ECG Database Applicable for Development and Testing of Pace Detection Algorithms

Irena Jekova[1*], Valentin Tsibulko[2], Ivo Iliev[2]

[1]*Institute of Biophysics and Biomedical Engineering*
Bulgarian Academy of Sciences
Acad. G. Bonchev Str., bl. 105, 1113 Sofia, Bulgaria
E-mail: irena@biomed.bas.bg

[2]*Department of Electronics and Electronics Technologies*
Faculty of Electronic Engineering and Technologies
Technical University – Sofia
8 Kliment Ohridski Blvd., 1000 Sofia, Bulgaria
E-mails: valentin.tsibulko@gmail.com, izi@tu-sofia.bg

[*]*Corresponding author*

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Abstract: *This paper presents an ECG database, named 'PacedECGdb' (available at http://biomed.bas.bg/bioautomation/2014/vol_18.4/files/PacedECGdb.zip), which contains different arrhythmias generated by HKP (Heidelberger Praxisklinik) simulator, combined with artificially superimposed pacing pulses that cover the wide ranges of rising edge (from <10 μs to 100 μs) and total pulse durations (from 100 μs to 2 ms) and correspond to various pacemaker modes. It involves a total number of 1404 recordings – 780 representing 'pure' ECG with pacing pulses and 624 that comprise paced ECGs corrupted by tremor. The signals are recorded with 9.81 μV/LSB amplitude resolution at 128 kHz sampling rate in order to preserve the steep raising and trailing edges of the pace pulses.*

To the best of our knowledge, 'PacedECGdb' is the first publicly available paced ECG database. It could be used for development and testing of methods for pace detection in the ECG. The existence of ECGs corrupted by tremor (the only physiological noise that could compromise the methods for pacing pulses detection) is an advantage, since such signals could be applied to define the signal-to-noise level for correct operation of the algorithm, or for improvement of the noise immunity of a method that is under development. The open access of the database makes it suitable for comparative studies including different algorithms.

Keywords: *Electrocardiogram, Pace pulses, ECG database, Pace detection algorithms.*

Introduction

The heart is a muscular organ composed by atria (left, right) and ventricles (left, right). In normal situation the contractions of these four chambers follow a regular sequence, which is managed by the cardiac electrical system including sinoatrial (SA), atrioventricular (AV) nodes and His-Purkinje system. A problem in this system could disrupt the normal heart rhythm that could lead to patient's discomfort and even to fatal end. The pacemakers are small battery-operated medical devices that compensate the failure of the natural heart's electrical system by delivering electrical impulses to the cardiac muscles in order to provide regular heart contractions and normal blood circulation.

Depending on the underlying heart disease, the pacemaker could be programmed to pace atria in case of SA node dysfunction, ventricles for patients with AV or intraventricular conduction block or both, at either regular time-intervals or 'on demand' [7]. During the last decade, electrical stimulation advanced further and ventricular resynchronization therapy for patients with drug-refractory heart failure and ventricular conduction delay was introduced [11].

The correct detection of pacing pulses is important, since they indicate the presence of a pacemaker and help to evaluate the reaction of the heart. There are different medical standards with variable requirements regarding the amplitude and width of the pace pulse that has to be captured and indicated on the screen of the device. According to ANSI/AAMI EC11 [3] the pacemaker pulses that should be obligatory detected are those with duration from 0.1 ms to 2 ms, amplitude between 2 mV and 250 mV, pacing rate up to 100 impulses per minute and rising edge duration less than 100 μs. The IEC60601-2-27 standard [4] states different requirements towards the duration (0.5 ms to 2.0 ms) and the amplitude (2 mV to 700 mV) of the pulses. However, modern pacemakers could generate smaller pacing pulse amplitudes that could fall below the requirements set in the standards and could be omitted by the algorithms for pacing pulses detection [8].

Another factor that could complicate the correct recognition of pacing pulses is the electromyographic (EMG) noise, with frequency band reported to be up to 5000 Hz [5]. Depending on the sampling rate, the EMG could overlap with the pacing pulses frequencies, thus causing some serious difficulties for their correct detection. Simple filtering is not applicable, since the pace pulses could be significantly widened after low-pass filtration.

Considering the above mentioned problems, the methods for pacing pulse detection should be designed and tested on high-resolution ECG databases [9, 10] that preserve the frequency content of the pacing pulses. Such database should contain ECGs from patients with various arrhythmias and different types of pacemakers, as well as recordings corrupted by EMG noises that could be applied for improving the noise immunity of the methods under development. The collection of ECG signals corresponding to the above criteria is a difficult task in real conditions and according to our knowledge, such database is not publicly available.

The aim of this paper is to present an ECG database, named 'PacedECGdb' (available at http://biomed.bas.bg/bioautomation/2014/vol_18.4/files/PacedECGdb.zip), which contains different arrhythmias combined with artificially superimposed pacing pulses, corresponding to various pacemaker modes. 'PacedECGdb' involves pure and noise contaminated paced ECGs which makes it suitable for development and testing of pace pulses detection methods.

Materials and methods

Hardware

The data collection was performed by ADAS1000 evaluation board [2] including two cascaded ADAS1000 chips, connected in master and slave mode. Ten electrodes, directly connected to the ADAS1000 inputs, are used for ECG signal acquisition. The evaluation board supports recording of ECG data for offline review and implements all of the features that are commonly required for a complete ECG module:

- High-resolution measurement of up to 10 ECG channels.
- Internal pace detection algorithm.
- Detection of bad electrode contact.
- Generation of Wilson Central Terminal.
- Driven right leg.
- Patient cable shield driving for suppression of the common mode interferences.

Additionally, this board provides selection between ECG acquisitions with:

- 2 kHz sampling rate, 19 bit amplitude resolution;
- 16 kHz sampling rate, 18 bit amplitude resolution;
- 128 kHz sampling rate, 16 bit amplitude resolution.

The device has the option to use an external reference voltage or the integrated high performance, low noise, on-chip 1.8 V reference voltage for the ADC and DAC circuits. It also has 4 settings for the internal amplifier:

- GAIN0 = ×1.4;
- GAIN1 = ×2.1;
- GAIN2 = ×2.8;
- GAIN3 = ×4.2.

We applied the default GAIN0, with the internal 1.8 V reference voltage for ECG signals acquisition. This configuration provides the following values for the LSB:

- 4.9 μV/LSB for 2 kHz sampling rate, 19 bit amplitude resolution;
- 9.81 μV/LSB for 16 kHz sampling rate, 18 bit amplitude resolution;
- 39.24 μV/LSB for 128 kHz sampling rate, 16 bit amplitude resolution.

SDP board based on ADSP-BF527 Blackfin processor maintains the communication between the evaluation board EVAL-ADAS1000SDZ and the PC via USB.

ECG signals

The ECG signals are recorded using the software provided with the ADAS1000 evaluation board. The ECGs are generated by HKP (Heidelberger Praxisklinik) arrhythmia simulator, which supports selection from 16 programs as follows:

- Program1 – P01: sinus rhythm (SR);
- Program2 – P02: AV rhythm;
- Program3 – P03: Atrial flutter combined with absolute arrhythmia;
- Program4 – P04: Idioventricular rhythm;
- Program5 – P05: Ventricular fibrillation;
- Program6 – P06: SR with ventricular extrasystoles (monomorphic/unifocal, compensated);
- Program7 – P07: Bigeminy;
- Program8 – P08: SR with ventricular extrasystoles (interpolated and compensated);
- Program9 – P09: 2nd degree AV-block 2:1;
- Program10 – P10: SR, heart catheter program;
- Program11 – P11: 3rd degree AV-block without replacement rhythm;
- Program12 – P12: 3rd degree AV-block with ventricular replacement rhythm;
- Program13 – P13: SR with intermittent SA-block;
- Program14 – P14: SR with bundle branch block;
- Program15 – P15: Special program for 24 hours long-term rhythm sequence;
- Program16 – P16: Special program for reanimation training.

In order to limit the database size, the following approach is accepted:

- The duration of the recorded ECG signals is limited to 10 s. Considering that the characteristics of the simulated ECG signals do not change over time, longer recordings would only increase the size of the database.

- The ECG lead II is selected for subsequent mixing with the pace pulses because for great part of the paced patients it displays the pacing pulses in the best way [1].
- Only the programs which generate either SR or arrhythmias compatible with the application of pacemakers are used. The two special programs (Program15, Program16), ventricular fibrillation (Program5), idioventricular rhythm (Program4) and bigeminy (Program7) are excluded. Program12 is selected to represent the signals with 3rd degree AV-block.
- The special option for EMG generation is applied with part of the programs to provide noisy signals. Thus, the total number of different simulated ECGs in the database becomes 18, including 10 pure and 8 noisy signals. By subsequent superimposing with pacing pulses corresponding to different pacemaker modes we focus at the design of substantial database with reasonable size.

Aiming at a compromise between amplitude and time resolution of the recorded signal we have sampled the ECG at 16 kHz, thus simultaneously keeping 9.81 μV/LSB amplitude resolution and preserving all ECG and EMG frequency components. To become suitable for combination with different pace pulses, the ECG signals are upsampled to 128 kHz using cubic interpolation.

Pacing pulses

The typical pacing pulses could be represented by:

1) Pacing phase – a positive pulse with fast rising edge, followed by slower droop and fast trailing edge. The pulse duration is defined as duration of this phase [6].
2) Recharge phase – a negative portion, required to leave the heart tissue with a net-zero charge.

We simulated thirteen different pacing pulses in Matlab, to cover the wide variety of raising edge durations in the range from less than 10 μs to 100 μs and pulse durations between 100 μs and 2 ms. The pulses were designed with five segments as follows:

1) Linear first raising edge with duration listed in Table 1:
   $DurRE1 = RE$;
2) Linear first falling edge with duration equal to:
   $DurFE1 = PD - 2RE$, where PD is Pulse Duration listed in Table 1;
3) Linear second falling edge with duration equal to:
   $DurFE2 = RE$;
4) Exponential second raising edge with duration:
   $DurRE1 = 3PD - (3RE + DurFE1)$;
5) Linear third raising edge with duration:
   $DurRE3 = min(RE)$.

Table 1 represents combinations of RE and PD as number of samples and time interval duration. The designed pacing pulses are shown in Fig. 1. All pulses are designed with positive amplitude 3 mV, which is the doubled amplitude of the normal QRS complexes generated by HKP arrhythmia simulator. The absolute amplitude of the rechargeable phase is half of the pacing phase amplitude.

Table 1. Features of the simulated pacing pulses

Pacing pulse	Rising edge duration (RE)		Pulse duration (PD)	
	No samples	Time	No samples	Time
PacePulse_01	2	7.8 μs	14	102 μs
PacePulse_02	3	15.6 μs	14	102 μs
PacePulse_03	4	23.4 μs	28	211 μs
PacePulse_04	5	31.3 μs	42	320 μs
PacePulse_05	6	39.1 μs	56	430 μs
PacePulse_06	7	46.9 μs	70	539 μs
PacePulse_07	8	54.7 μs	84	648 μs
PacePulse_08	9	62.5 μs	98	758 μs
PacePulse_09	10	70.3μs	112	867 μs
PacePulse_10	11	78.1 μs	126	977 μs
PacePulse_11	12	85.9 μs	140	1086 μs
PacePulse_12	13	93.8 μs	210	1633 μs
PacePulse_13	14	102 μs	280	2180 μs

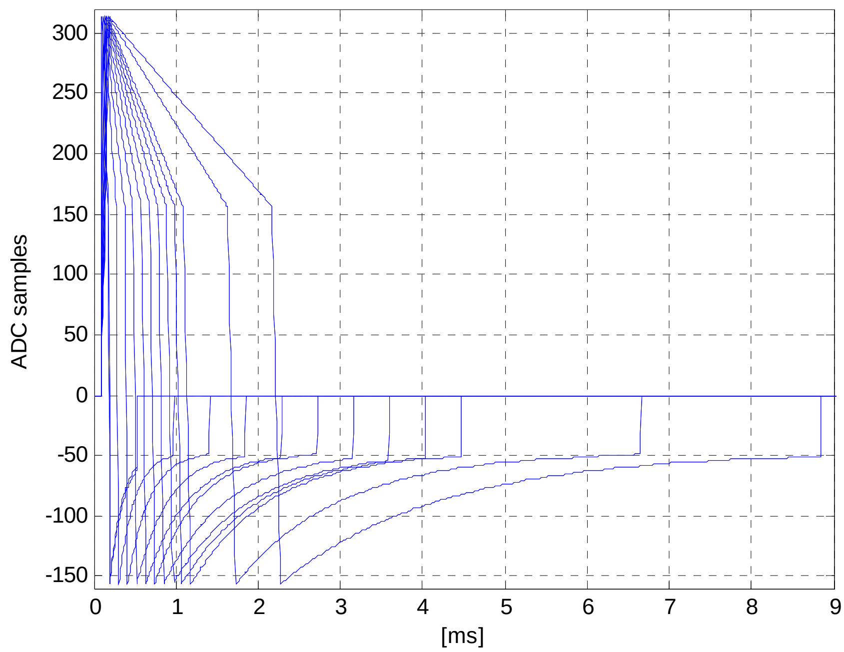

Fig. 1 Illustration of the simulated 13 pacing pulses

Paced ECG

The database with paced ECGs was designed by superimposing each one of the 13 pacing pulses over each one of the 18 ECG signals at manually annotated positions that mimic a variety of pacemaker modes, conformed to the generated arrhythmia (see Table 2). The DC offset in the ECG signals was removed by subtraction of the average signal value calculated for the full duration of 10 seconds. Six settings for the pacing pulses amplitude were used – from ~3 mV (312*LSB) down to ~100 μV (10*LSB). The obtained paced ECGs were recorded in DAT files as 16-bit integer values. The time of pacing pulses occurrence was recorded in a corresponding ANN file, named as the DAT file of the paced ECG.

Table 2. Combination between HKP arrhythmias and pacing pulses simulating different pacemaker types/modes

HKP program	Arrhythmia type	Simulated pacemaker type/mode
P01	SR	Atrial pacing on demand
P01 with tremor	SR + tremor	Fixed atrial rate pacing
P02	AV rhythm	Ventricular pacing on demand
P02 with tremor	AV rhythm + tremor	Fixed ventricular rate pacing
P03	Atrial flutter combined with absolute arrhythmia	Ventricular pacing on demand
P03 with tremor	Atrial flutter combined with absolute arrhythmia + tremor	Fixed ventricular rate pacing
P06	SR with ventricular extrasystoles	Ventricular pacing before each normal beat (following sensed atrial activity)
P06 with tremor	SR with ventricular extrasystoles + tremor	Ventricular pacing before each normal beat
P08	SR with ventricular extrasystoles	Atrial pacing before each normal beat, on demand
P09	2^{nd} degree AV-block	Fixed ventricular rate pacing (some of the pacing pulses are not effective)
P09 with tremor	2^{nd} degree AV-block + tremor	Fixed ventricular rate pacing
P10	SR	Fixed pacing before each P-wave and QRS complex
P12	3^{rd} degree AV-block with ventricular replacement rhythm	Bi-ventricular pacing
P12 with tremor	3^{rd} degree AV-block with ventricular replacement rhythm + tremor	Bi-ventricular pacing
P13	SR with intermittent SA-block	Atrial pacing on demand + bi-ventricular pacing
P13 with tremor	SR with intermittent SA-block + tremor	Bi-ventricular pacing
P14	SR with bundle branch block	Fixed pacing before each P-wave and QRS complex
P14 with tremor	SR with bundle branch block + tremor	Fixed pacing before each P-wave and QRS complex

The name of each recording represents:

- HKP simulator program – P01 to P14;
- Data format – 16-bit integer values for the entire database;
- Existence of tremor artifacts – T (optional);
- Pacing pulse number – 01 to 13;
- Coefficient for multiplication of the pacing pulse –
  Kp = 1, 0.5, 0.25, 0.125, 0.0625, 0.03125.

For example, ‘P14_16_PacePulse_07_Kp=0.125.dat’ file in the database represents ECG signal generated by the 14^{th} program of the HKP simulator, superimposed with pacing pulse No 7, which is multiplied by Kp = 0.125. The signal with the same features but corrupted by tremor is named ‘P14_16_T_PacePulse_07_Kp=0.125.dat’.

Results

The generated paced ECG database ‘PacedECGdb’ involves a total number of 1404 recordings – 780 representing ‘pure’ ECG with pacing pulses and 624 that contain paced ECG corrupted by tremor. Examples of different arrhythmias combined with different pacing pulses are presented in Figs. 2-4.

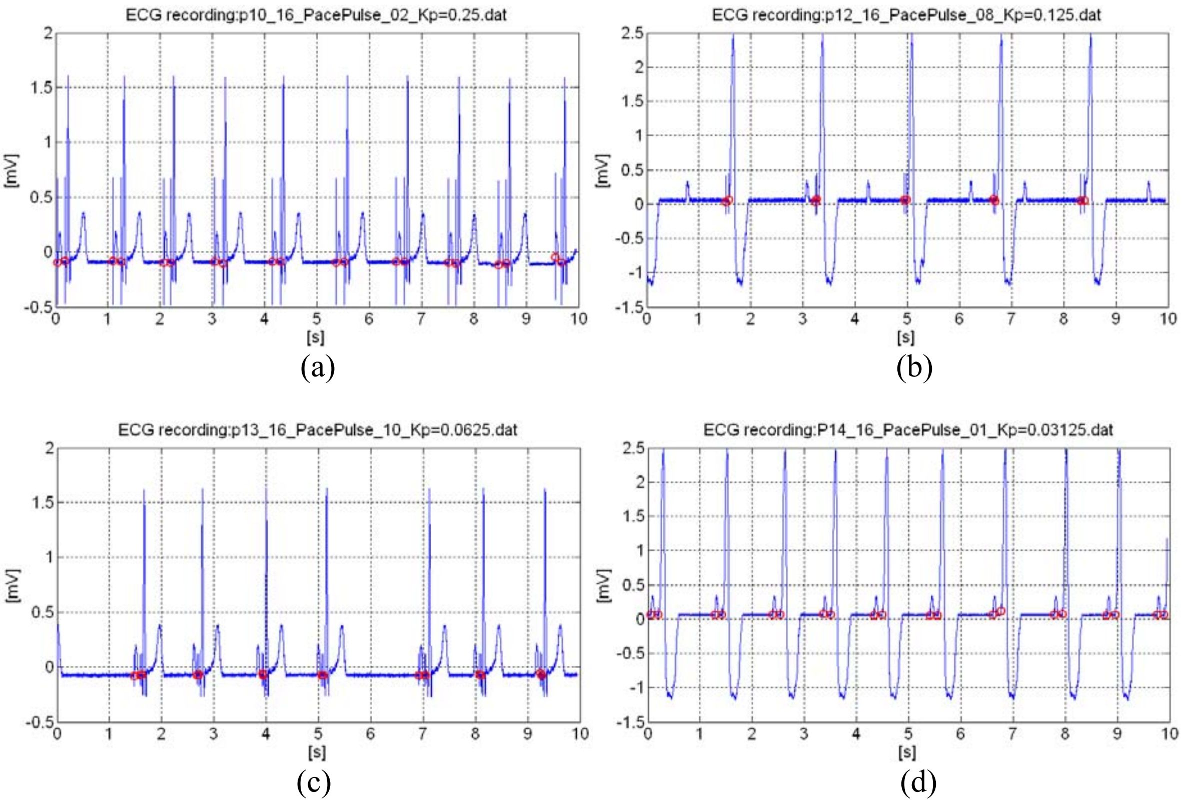

Fig. 2 Examples of simulated dual chamber and/or bi-ventricular pacing:
(a) Dual chamber, fixed-rate pacing on SR;
(b) Bi-ventricular pacing;
(c) Bi-ventricular pacing on SR with intermittent SA-block. For the prolonged RR intervals atrial pacing ‘on demand’ is imitated;
(d) Fixed-rate dual chamber pacing.
The red circles (‘o’) show the positions of the pacing pulses.

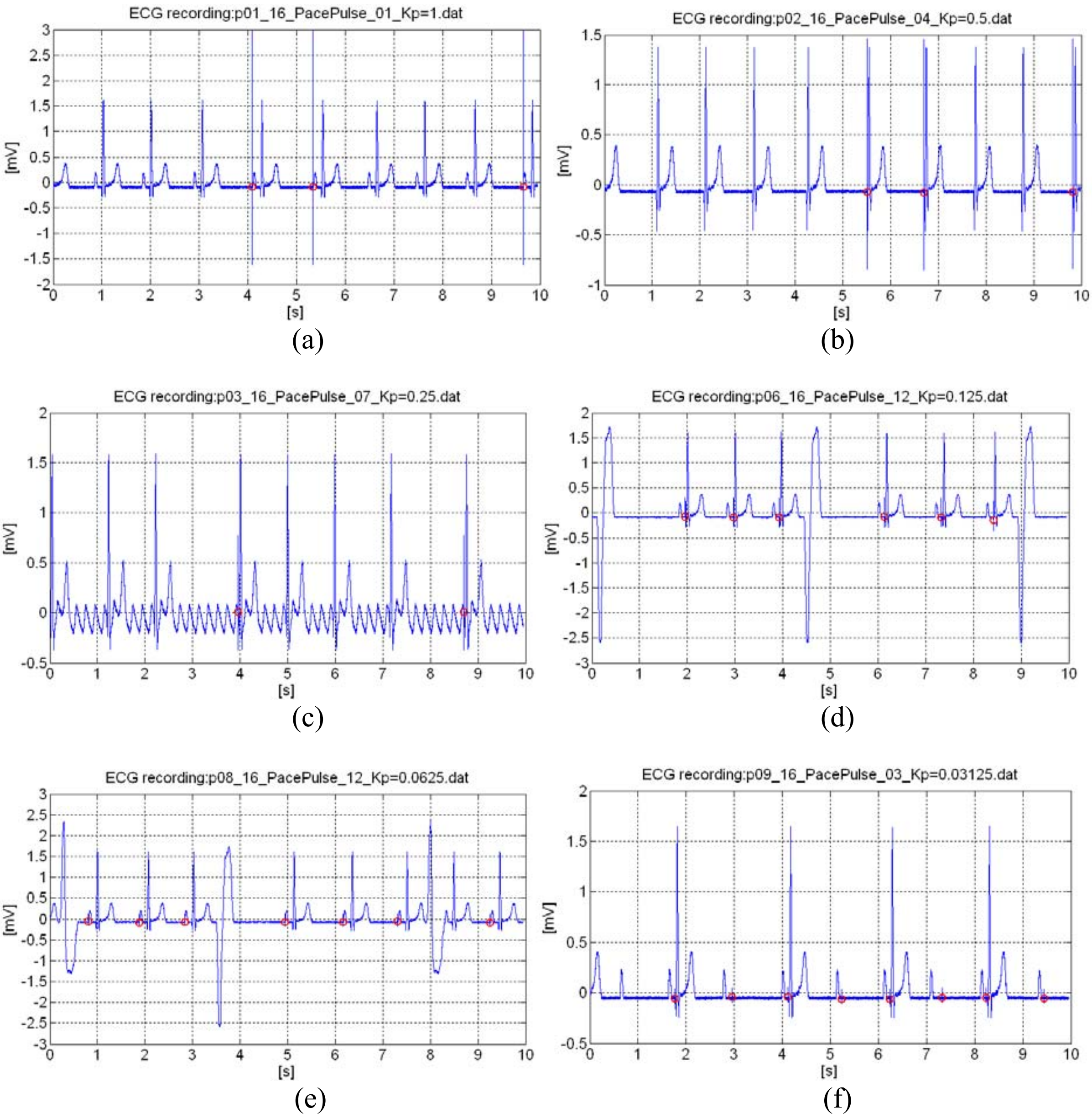

Fig. 3 Examples of simulated single chamber pacing:
Subplots (a), (b), (c) represent sinus rhythm, AV rhythm, atrial flutter respectively, with pacing pulses that simulate pacemaker type 'on demand'. The pacing pulses precede only the QRS complexes with prolonged RR interval;
(d) illustrates operation of the pacemaker in VDD mode – pacemaker paces only the ventricle, senses both atrium and ventricle, and responds by both inhibition of ventricular pace when intrinsic ventricular activity is sensed and triggering a ventricular pace in response to an intrinsic P-wave;
(e) shows atrial pacing 'on demand';
(f) demonstrates fixed-rate ventricular pacing, for which part of the pacing pulses are not effective and are not followed by ventricular contraction.
The red circles ('o') show the positions of the pacing pulses.

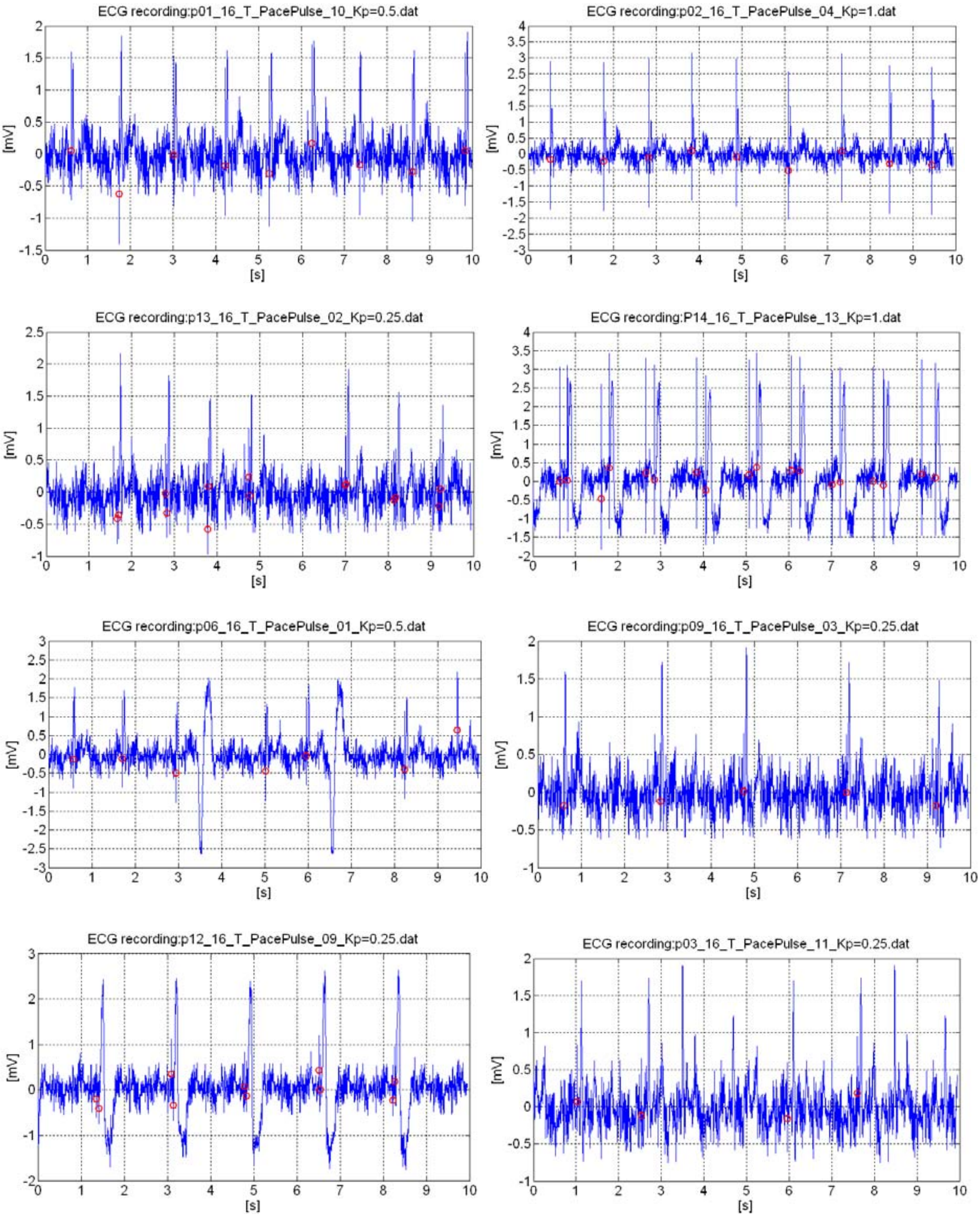

Fig. 4 Examples of paced ECGs with tremor. It is obvious that the low-amplitude pacing pulses are hardly recognizable on the EMG background.
The red circles ('o') show the positions of the pacing pulses.

Discussion

The collection of large enough database with real paced ECG recordings is a difficult task. The content of such database is determined by chance and its application for development purposes could bias the adjustments towards the recognition of pacing pulses generated by specific pacemaker type/mode. Moreover, public ECG database from paced patients is still not available and the developers of methods for pacing pulses detection use their own signals.

This paper presents an artificially generated database with paced ECG recordings. The HKP arrhythmia simulator provides a great variety of ECG rhythms which are combined with pacing pulses that cover the wide ranges of rising edge and total pulse durations. The amplitudes of the pacing pulses are conformed to the ECG, so that they vary from twice the amplitude of the normal heartbeats down to 100 μV. Although the current requirements towards the algorithms are to detect pace pulses with amplitudes between 2 mV and 250 mV [3], modern pacemakers could generate smaller pacing pulses that also should be captured for the correct analysis of the ECG.

In the designed database, the different ECG arrhythmias are combined with pacing pulses at positions that are consistent with single, dual chamber and bi-ventricular pacemaker types, as well as fixed-rate and 'on demand' pacing (see Figs. 2-4). Thus we mimic a variety of pacemaker types and modes, applying our previous experience [7] to conform them to the generated arrhythmias. The different combinations between pulse amplitude, rising edge and total pulse duration settings, as well as the different number of pacing pulses per heartbeat and the time intervals between them, provide the opportunity for adjustment of amplitude, slope and time threshold values in the designed detection methods. The recordings have the advantage to contain a lot of cases, which rarely may be encountered if the test is carried out by real signals only. An additional benefit is the existence of paced ECGs corrupted by tremor, which is the only physiological noise that could compromise the methods for pacing pulses detection. These noisy signals could be used to define the signal-to-noise level for correct operation of the algorithm, which is under testing, or for training and improvement of the noise immunity of a method that is under development.

Another advantage of the collected database is the high sampling rate of 128 kHz which gives the opportunity for precise recording even of the steepest pulses with rising edges about 10 μs. These paced ECG signals could be easily down-sampled and applied for development and testing of methods at a target sampling rate.

Limitation

Although the presented database contains variety of ECG arrhythmias combined with different pacing pulses, it is strongly recommendable the final validation of the pace detection methods to be performed on real signals from patients with pacemakers. Unfortunately, such ECG database is still not publicly available.

Conclusions

To the best of our knowledge, the described in this paper database – 'PacedECGdb' (http://biomed.bas.bg/bioautomation/2014/vol_18.4/files/PacedECGdb.zip), is the first publicly available paced ECG database. It could be used for development and testing of methods for detection of pacing pulses in the ECG. The open access of this database makes it suitable for comparative studies including different pace detection algorithms.

Acknowledgements

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Assoc. Prof. Irena Jekova, Ph.D.
E-mail: irena@biomed.bas.bg

Irena Jekova graduated Technical University – Sofia, Faculty of Electronic Engineering and Technology, specialization Electronic Medical Equipment in 1998. She has been working in the Bulgarian Academy of Sciences since 1999 – Centre of Biomedical engineering in the period 1999-2010 and Institute of Biophysics and Biomedical Engineering after 2010. She defended her Ph.D. thesis in the field of ventricular fibrillation detection in 2001. In 2007 she became Associate Professor. Her scientific interests are in the field of biomedical data and signals processing.

Valentin Tsibulko, Ph.D. Student
E-mail: valentin.tsibulko@gmail.com

Valentin Tsibulko graduated Technical University – Sofia, Faculty of Electronic Engineering and Technology, specialization Electronic Medical Equipment in 2009. He is currently working on a doctorate related to detecting pacemaker signals in ECG. He has 9 years of experience with different medical equipment – clinical laboratory, infusion systems, patient monitors. His scientific interests are in the field of biomedical signals registration and processing, ECG analysis and pacemaker detection.

Prof. Ivo Iliev, Ph.D.
E-mail: izi@tu-sofia.bg

Prof. Ivo Iliev graduated from the Technical University – Sofia, Faculty of Electronic Engineering and Technology, division of Biomedical Engineering in 1989. He is presently with the Department of Electronics of the Technical University – Sofia, working on methods and instrumentation for bio-signal registration and analysis, telemetry and wireless monitoring of high-risk patients.