricular pacing pulse duration. With the detection level at $-5\, \text{mV}$ the first ventricular beat is not detected although the evoked response is present. It should be noted that in this example a second order input filter has been applied, causing a negative undershoot in response to the PPA signal. However, the combination of the PPA, filtered by this second order filter and the evoked response does not exceed the negative detection level and therefore does not cause a detection. While the positive PPA amplitude gradually returns to its steady state value subsequent beats are detected again.

Dynamic response in combination with the negative undershoot of a second order input filter may result in unexpected observations during atrial threshold tests, as shown by an example in Fig. 9. In this example the detection level is actually inappropriate to detect evoked responses in the steady state situation. However, the first beat following a reduction in the pacing pulse duration shows a larger negative deflection, resulting in detection by the system. The larger polarization artefact is again minimised is reached after one or two stimuli. The implementation of an automatic threshold test, in which the amplitude or duration of the pacing pulse is gradually reduced and loss of capture is detected by the pacemaker, should account for this dynamic response [10].

Fig. 8 shows an example of the dynamic response as observed during a ventricular pulse duration threshold test. Immediately after reduction of the pulse duration the ventricular signal, which is a summation of the true evoked response and the PPA, has a smaller negative deflection. This is caused by a higher positive PPA as a result of the change in ventricular pacing pulse duration. With the detection level at $-5\, \text{mV}$ the first ventricular beat is not detected although the evoked response is present. It should be noted that in this example a second order input filter has been applied, causing a negative undershoot in response to the PPA signal. However, the combination of the PPA, filtered by this second order filter and the evoked response does not exceed the negative detection level and therefore does not cause a detection. While the positive PPA amplitude gradually returns to its steady state value subsequent beats are detected again.

Dynamic response in combination with the negative undershoot of a second order input filter may result in unexpected observations during atrial threshold tests, as shown by an example in Fig. 9. In this example the detection level is actually inappropriate to detect evoked responses in the steady state situation. However, the first beat following a reduction in the pacing pulse duration shows a larger negative deflection, resulting in detection by the system. The larger polarization artefact is again minimised is reached after one or two stimuli. The implementation of an automatic threshold test, in which the amplitude or duration of the pacing pulse is gradually reduced and loss of capture is detected by the pacemaker, should account for this dynamic response [10].

Fig. 8 shows an example of the dynamic response as observed during a ventricular pulse duration threshold test. Immediately after reduction of the pulse duration the ventricular signal, which is a summation of the true evoked response and the PPA, has a smaller negative deflection. This is caused by a higher positive PPA as a result of the change in ventricular pacing pulse duration. With the detection level at $-5\, \text{mV}$ the first ventricular beat is not detected although the evoked response is present. It should be noted that in this example a second order input filter has been applied, causing a negative undershoot in response to the PPA signal. However, the combination of the PPA, filtered by this second order filter and the evoked response does not exceed the negative detection level and therefore does not cause a detection. While the positive PPA amplitude gradually returns to its steady state value subsequent beats are detected again.

Dynamic response in combination with the negative undershoot of a second order input filter may result in unexpected observations during atrial threshold tests, as shown by an example in Fig. 9. In this example the detection level is actually inappropriate to detect evoked responses in the steady state situation. However, the first beat following a reduction in the pacing pulse duration shows a larger negative deflection, resulting in detection by the system. The larger

**Figure 6**  To avoid major disturbance of the input amplifier and filter section by the pacing pulse, the input circuit is disconnected from the electrode for a short period immediately around the pacing pulse (blanking). After connecting the sense amplifier to the electrode the residual polarization potential will appear as a step wave and result in the typical step response of a second order band-pass filter. The negative undershoot of this response will add to the negative amplitude of the evoked response and increases the risk of false positive capture detection.

**Figure 7**  The result of a second order band-pass filter on the polarization potential. The polarization artefact is distorted to a sharp positive-negative deflection.
Figure 8  A part of a ventricular threshold test during which the duration of the stimulation pulse is decreased every fourth beat (arrows). In this example the negative capture detection level is set to a value allowing detection in the steady state situation. The PPA amplitude is temporarily increased in the first beat following a change in the stimulation pulse duration (dynamic response). Due to the increased positive contribution from the PPA to the combined signal (PPA + evoked response) the detection level is not exceeded, resulting in a false negative capture detection, immediately after a reduction in the stimulation pulse duration. It should be noted that the negative undershoot of the PPA, resulting from the second order input filter, is also increased due to the dynamic response. Unlike in the atrium (see Fig. 9), this increased negative undershoot is compensated by the evoked response to such an extent that no detection occurs. In the subsequent three beats the PPA amplitude returns to its steady state value and true positive capture detection occurs.

Figure 9  A part of an atrial pulse duration threshold test during which the duration of the stimulation pulse is decreased every fourth beat (arrows). In this example the negative capture detection level is insufficient to allow detection in the steady state situation, although atrial capture occurs. The PPA amplitude is temporarily increased in the first beat following a change in the stimulation pulse duration (dynamic response). Similar to the ventricular example (see Fig. 8) the negative undershoot of the PPA, resulting from the second order input filter, shows an increased amplitude. Unlike in the ventricle, this increased negative undershoot is only partially compensated by the relatively small atrial evoked response, resulting in a true positive detection immediately after reduction of the stimulation pulse duration. In the subsequent three beats, the PPA amplitude returns to its steady state value and no further detections occur. This example shows how the dynamic response results in a true positive capture detection while the detection level is inappropriately set. In a situation without true atrial capture, the same phenomenon is likely to result in false positive capture detection immediately after changing the stimulation pulse duration.
negative deflection is a result of the negative undershoot from the second order input filter that adds up to the negative evoked response amplitude. Unlike in the ventricle, the combination of the filtered PPA and the smaller atrial evoked response shows a large negative deflection, causing a detection. Subsequent beats are not detected due to a gradual reduction of the PPA amplitude and the negative undershoot due to the input filter.

Due to the dynamic response in combination with a second order input filter atrial threshold tests occasionally show false positive capture detections immediately following a change in the atrial pacing parameters. The relative amplitude of the ventricular evoked response is usually larger than in the atrium. As a consequence the dynamic response is less pronounced during ventricular threshold tests and has less effect on detection of ventricular evoked responses.

Dynamic response after inhibition

Dynamic response can also be observed after a longer period of inhibition, during which no pacing occurs and therefore, no charge is delivered to the electrode—tissue interface. Due to the absence of pacing the electrode—tissue interface tends to drift towards the initial cell potential. When pacing occurs after such a period of inhibition, changes take place within the electrode—tissue interface due to the delivery of charge and a dynamic response is observed. Again, this effect may take several pacing pulses before the electrode—tissue interface is stable again and the PPA is minimised as in the adjusted and stable condition. The dynamic behaviour of the pace polarization artefact observed after a longer period of inhibition requires more advanced capture detection systems to enable automatic detection of pacing thresholds.

The CADET study

This CADET study was conducted in order to evaluate the concept of reducing the PPA by adjustment of the post-stimulus pulse [11]. During the study atrial and ventricular stimulation pulse duration threshold tests were performed after optimal reduction of the PPA.

Fig. 10 shows an example of the effects resulting from the combination of dynamic response and undershoot due to the input filter, as observed during this study. During an atrial threshold test a dynamic response is observed in each test cycle of four beats with a reduced pacing pulse duration, similar to the example displayed in Fig. 9. During the first beat following reduction of the pacing pulse duration a large PPA is present, resulting in a relatively large negative undershoot, which is erroneously detected by the capture detection system as an evoked response. During the remaining three beats of each test cycle the pace polarization artefact is reduced but the negative evoked response is too small to be detected. During the CADET study this effect was not observed in the ventricle due to the larger amplitude of ventricular evoked responses.
These findings prompt development of a capture detection system applying first order input filtering and accounting for the dynamic response following a change in the pacing pulse parameters.

Conclusions

In order to develop reliable automatic capture detection the complex behaviour of the electrode—tissue interface, resulting in the development of the polarization voltage after a pacing pulse, should be fully understood. Three aspects related to the detection of evoked responses following a stimulus need to be considered:

- **Electrode design** aimed at lower polarization effects can play an important role in reducing the artefacts that arise during the process of evoked response detection.

- A **fast recharge** of the output capacitor is imperative in the reduction of the amplitude of the PPA. Adjustment of this fast recharge to the individual situation of a patient is required in order to assure reliable detection of evoked responses in all situations.

- The **filter characteristics** of currently applied second order band-pass filters in the input circuit of the pacemaker may distort the polarization voltage to such an extent that the polarization signal is falsely interpreted as an evoked response. Therefore, these characteristics should be adapted and a change in first order filters will have to be considered.

References


