Atrial Near-Field and Ventricular Far-Field Analysis by Automated Signal Processing at Rest and During Exercise

Frank Eberhardt, M.D.,* Hendrik Bonnemeier, M.D.,* Martin Lipphardt, M.Sc.,† Ulrich G. Hofmann, Ph.D.,† Heribert Schunkert, M.D.,* and Uwe K. H. Wiegand, M.D.*

*From the *University Hospital Schleswig Holstein, Campus Luebeck, Medicine II, Luebeck, Germany and †Institute for Signal Processing, University of Luebeck, Luebeck, Germany*

Introduction: Sophisticated monitoring of atrial activity is a prerequisite for modern pacemaker therapy. Ideally, near-fields and ventricular far-fields ought to be distinguished by beat-to-beat template analysis of the atrial signal. A prerequisite is that atrial signals are stable under different conditions.

Methods and Results: A Matlab routine was developed to analyze atrial electrograms of 23 patients at least 3 months after implantation of a dual chamber pacemaker under several conditions including at rest, bipolar at rest, in an upright position, during treadmill exercise, and postexercise. A near-field and far-field template was created and amplitudes, widths, and slew rates were measured. In bipolar configuration, near-field amplitude at rest was 3.04 ± 0.94 mV (unipolar)/3.36 ± 1.0 mV (bipolar) versus 3.18 ± 1.0 mV (bipolar) at peak exercise. Far-field amplitude at rest was 1.66 ± 1.18 (unipolar)/0.47 ± 0.27 mV (bipolar) and 0.41 ± 0.21 mV (bipolar) at peak exercise (n.s. for bipolar measurements). No overall significant changes were observed for near- and far-field widths and slew rates during exercise. Shorter tip-ring distances of the atrial bipole, lead position, and the presence of sinus node disease did not have any impact on overall near- and far-field signal characteristics. Intraindividual differences between rest and peak exercise were moderate (range: near-field +0.15 to −0.54 mV; range: far-field +0.05 to −0.18 mV).

Conclusions: Atrial near and far fields can be automatically classified and quantified by automated signal processing. Signals did not change during exercise or change of posture. This is a prerequisite for the implementation of beat-to-beat template analysis into pacemakers.

A.N.E. 2006;11(2):118–126

P wave; ventricular far-field; signal processing; atrial leads; morphology analysis; dual-chamber pacemaker

Effective monitoring of atrial activity is a prerequisite for modern pacemaker therapy, in particular for detection and treatment of atrial tachyarrhythmias. The atrial electrogram (EGM) reflects the atrial depolarization itself (near-field signal), the ventricular depolarization (far-field signal), myopotentials, and electromagnetic interference. Bipolar atrial sensing has been shown to reduce the incidence of ventricular far-field sensing.[1–3] The atrial sensing performance, i.e., the discrimination between atrial near- and far-field signals is also influenced by electrode surface and material, interelectrode distance of the atrial bipole, electrode position in the atrium as well as exercise and posture.[2] Previous studies have suggested a better near-field to far-field discrimination with smaller tip-to-ring distances of the atrial bipole[2,4,5] and lateral electrode positions, although conflicting study data exist regarding electrode position.[1–3,4,6] Several investigators have also reported a decrease of atrial signal amplitude during exercise.[7–9] This, however, is not confirmed by more recent data.[10] Moreover, lower signal amplitudes and prolongation of the atrial activation have been reported in sinus node disease.[11,12] The incidence of ventricular far-field sensing can be reduced by programming long blanking intervals and higher thresholds for atrial sensitivity. However, this might be counterproduc-

Address for reprints: Frank Eberhardt, M.D., Universitätsklinik Schleswig Holstein, Campus Luebeck, Medizinische Klinik II, Ratzeburger Allee 160, 23538 Lübeck, Germany. Fax: +49-451-500-4951; E-mail: eberhard@uni-luebeck.de

tive if close monitoring of atrial activity is needed, e.g., for effective mode-switching and atrial therapy algorithms. Ideally, the problem of ventricular far-field sensing would be solved by beat-to-beat template analysis of the atrial signal with minimal blanking times. A prerequisite for this kind of technique is that atrial sensing is stable under different conditions. The aim of this study was to investigate the influence of several variables on the atrial near-field and ventricular far-field signals by automated signal processing. The majority of previous studies have used rhythms strips from programmer printouts to analyze atrial signals. Far-field quantification was performed by counting the number of marker events in the atrial channel corresponding to ventricular far-fields at a given sensitivity setting. Automated signal processing provides analysis of atrial signals independent of sensitivity settings and without investigator bias.

METHODS

Patient Characteristics and Pacing Systems

Atrial EGMs of 23 patients were recorded at least 3 months after implantation of a DR 353 dual chamber pacemaker (Medtronic Inc., Minneapolis, USA). A single pacemaker device type was chosen to exclude the influence of different sense amplifiers and filters on the study result. Measurements were performed 7 ± 3 months (range 3–14) after implantation of the device and pacing leads. Patient age was 66 ± 10 years, 79% of patients were male. Ten patients had sinus node or binodal disease; the remaining 13 patients had intermittent AV-nodal disease. The implanted atrial leads were either Medtronic 5068 (n = 16), an active-fixation lead with a 17.8-mm tip-ring spacing or Medtronic 6940 with a 9.0-mm tip-ring spacing (n = 7). Atrial leads were placed in the right atrial appendage (n = 11) or the lateral right atrium (n = 12) according to operator preference. Two out of 23 had the lead with the shorter tip-ring spacing (Medtronic 6940) implanted laterally while the remaining 5 out of 23 patients had the 6940 lead implanted in the right atrial appendage. All patients had bipolar tined ventricular leads. Pacemakers were programmed to DDD or DDI 30/min with a wide AV-interval (to a maximum of 300 ms) to allow for spontaneous AV-conduction. Atrial sensitivity was programmed to 0.5 mV. Atrial sensing and pacing thresholds and impedances were measured at rest via the 9370 programmer. A rhythm strip with marker channels was recorded for 2 minutes. Subsequently, atrial EGMs were recorded using automated signal analysis, unipolar at rest as well as bipolar at rest supine, upright, during treadmill-exercise using the CAEP-protocol, and postexercise. The workload during exercise was increased every 2 minutes until the age-related maximum workload was reached.

Signal Analysis

Atrial signals were sampled at 256 Hz with an 8-bit resolution by the DR 353 pacemaker. Effectively, signals are registered in a 1- to 100-Hz frequency band. The signals are processed by the pacemaker filters and sense amplifier and transferred as digital signals using the programming head of the Medtronic 9370 programmer. As the programmer features only an analogue interface, signals had to be transferred to an A/D converter card using a standard cable and sampled at a 1-kHz sampling rate with the Labview software (National Instruments Corp, Austin, TX, USA). Signal analysis was performed using Matlab software (The Mathworks Inc., Natick, MA, USA). Signals were analyzed at different stages (supine, upright, different stages of exercise, and postexercise) as follows: The signals S at each stage have a length T between 120.000 and 180.000 data points $S = (s_1, \ldots, s_T)$. Near-fields and far-fields have to be set apart from the noise level. In most cases, near-field signals have positive and negative deflections and might pass through the noise level once or twice; however, a near-field signal must still be classified as one signal by automatic signal analysis. The noise level is determined by the following formula:

$$\text{Noise} = \sqrt{\frac{s_1^2 + \cdots + s_T^2}{T}}$$

Next, we find all s with $|s_i| \geq$ threshold, i.e., we define all positions i where the total value of the examined signal is higher than the rounded noise level. Rounding the noise is possible as the values of the signal are integer values. Then a new vector $\hat{S}$ is created which has the same length as the signal S. At those positions where the original signal S is above the threshold, a value of 1 is entered in the vector $\hat{S}$.

$$\hat{S} = (\hat{s}_1, \ldots, \hat{s}_T) \text{ with } \hat{s}_i = \begin{cases} 1 & \text{for } s_i > \text{threshold} \\ 0 & \text{else} \end{cases}$$

The regions where the near field or the far field could be located are not yet completely covered by the vector $\hat{S}$ because signals can disappear in the noise. Within the vector $\hat{S}$, we found a succession of zeros with different lengths that can be divided into four groups. We used this feature for a simple classification. Short zero sequences occur, when the near-field or the far-field signal disappears into in the noise level for a few data points. Medium short zero sequences denote the delay between a near-field and a far-field signals. Medium long zero sequences represent the delay between a far-field and a near-field signals whereas long zero sequences occur between two near fields in the absence of a far field. Those positions within the vector $\hat{S}$ where short zero sequences are found are set on 1. A histogram can be created which represents the frequency of every sequence of zeros within the vector $\hat{S}$. This categorization allows attributing any individual signal point to a near-field or a far-field and to quantify near- and far-field amplitude, width, and slew rate. A spike template was created by displaying the average of all detected depolarizations aligned to their maximum amplitude (Fig. 1). As atrial signals were mono-, bi-, or in rare instances triphasic, amplitudes are given as peak-to-peak amplitudes. Slew rates were calculated as the tangent to the signal at the point of maximum deflection (either positive or negative).

Statistical Analysis

Statistical analysis was performed with SPSS for Windows Version 10.0.1. Data are expressed by mean ± standard deviation. Normal distribution of variables was tested. Normally distributed variables were compared using student's *t*-test. Not normally distributed variables were compared using the Wilcoxon test. A P value less than 0.05 was considered significant.

RESULTS

Atrial signals were reliably classified as near- and far-field signals by automated signal processing. A template of the near- and far-fields can be displayed under different conditions. The morphology of atrial near fields can be mono-, bi-, or in rare cases triphasic, whereas the morphology of the ventricular far field is essentially monophasic. All ventricular far-fields could be attributed to far-field R wave sensing. Comparison of near-field templates under different conditions shows that the morphology does not change during change of posture or exercise (Fig. 1). Signals are subsequently described in terms of signal amplitude, width, and slew rate.

Unipolar Measurements

Sensing threshold measured via the 9370 programmer was 4.87 ± 2.01 mV for unipolar configu-

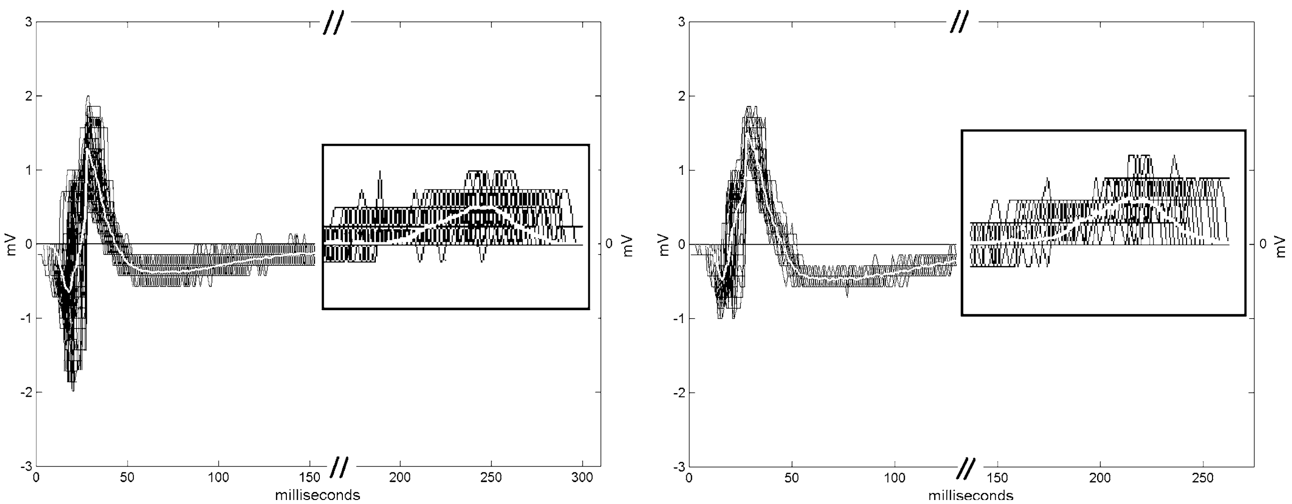

Figure 1. Example of an atrial near-field and ventricular far-field template (square box) at rest (left panel) and during maximum exercise (right panel). The far-field has been magnified by the factor two for clarity. All detected depolarization events classified as near-fields are displayed aligned to their maximum amplitude. The white line represents the template of all depolarizations. The ventricular far field in this case occurs 270 ms after the beginning of the atrial near-field deflection.

ration and 4.72 ± 2.17 mV for bipolar configuration (P = 0.80); atrial pacing threshold was unipolar 0.74 ± 0.29 V at 0.5 ms versus bipolar 0.92 ± 0.42 (P = 0.08); atrial lead impedance was unipolar 486 ± 115 Ohm versus bipolar 627 ± 121 Ohm (P = 0.001). Amplitude and width of the near field measured by signal analysis are not different between unipolar and bipolar configurations (Table 1). Bipolar sensing configuration yielded a "sharper" near-field signal as corroborated by the higher near-field slew rate during bipolar sensing. As far-field signals in the bipolar mode tended to be more blunted, significant differences could be observed for amplitude and width of the far-field.

Bipolar Measurements

Amplitudes (in mV), width (in ms), and slew rates (in V/ms) of the atrial near and far-fields are shown in Figure 2. A change of position from a supine to upright did not effect any significant changes in the parameters measured. Of the 23 patients investigated, 21 reached at least exercise level four. Two patients had to abort exercise at level three due to physical exertion. Exercise did not have any significant impact on the measured near- and far-field amplitudes, width, and slew rates, although a tendency toward lower values during exercise can be observed. Postexercise values were not significantly different from the previously measured values (Fig. 2). The individual variability of measured near- and far-field amplitudes are shown in Figure 3. The change of near-field amplitude during exercise is quite variable between individuals (Fig. 3) if values measured at rest are compared to values at peak exercise (range: −0.54 to +0.15 mV; −19.42% to +3.9%), although the mean decrease in amplitude is quite small (−0.18 ± 0.18 mV; −5.6%). The same applies to the change in individual far-field amplitudes at rest and during peak exercise (range: −0.32 to 0.05 mV; −33.9% to 12.1%; mean change −0.05 ± 0.09 mV; −8.8%). The amplitude ratio between near and far fields (Fig. 4) ranges from 2.5 to 24.0; mean 9.0 ± 5.4; and did not change significantly at peak exercise (range: 2.9–26.8; mean: 9.3 ± 6.0). The time interval between the peak amplitude of the near and the far fields did not change significantly from rest (260 ± 52 ms; range: 178–379 ms) to peak exercise (264 ± 59 ms; range 189–402 ms). This time interval comprises AV-conduction time and the interval between ventricular activation and the peak amplitude of the far-field signal. Notably, both increases and decreases of the time interval were observed, most likely because a mixed collective of patients with AV-nodal disease and sinus node disease was examined.

Influence of Tip-Ring Spacing

Measured amplitudes of near- and far-fields were not different for leads with shorter tip-ring spacing (Medtronic 6940) compared to leads with wider tip-ring spacing (Medtronic 5068) and did not change significantly during exercise (Fig. 5). Width of the near-field was 29 ± 6 ms for the Medtronic 6940 lead and 32 ± 7 ms for the Medtronic 5068 lead. Slew rate of the near field was 776 ± 167 V/ms at rest for the 6940 lead and 840 ± 186 V/ms for the 5068 lead. Both values did not change during exercise. Far-field widths and slew rates were not influenced by tip-ring spacing and did not change during exercise.

Influence of Lead Position

Atrial near- and far-field amplitudes in relation to atrial lead position are shown in Figure 6. The width of the near-field was 33 ± 7 ms for a lateral lead position and 32 ± 9 ms for a position in the right atrial appendage at rest. Slew rate was 800 ± 95 V/s for a lateral position and 809 ± 81 V/s for a position in the right atrial appendage. Both width

Table 1. Atrial Signals Measured by Automated Signal Processing at Rest

	Unipolar	Bipolar	P Value
Near-field amplitude (mV)	3.04 ± 0.94	3.36 ± 1.0	0.191
Far-field amplitude (mV)	1.66 ± 1.18	0.47 ± 0.27	0.001
Near-field width (ms)	31.9 ± 7.8	32.2 ± 6.61	1.00
Far-field width (ms)	54.3 ± 23.7	13.9 ± 11.1	0.061
Near-field slew rate (V/ms)	679 ± 246	833 ± 313	0.03
Far-field slew rate(V/ms)	177 ± 63	137 ± 54	0.04

Values are given as mean ± SD.

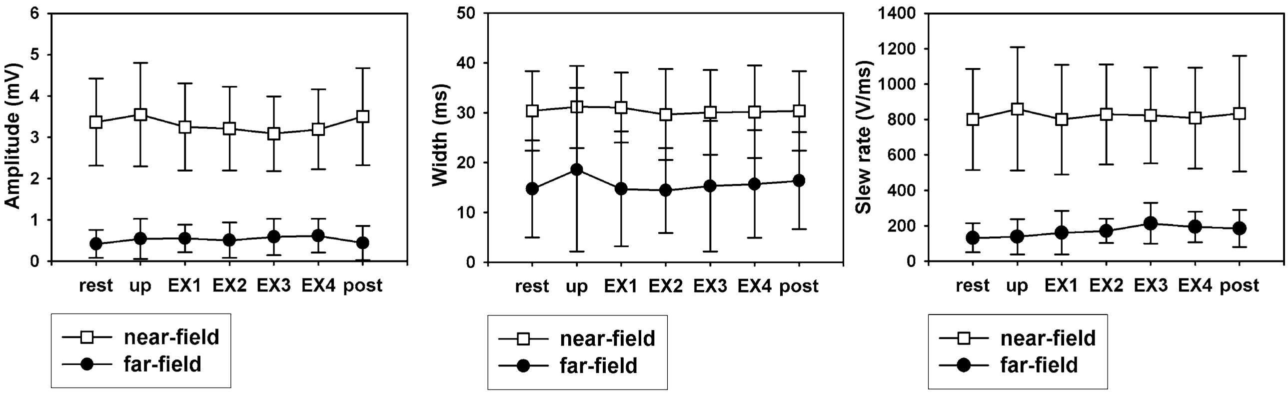

Figure 2. Amplitude (left panel), width (middle panel), and slew rate (right panel) of the near- and far-fields supine at rest, upright (up), during increasing exercise levels (EX1–EX4), and postexercise.

and slew rate of the near-field did not change significantly during exercise. Similarly, there was no difference in far-field width and slew rate in relation to lead position and no change during exercise. During higher levels of exercise, the near-field amplitude decreased with a lead position in the right atrial appendage (Fig. 6). Thus, a tendency toward a better near-field to far-field ratio can be seen for a lateral lead position ($P = 0.14$) at maximum exercise.

Influence of Sinus Node Disease

The presence of sinus node disease did not have any effect on the measured near- and far-field amplitudes (Fig. 7). The width of the near field did not change in patients with sinus node disease (31 $\pm$ 5 ms at rest, 32 $\pm$ 6 ms at maximum exercise, and 32 $\pm$ 5 ms postexercise) and was not significantly different from patients with AV nodal disease (30 $\pm$ 8 ms at rest, 30 $\pm$ 8 ms at maximum exercise, and 31 $\pm$ 7 ms postexercise). The slew rate of the atrial near field did not change during exercise in patients with sinus-node disease (836 $\pm$ 156 V/ms at rest, 790 $\pm$ 144 V/ms at maximum exercise 920 $\pm$ 181 V/ms postexercise). Again, there was no significant difference to the patients with AV-nodal disease (770 $\pm$ 171 V/ms at rest, 780 $\pm$ 156 V/ms at maximum exercise 790 $\pm$ 180 V/ms postexercise). The width and slew rate of the far-field signal did not change significantly during exercise and was not influenced by the presence of sinus node disease.

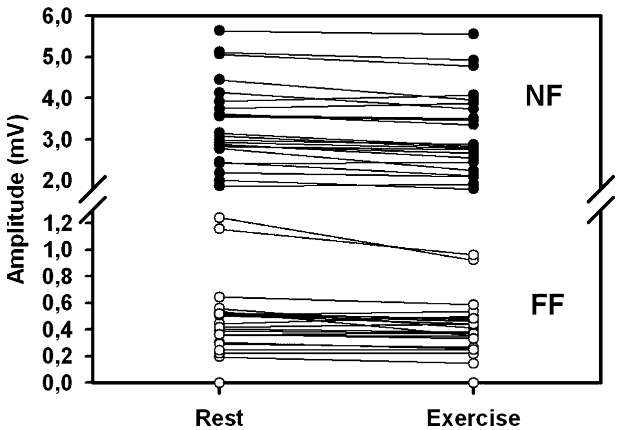

Figure 3. Individual variability of near-field (NF). Top half (black circles), and far-field (FF); bottom half (white circles), amplitude at rest, and during peak exercise.

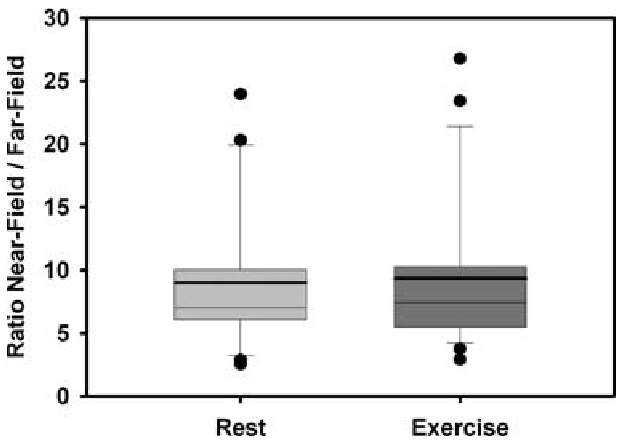

Figure 4. Box plot showing the ratio between near- and far-field amplitudes at rest (left) and during peak exercise (right). Values are represented as median (thick line), mean (thin line), 25th and 75th percentiles (lower and upper boundary of box), 10th and 90th percentiles (error bars) and outlying values (dots).

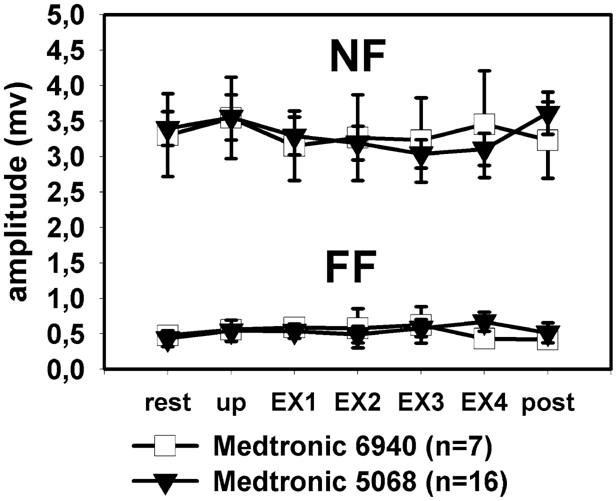

Figure 5. Amplitude of near-field (NF) and far-field (FF) with different tip-to-ring distance supine at rest, upright (up), during increasing exercise levels (EX1–EX4), and postexercise

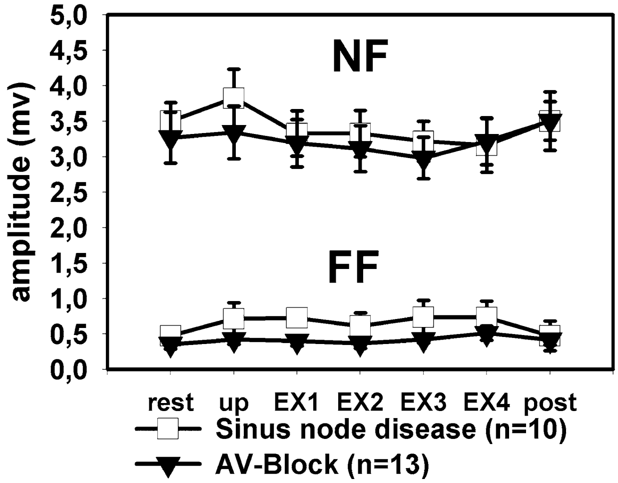

Figure 7. Amplitude of near-field (NF) and far-field (FF) in patients with sinus node or binodal disease in comparison with patients with AV-nodal disease supine at rest, upright (up), during increasing exercise levels (EX1–EX4), and postexercise

DISCUSSION

Theres et al. showed the feasibility of a real-time algorithm to distinguish P waves from far-field R waves tested during the implantation procedure.[13] However, a prerequisite for any real-time morphology analysis is a stable signal under different conditions. Our study shows for the first time by means of automated signal processing that the atrial signal morphology does not significantly change during exercise or change of posture.

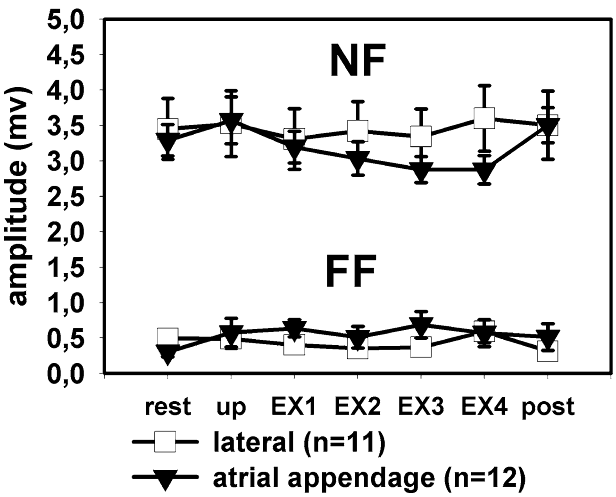

Figure 6. Amplitude of near-field (NF) and far-field (FF) with different lead positions supine at rest, upright (up), during increasing exercise levels (EX1–EX4), and postexercise

Unipolar Versus Bipolar Measurements

We could not find any significant difference in amplitudes and width of the atrial near field between unipolar and bipolar configuration. In unipolar configuration, we found ventricular far-field amplitudes of up to 3.0 mV. The incidence of far-field sensing was almost 100%. Although the incidence of far-field sensing in bipolar configuration was not considerably lower (89%), we found that amplitude and width of ventricular far fields was significantly lower in bipolar configuration. This coincides with previous studies which showed a high incidence of ventricular far-fields sensing at high sensitivity settings of 0.1 mV.[14] In our case, the incidence of ventricular far-field sensing was not determined by the maximum sensitivity setting of the pacemaker but the noise level of the system. Our study supports previous findings that a bipolar configuration is superior in rejecting ventricular far fields depending on the programmed sensitivity.[1,3,10,14]

Bipolar Measurements During Exercise

A sufficient difference in amplitude between near and far fields under different levels of exercise can be observed in bipolar configuration during sinus rhythm. Contrary to previous investigations, the amplitudes of the atrial near field did not change significantly during exercise or change of posture,[7–9] although a tendency toward lower amplitudes was observed in our study. However, there is a certain amount of individual variability that has to be taken into account. A possible explanation is that more modern lead-designs (bipolar active-fixation and relatively narrow tip-to-ring distances) were used in this study. Our finding is supported by a recent study.[10] Moreover, we used atrial signals which were analyzed by automated signal processing. By creating templates of individual signal points, a more accurate analysis without investigator bias is achieved. We could also prove that other characteristics such as signal width and slew rate of both the atrial near and far field do not change during exercise, which results in almost identical intraindividual templates. Although we did not measure the frequency content of the atrial signals, an estimate may be given through the amplitudes and slew rates of the signal. As these did not change during exercise, a change in the frequency content during exercise as previously reported seems unlikely.[15] As opposed to the digital signals with a limited temporal resolution (8 bit) which were used in our study, Fröhlig et al. investigated pacemakers that had analogue output signals in their study.[15] Although signal transformation of the digital signals used in our study is theoretically possible, the limited temporal and spatial resolution of our signal does not yield adequate results. A higher resolution of digital signals can be expected with the new generation of so-called "digital" pacemakers with a sampling rate of up to 800 Hz. Signal transformation of these high-resolution signals might be a feasible option to distinguish near and far fields. However, even on the basis of amplitude, width, and slew rate criteria, beat-to-beat template analysis of the atrial signal to discriminate near- and far-fields during sinus rhythm is a feasible option. As we observed far-field amplitudes up to 1.0 mV, discrimination between far and near fields on the basis of atrial amplitude is probably inadequate during atrial fibrillation/flutter. Previous studies reported that atrial fibrillation amplitudes are correlated to sinus rhythm amplitudes and that the minimal amplitude of atrial fibrillation amplitudes are about 30% of sinus rhythm amplitudes with a considerable intraindividual variation.[16] The ratio of near-field to far-field can be quite variable between patients as corroborated by our data. Feasibility of beat-to beat template analysis to discriminate near and far fields during atrial fibrillation remains a question for further studies.

Influence of Tip-Ring Spacing

A reduction of the tip-to-ring distance of bipolar atrial leads has been shown to improve the discrimination of the atrial signal.[2,4,5] However, previous studies have not investigated leads with a tip-ring spacing of the atrial bipole less than 10 mm. Although the number of patients investigated in our study is small, it seems that a further reduction of tip-to-ring spacing does not yield a significantly improved signal ratio between the atrial and the far-field signal. This is also supported by more recent data in an analysis of 365 pacemaker patients which showed a definite, but rather limited effect of reduced tip-ring spacing on ventricular far fields.[5] If a further reduction of tip-ring spacing is sought, a possible solution might be the use of a recessed anodal ring to exclude interference between two very narrowly spaced bipoles. Using a recessed anodal ring, tip-to-ring distances of 4 mm can be achieved, which yield significantly lower ventricular far-field amplitudes than a lead with 9 mm tip-ring spacing in an animal model.[17]

Influence of Lead Position

A lateral lead position in the atrium has been shown to provide better atrial signal discrimination between the near-fields and the ventricular far-fields,[4,6] although the results of previous studies are not unequivocal regarding this issue.[1,2] We could not show a significant difference between the two lead positions; however, near-field to far-field ratio tended to be worse with a lead position in the atrial appendage. The effect of alternative atrial stimulation sites on ventricular far-field sensing has still to be investigated. It is likely that stimulation sites at the lower atrial septum will lead to larger ventricular far-field potentials.[1]

Influence of Sinus Node Disease

Lower intraatrial P wave amplitudes have been reported in the presence of higher age and sinus node disease.[3,10,18] This has been explained by degenerative changes in the atrial myocardium. Moreover, prolongation of the atrial activation has been shown during pacing in signal-averaged electrocardiograms of the P wave.[12] If prolongation of atrial depolarization occurs during exercise using atrial EGMs is not known. In our study, we could not observe any effect of sinus node disease on the atrial EGM at rest or during exercise.

Limitations

We showed that both the atrial near field and the ventricular far field remain stable under different conditions. We are aware that the investigation was done in a very limited number of patients. We did not compare the effect of paced R waves and spontaneous R waves on the atrial far field. As we chose a vigorous exercise protocol, a repeat measurement with a short AV-interval and continuous ventricular pacing was not possible. However, ventricular pacing is detected earlier and can be easily blanked. Certain variables such as the effect of shorter tip-ring spacing or lead position in the atrium on near-field/far-field discrimination might only become significant in a larger number of patients. A possible bias of our study which might underestimate the effect of shorter tip-ring spacings on the reduction of ventricular far-fields might derive from the fact that the majority of the Medtronic 6940 leads with shorter tip-ring spacing were implanted in the atrial appendage. As a vigorous exercise protocol was part of the study, only a limited number of patients could be selected with a possible selection bias. Other factors that influence atrial signal discrimination such as the difference between active- and passive-fixation leads or coating of leads were not addressed by our study. It must be stressed again that the resolution of the individual signal was limited to 8 bit at a 256-Hz sampling rate in our study. The algorithm used in our study analyzes atrial signals retrospectively, i.e., the signal is averaged over a certain amount of time and allows the attribution of individual signal points to either near-field or far-field. It does not provide a beat-to-beat template analysis of the atrial signal, although we could envisage this algorithm to be part of a "learning" algorithm to characterize near fields and far fields in individual patients which could then be used in a beat-to-beat template algorithm. The presence of atrial arrhythmias would also influence the accuracy of the algorithm. As the patients in our study were in stable sinus rhythm throughout the investigation, the signal processing routine was not influenced by this factor.

CONCLUSIONS

A distinction between atrial near-fields and ventricular far-fields on the basis of beat-to-beat template analysis during sinus rhythm seems to be possible. A prerequisite is a stable signal of both near- and far-fields under different conditions as shown in our study. The presence of atrial arrhythmias might be a more difficult problem, although the detection of atrial fibrillation might be possible by a negative template match, i.e., the loss of the stable atrial near-field template. The feasibility of such algorithms, particularly in the light of the new generation of "digital" pacemakers, needs further investigations.

REFERENCES

1. Brouwer J, Nagelkerke D, Heijer P, et al. Analysis of atrial sensed far-field ventricular signals: A reassessment. Pacing Clin Electrophysiol 1997;20:916–922.
2. Fröhlig G, Helwani Z, Kusch O, et al. Bipolar ventricular far-field signals in the atrium. Pacing Clin Electrophysiol 1999;22:1604–1613.
3. Wiegand UK, Bode F, Peters W, et al. Efficacy and safety of bipolar sensing with high atrial sensitivity in dual chamber pacemakers. Pacing Clin Electrophysiol 2000;23:427–433.
4. Adler SW, Brown ML, Nelson LK. Interelectrode spacing and right atrial location, both influence far-field ventricular electrogram amplitude. (Abstract) Pacing Clin Electrophysiol 1999;22:877.
5. Molon G, Santini M, Botto G, et al. Analysis of far field R wave oversensing in a dual chamber pacemaker for atrial arrhythmia management. (Abstract) Europace 2004;6(Suppl.1):89.
6. Okreglicki A, Kim CH, Akiyama T. Atrial lead position: The effect of measured farfield ventricular signals. (Abstract) Pacing Clin Electrophysiol 1999;21:876.
7. Fröhlig G, Blank W, Schwerdt H, et al. Atrial sensing performance of AV universal pacemakers during exercise. Pacing Clin Electrophysiol 1988;11:47–60.
8. Chan C, Lau C, Leung SK, et al. Comparative evaluation of bipolar atrial electrogram amplitude during everyday activities. Pacing Clin Electrophysiol 1994;17:1873–1877.
9. Ross B, Zeigler V, Zinner A, et al. The effect of exercise on the atrial electrogram voltage in young patients. Pacing Clin Electrophysiol 1991;14:2092–2097.
10. Cools F, Twembeke R, Backers J, et al. Stability of far field R wave signals in different conditions. Europace;5:175–183.
11. Brandt J, Attewell R, Fahraeus T, et al. Acute endocardial p wave amplitude and chronic pacemaker sensitivity requirements: Relation to patient age and presence of sinus node disease. Pacing Clin Electrophysiol 1990;13:417–424.
12. Keane D, Stafford P, Baker S, et al. Signal averaged electrocardiography of the sinus and paced P wave in sinus node disease. Pacing Clin Electrophysiol 1995;18:1346–1353.
13. Theres H, Sun W, Combs W, et al. P wave and far-field R wave detection in pacemaker patient atrial electrograms. Pacing Clin Electrophysiol 1997;23:434–440.
14. Brandt J, Worzewski W. Far-field QRS complex sensing: Prevalence and timing with bipolar atrial leads. Pacing Clin Electrophysiol 2000;23:315–320.

15. Fröhlig G, Schwerdt H, Schieffer H, et al. Atrial signal variations and pacemaker malfunction during exercise: A study in the time and frequency domain. J Am Coll Cardiol 1988;11:806–813.
16. Kerr CK, Mason MA. Amplitude of atrial electrical actitvity during sinus rhythm and during atrial flutter-fibrillation. Pacing Clin Electrophysiol 1985;8:348–352.
17. Whitman T, Zilinski J, Marshall MT, et al. A novel 4 french atrial lead design to improve far-field R wave rejection. (Abstract) Pacing Clin Electrophysiol 2003;26:1076.
18. Wiegand UK, Potratz J, Bode F, et al. Age dependency of sensing performance and AV synchrony in single lead VDD pacing. Pacing Clin Electrophysiol 2000;23:863–869.