ECG, QRS detector, ventricular assist device VAD, defibrillation, cardioversion

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HYBRID SYSTEM OF ECG SIGNAL ACQUISITION AND QRS COMPLEXES DETECTION FOR SPECIAL MEDICAL DEVICES SYNCHRONIZATION

Some medical devices such as mechanical circulatory support systems and defibrillators require synchronization with the appropriate phase of the cardiac cycle of the patient. This paper presents a description of the electrocardiographic (ECG) signal amplifier and QRS detector designed for use with such devices. The detector system was built using a programmable analog array AN231E04 and the ECG amplifier with an analog-digital (A/D) converter based on a programmable circuit (front-end) ADS129x. By using the programmable elements and exploiting the potential of dynamic analog matrix reconfiguration, the presented detector achieved the desired features, such as low latency of QRS detection, automatic gain control and the ability to change the time constant by software. High-resolution of the A/D converter in the ADS1298x and the possibility of programming the gain of the amplifier allow the acquisition of the ECG signal acquired from different types of electrodes: disposable standard, epicardial or endocavitary. The tests of the prototype system proved that it is highly effective for the detection of QRS complexes in ECG waveforms recorded from all kinds of electrodes.

1. INTRODUCTION

Because of multiple functions of the cardiovascular system, heart diseases are among the most serious diseases of the human body. One method of treating them is the use of a ventricular assist device (VAD)[4]. Such devices should be equipped with a module of ECG amplifier and QRS detector necessary for synchronizing them with the proper phase of the cardiac cycle. The synchronization can be based on the signals derived from epicardial or endocavitary electrodes. The amplitudes of the ECG signals recorded from epicardial electrodes are much more diverse than the ones obtained from standard disposable surface electrodes. This is a result of the biochemical processes which take place on the electrodes. These processes cause gradual decrease of contact quality between the electrodes and tissue. The effect is visible as slow lowering of the ECG signal amplitude and it makes high demands on the design of ECG measurement system.

QRS detection is the main problem in the analysis of the ECG signal. It is based on identifying the QRS complex and specifying the location of the R-wave in the electrocardiogram. Depending on their construction, the detectors can be divided into analog, digital and hybrid (analog and digital). Analog detectors are implemented in hardware, while digital detectors - in software. Analog detectors have short response time, however, they have several disadvantages like a complex structure and limited ability to adapt to changing waveform parameters. Digital detectors have a high potential to be tuned to the

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parameters of the signal, but they typically introduce a significant delay of up to fractions of a second [1][3]. In most applications, for example in heart rate measurement (eg. in cardiomonitors), such a delay does not matter. However, in the case of synchronous operation of the VAD, the time required to detect the R-wave should not exceed 40 ms, which practically eliminates classic digital detectors from this application. Therefore, the authors decided to use a programmable analog circuit FPAA in order to construct the detector of a mixed (analog-digital) structure [7][8][9]. This concept combines the ease of tuning the parameters with a small delay in the detection of the QRS complexes. Previous version of the system is descibed in [12].

2. GENERAL DESCRIPTION OF THE ECG AMPLIFIER

The ECG amplifier designed for the VAD synchronization allows the acquisition of a signal using standard disposable surface electrodes, epicardial or endocavitary electrodes and the standardized (1V/mV) analogue output ECG signal of a cardiomonitor.

In the proposed module, the authors used the latest technology available on the market in the form of an integrated circuit (Analog Front End) ADS129x manufactured by TI [6], low energy, 32-bit microcontroller series STM32L151 from ST [10], a DC/DC converter and digital barrier. The detection system uses a programmable analog array (Field Programmable Analog Array FPAA) AN231E04 from Anadigm [2]. The design meets the requirements of EN 60601 [11]. The Block diagram of the ECG amplifier and QRS detector is shown in Fig. 1.

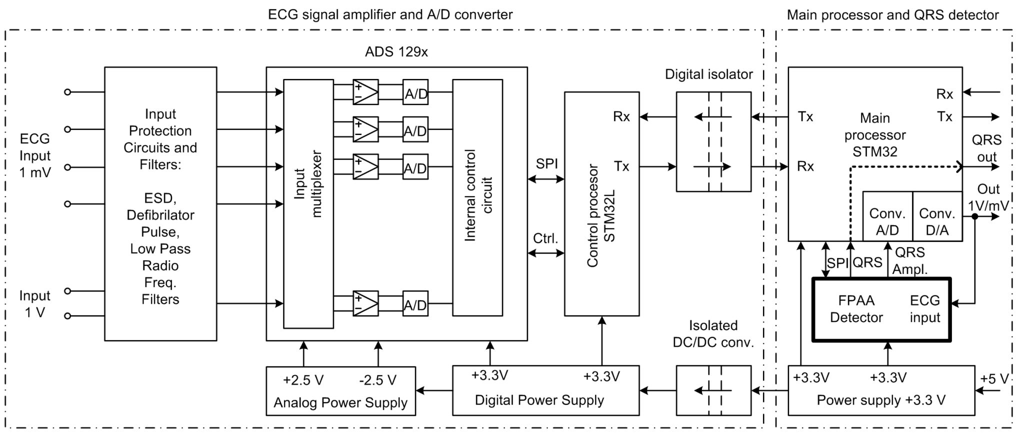

Fig. 1. The Block diagram of the ECG amplifier and QRS detector for VAD.

The ADS129x front-end includes a 4 or 8-channel differential amplifier and a sufficient number of 24-bit A/D $\Delta - \Sigma$ type converters. It also contains blocks allowing to test the performance of the amplifier and the quality of the electrode-tissue (skin) contact. The ADS129x circuit is controlled by an STM32L151 microcontroller through an isolated digital serial interface. The interface is also used for data transmission. The amplifier module is powered by an isolated DC/DC converter and a set of linear regulators. By using the ADS129x circuit it is possible to realize a new concept of the construction of a biomedical signal processing system [5]. This solution involves the use of a DC amplifier with a small programmable gain (1-12), as well as an A/D converter with high resolution, so that the amplified desired signal can be quantized with 12-16 bit resolution, as in the traditional solutions of ECG signal acquisition. The proposed application amplifies the input ECG signal with a DC component to such a level that it is not distorted by the amplifier input. Then, it quantizes the signal with a resolution of 24 bits. Afterwards, the ECG signal is pre-filtered and standardized by the control processor, and transmitted via a serial digital barrier to the main processor. The digital ECG signal is converted to an analog signal by a 12 bit digital-analog (D/A) converter built in the main processor. Next, the analog ECG signal is transmitted to the QRS detector. The use of high-performance microprocessors and programmable systems made it also possible to monitor the quality and the amplitude of the acquired ECG signal.

Consequently, it gave the possibility of an optimal choice of ECG amplifier gain required for optimum operation of the R-wave detector.

3. ANALOG DETECTOR, THE PRINCIPLE OF OPERATION

The block diagram of a typical analog detector is shown in Fig. 2 (left). The principle of detection is based on a comparison of the filtered and rectified ECG signal with the threshold voltage obtained from the peak detector. Fig. 2 (right) shows the waveforms at characteristic points of the analog detector. They were obtained by simulating a detector circuit shown in Fig. 2 (left) in the SPICE. Waveforms (A) and (D) are shifted to improve clarity. Relation (1) defines the transfer function of the bandpass filter, while equation (2) describes the change of the threshold value (point C). During the simulation the following values were assumed: $H_0 = 4$, $Q = 4$, $\omega_0 = 2\ \pi \cdot 16Hz$, $U_{offset} = 0.1V$. The time constant of the peak detector was set to $1s$. The filter parameters were matched to the spectrum of a typical QRS complex.

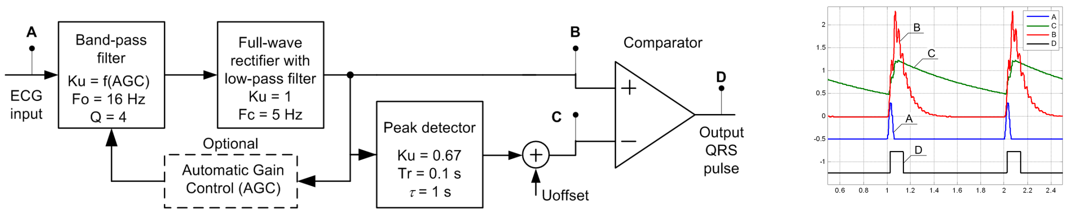

Fig. 2. The block diagram of the analog QRS detector (left) and simulation results (right).

$$H(s) = \frac{H_0 \cdot \frac{s}{Q \cdot \omega_0}}{(\frac{s}{\omega_0})^2 + \frac{s}{Q \cdot \omega_0} + 1} \tag{1}$$

$$y(t) = U_m \cdot \exp(-\frac{t}{\tau}) + U_{offset} \tag{2}$$

3.1. HARDWARE IMPLEMENTATION OF THE QRS DETECTOR IN A PROGRAMMABLE ANALOG ARRAY

The idea of the analog QRS detector presented above was implemented in a Field Programmable Analog Array (FPAA) AN231E04 manufactured by Anadigm [2]. This solution combines the advantages of analog detectors (especially low delay time) with the possibility of software controlled parameter changing. It utilizes the dynamic reconfigurability of the FPAA described in details in the subsequent section. Fig. 3 (left) presents the implementation of the detector created in AnadigmDesigner2 environment. Fig. 3 (right) presents waveforms registered in characteristic nodes of the circuit for the real ECG signal given to the input. The ECG signal (A) is provided to the input IN of the FPAA matrix. The signal is band-pass filtered (BPF block) in order to extract spectral components correspondent with QRS complexes. Additionally, a second order low-pass filter (LPF) was implemented to eliminate high frequency noise. The filtered signal is rectified by a full wave rectifier with a low-pass filter (RLF). Unipolar pulses (C) generated at its output are supplied to the peak detector (PD) with programmable decay time constant. A small DC voltage is added to the output signal of the peak detector in order to obtain better noise immunity (block SUM). QRS detection is performed in the comparator block (CMP), in which unipolar pulses (B) are compared with the exponentially falling wave at the peak detector output (C). The output signal of the comparator (waveform D) is supplied to the output cell, which is connected to the microcontroller digital input. One of the tasks of the microcontroller is standardization of the detection pulses.

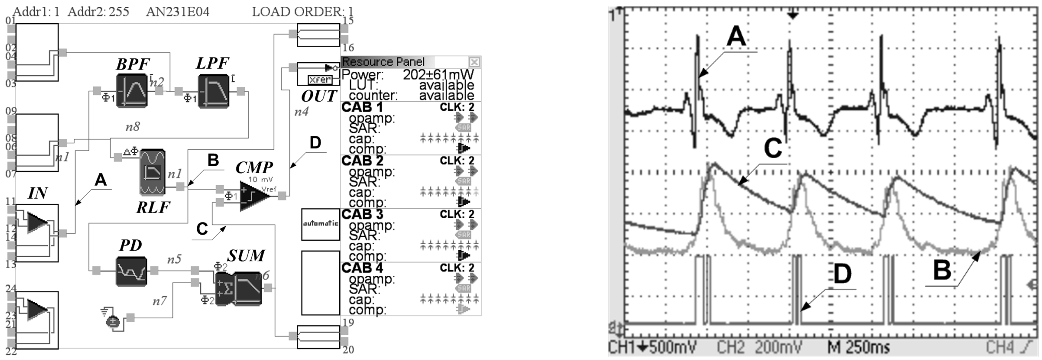

Fig. 3. The QRS detector implementation in the FPAA (left) and waveforms in the characteristic nodes (right).

3.2. APPLICATION OF DYNAMIC RECONFIGURATION

The AN231E04 circuit is a dynamically reconfigurable field programmable analog array (FPAA). It allows to change the parameters of each block or even the whole structure in runtime without any circuit reset or loss of the signal continuity. It is possible due to special memory organization, which is divided into configuration memory (CM) and shadow memory (SM). The CM controls the actual functionality of the circuit, while at the same time the SM can be loaded through the SPI interface. The new configuration can be activated in a single clock cycle after the "execute" signal. This signal can be provided externally (e.g. through the SPI interface) or generated inside the FPAA matrix, for example by a comparator.

3.2.1. AUTOMATIC GAIN CONTROL

Real ECG records used in the research work obtained from [4] show large dispersion of the signal amplitude. The ratio of the maximum and minimum amplitude in particular records is about 20 to 1. In case of such a dispersion of the signal level, the gain control has the key meaning in the QRS detection efficiency. Due to the specific nature of the ECG signal, classical Automatic Gain Control (AGC) circuits are ineffective. For the QRS detection purpose a new hybrid AGC algorithm was developed. It utilizes the dynamic reconfigurability of both the AN231E04 circuit and the ADS129x. The proposed AGC algorithm is based on the measurement of the amplitude of the unipolar pulses obtained after filtration, rectification and smoothing of the ECG signal - Fig. 3 (left), node C. The amplitude of the pulses is measured using an A/D converter implemented in the microcontroller which controls the detector function. After each successful QRS detection a new pulse amplitude is derived. The QRS amplitude can vary from the mean value, therefore the amplitude of the pulses is averaged using a simple first order digital IIR filter. The average pulses level is compared to the setpoint value to check if it belongs to the assumed interval. In the case of too low amplitude new configuration data is sent to the FPAA, which increases the gain by about 30%. The correction of the gain appears in the periods between the QRS complexes, therefore it does not cause undesired distortions or false detections. Dynamic reconfiguration of the applied circuit allows to change the gain in the range of $\langle 1\text{-}10 \rangle$, which is insufficient due to large signal level variability. Additional gain range increase was obtained using the gain configurability in the ADS129x circuit. When the gain of the FPAA circuit reaches the defined level and still has to be higher, the detector controller sends a command to the amplifier circuit to increase its gain twice. At the same time the FPAA circuit decreases its gain by about 30%. Similarly, when the amplitude is too high, the FPAA gain is gradually decreased. When the FPAA gain is minimal and the signal level is still too high, the detector circuit sends a command to the amplifier to decrease its gain twice. At the same time the FPAA gain is increased by about 30%. Thanks to combining the dynamic reconfigurability of the FPAA circuit and the gain switching possibility in the ADS129x circuit, the range of the gain regulation is $\langle 1\text{-}20 \rangle$, which is sufficient for the QRS detection purpose.

3.2.2. AUTOMATIC TIME CONSTANT CORRECTION OF THE PEAK DETECTOR

Another functionality which utilizes dynamic reconfigurability of the FPAA circuit is the time constant correction of the peak detector (Fig. 3 left, block PD). This parameter determines the detection threshold (curve C in Fig. 3 right). The optimal value of the time constant depends on the actual heart rate. The main processor measures the RR periods and, according to the average heart rate, it prepares reconfiguration data and tunes the peak detector "on the fly".

It was also checked that it is possible to change dynamically the center frequency of the band pass filter (Fig. 3 left, block BPF). As it is known from the literature [1], the typical spectrum of the QRS complex has its maximum power of about 16 Hz. However, this value can vary and is dependent on signal morphology, the type of rythm (sinus or ventricular) and individual features of the patient. Thanks to the dynamic reconfigurability, the filter characteristics can be adapted for example to the type of detected contraction or to the type of electrodes. This is the topic of future research works. The optimal solution will require close cooperation with medical specialists.

4. EXPERIMENTAL RESULTS

In order to test the operation of the detector and AGC algorithm, a special application was written in the LabView environment. Several versions of the microcontroller software were also prepared. The detector was tested using ECG signals recorded from epicardial electrodes. The records were obtained from the Foundation for Cardiac Surgery Development in Zabrze. Fig. 4 presents a block diagram illustrating the method of the detector test. The LabView application reads the signal samples from the database, sends the samples in real-time to the CPU (in the format used by the A/D module) and writes the results of the detection on a computer disk. The analysis of results was performed using MATLAB. For all ECG records the reference QRS detection was done by finding the position of the R-wave using a digital detector.

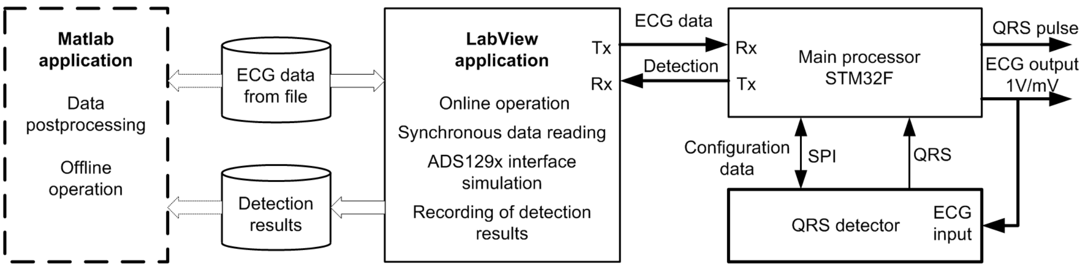

Fig. 4. The block diagram of test procedures.

4.1. TESTING THE AGC SYSTEM

In order to study the performance of the automatic gain control algorithm an experiment was done. It involved the stepwise amplitude change of the ECG signal at the detector input. There is no such situation in practice, however the experiment allows to evaluate the effectiveness of the applied solution. Fig. 5 (left) shows the system response to three-fold step increase in the amplitude of the ECG. The control system responds in an oscillating manner, reaching the steady state after approximately 15 seconds (about 20 QRS cycles). There is no associated atrophy of the detection of QRS complexes. Fig. 5 (right) shows the response to the abrupt five-fold decrease in the amplitude of the ECG. In this case, the steady state is reached after approximately 10 seconds (about 12 QRS). One of the QRS complexes was not detected at the same time, which is quite normal - a pulse with an amplitude several times smaller than those observed previously was classified by the detector as a fault and ignored. This experiment showed that the AGC algorithm used for slowly varying amplitude of the ECG is working properly.

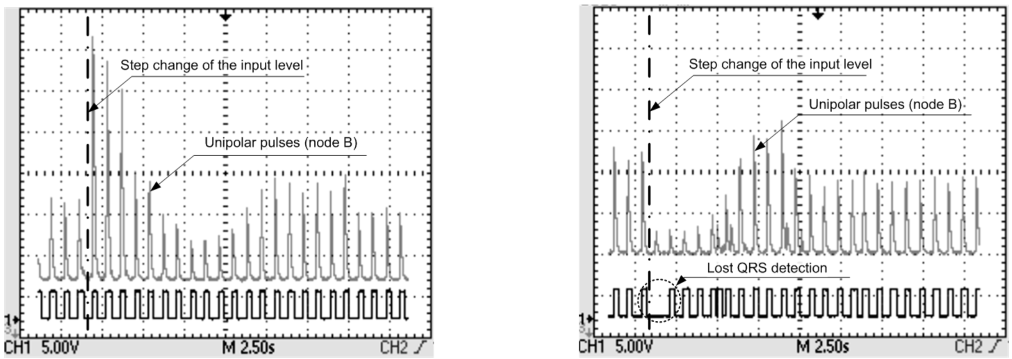

Fig. 5. The system response to a step 3-fold increase in amplitude (left) and step 5-fold decrease in the amplitude (right).

Figures 6 to 8 show the effect of operation of the AGC for an exemplary ECG signal with a slow amplitude change over time. The best detection results were obtained for the circuit using the above hybrid AGC algorithm. Tab. 1 compares the results of detection.

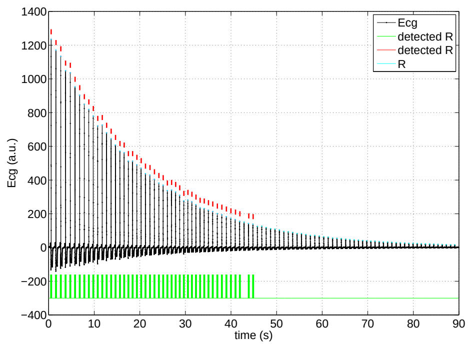

Fig. 6. An example of QRS detection without AGC (with constant parameters), the acceptable range of amplitude changes 1:8.

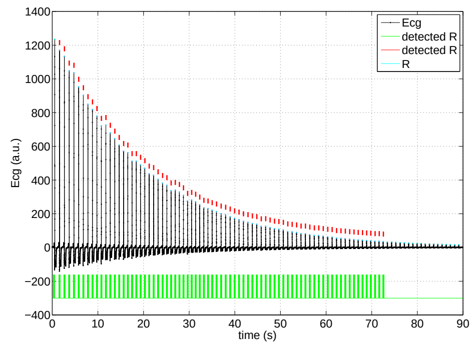

Fig. 7. An example of QRS detection without reconfiguration of the ADS129x, the acceptable range of amplitude changes 1:36.

Table 1. Summary results of the QRS detection for damped ecg5 signal (the amplitude change ratio: 40 to 1), the quality factor of the detector filter Q = 3, for three AGC operating modes.

AGC mode	ADS correction	NQRS	Fn(%)	Fp(%)	Dynamics	Pd40 (%)	Pd40_50(%)	Pd50+(%)
off	*off*	94	51.06	0	8	44.68	0	4.25
on	*off*	94	19.14	1.06	36	76.59	0	3.19
on	*on*	94	2.12	0	72	95.74	0	2.12

Description of abbreviations used in the Tab.1: NQR- number of QRS complexes in ECG test signal, Fn - percentage of incorrect detection (false negative), Fp - percentage of incorrect detection (false positive), Dynamics - the ratio of the maximum value of R-wave amplitude to the minimum value of R-wave amplitude, for which detection was correct, Pd40 - percentage of correct detection delay (0-40ms), Pd40_50 - percentage of late detection within the acceptable range (40-50ms), Pd50+ - Percentage of delayed detection in an undesirable range (over 50ms).

4.2. SYSTEM VALIDATION

Detector tests were carried out for two different circuit configurations. Particular configurations differed mainly by quality factor (Q) of the used band-pass filter. In the first case this value was 3.0 and in the second 4.7. During the detector tests the full AGC algorithm was applied. The QRS detection results are summarized in Tab. 2 and 3.

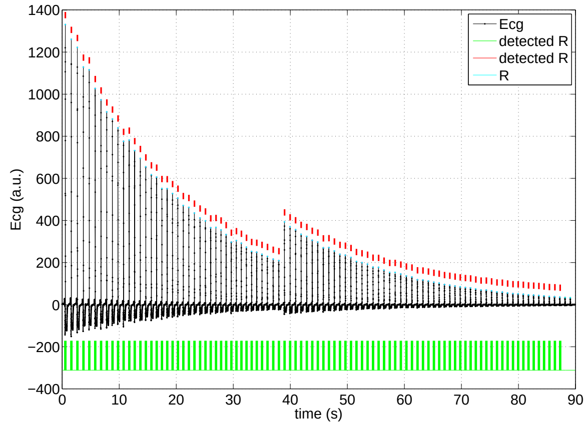

Fig. 8. An example of QRS detection with AGC and reconfiguration of the ADS129x, the acceptable range of amplitude changes 1:72.

Table 2. Summary of detection results (Q = 3)

Ecg Signal	NQRS	Fn(%)	Fp(%)	AvgD(ms)	minD(ms)	maxD(ms)	Pd40(%)	Pd40_50(%)	Pd50+(%)
*ecg*1	108	0.00	0.00	25.25	16	32	100.00	0	0
*ecg*2	123	1.62	3.25	9.29	−16	52	82.11	1.62	0.81
*ecg*3	165	0.60	0.00	36.04	20	56	51.51	43.63	4.24
*ecg*4	106	0.00	0.00	26.64	16	32	100.00	0	0
*ecg*5	94	0.00	0.00	16.76	12	20	100.00	0	0
*ecg*6	111	0.90	0.00	22.25	12	28	99.09	0	0
*ecg*7	125	0.00	0.00	24.67	12	44	99.20	0.80	0
*ecg*8	126	0.00	0.00	25.04	12	48	97.61	2.38	0
*ecg*9	125	0.00	0.00	24.80	12	44	98.40	1.60	0
*ecg*10	115	0.00	0.00	16.86	0	24	99.13	0	0
*ecg*11	117	0.00	0.00	26.35	16	32	100.00	0	0

The results are given as follows: the name of the record (Ecg Signal), NQRS, Fn , Fp, the mean delay of R detection (AvgD), minimum and maximum delay (minD, maxD), Pd40, Pd40_50 and Pd50+. The results for the second case (Q = 4.7) are shown in Tab.3. On the basis of these tests it can be concluded that the detections of QRS complexes were obtained after a short delay and the efficiency was high. The observed values of detection delays are dependent on the applied filter. For the used test signals lower values were obtained for a filter with Q = 3. For the first tested detector configuration (Q = 3) for 9 ECG signals there was more than 98% of detections with a delay of less than 40 ms, while in the remaining two cases less than 50ms. For one case 4.24% of the obtained detections did not fit the predetermined range of delay (0-50ms). Less than 2% of the total number of QRS complexes gave incorrect detections (premature, lost QRS complex, etc.). For test signals significantly worse results were obtained for the second detector configuration (Q = 4.7). They are presented in Tab.3.

Table 3. Summary of detection results (Q = 4.7)

Ecg Signal	NQRS	Fn(%)	Fp(%)	AvgD(ms)	minD(ms)	maxD(ms)	Pd40(%)	Pd40_50(%)	Pd50+(%)
*ecg*1	108	0.00	0.00	42.44	24	60	44.44	20.37	35.18
*ecg*2	122	2.45	1.63	19.11	4	64	92.62	0	3.27
*ecg*3	165	0.60	0.00	54.75	44	92	0	29.69	69.69
*ecg*4	106	0.00	0.00	47.62	20	52	1.88	71.69	26.41
*ecg*5	94	0.00	0.00	27.10	8	56	98.93	0	1.06
*ecg*6	111	0.00	0.00	43.49	8	64	51.35	0	48.64
*ecg*7	125	0.00	0.00	50.81	16	76	0.80	34.40	64.80
*ecg*8	126	0.00	0.00	50.25	16	56	0.79	39.68	59.52
*ecg*9	125	0.00	0.00	50.48	12	80	0.80	42.40	56.00
*ecg*10	115	0.00	0.00	29.71	20	48	88.69	10.43	0
*ecg*11	117	0.00	0.00	49.05	20	56	2.56	51.28	46.15

5. CONCLUSIONS

This paper describes the ECG signal amplifier and QRS detector designed for devices such as artificial VAD chamber, requiring a slight delay of less than 50 ms. The module implements an innovative programmable circuit ADS129x and a classic analog QRS detector built using a programmable analog array AN231E04. The use of dynamic reconfiguration of programmable analog array and input amplifier gave the possibility to work with changes of the ECG amplitude in the range of 1:72. The tests carried out on 11 signals recorded from the epicardial electrodes confirmed the correct operation of the system and high efficiency of detection.

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