Methods for Measuring the Heart Rate during Physical Activities

David Sevcik, and Jakub Rak

***Abstract*—**This contribution examines methods and procedures for the measurement of a person's heart rate during physical activities. The main emphasis is being placed on the use of a measuring device for a project called "Fireman – rescuer of the future". The article describes the most common methods of heart rate measuring, their advantages and disadvantages and also their possible use for the "fireman of the future". The conclusion is devoted to the design of a device for measuring the heart rate using a method of detection of an R wave of the ECG signal, a description of detection and the processing methods of QRS complex of the ECG signal.

***Keywords*—**Heart rate, Heart rate measurement, ECG signal, Fireman of the future, Informatics, Physiology.

I. Introduction

THE heart pulse rate is one of the fundamental diagnostic data used when determining a condition of an organism both at rest and during physical activity. In medicine, the monitoring of the heart rate of patients is most frequently done while they are on a bed. However, hospitals are not the only places where the heart rate is checked. Heart rate monitoring is also used with top sportsmen who optimize their training accordingly. The use of heart rate measurement is also relied on in the "Fireman – rescuer of the future" project. The fireman is to wear special clothing which enables measurements of physiological functions of the body to be obtained. Specifically, the heart rate is one of these functions. The information acquired from individual firemen will be sent on a regular basis to a commander who evaluates it and thus gains a better overview of the physical and medical condition of each one of them. Based on the change in physiological functions that can be recognised, for instance, exhaustion, the increased heart rate may indicate the beginnings of shock caused by internal bleeding. [7]

Therefore, the objective of the paper is to design an operational system for the measuring of the heart rate of the fireman in action.

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II. Problem formulation

The pulse is a pressure wave induced by the expulsion of blood from the left ventricle into the aorta and from there it spreads into peripheral arteries. It is a volume change of the artery. Pulse can be seen and felt by fingers or checked by a device. It is caused by the impact of blood flow on the walls of arteries. These impacts are induced by the left ventricular systole. The pulse is influenced by the aortal valve, the flexibility of the arteries and the vasculature content. [5]

The system of heart rate measuring is primarily intended for firemen – rescuers of the future. Undoubtedly, it can be employed in other fields as well, for instance for sportsmen. For the use by rescue services there are several requirements. Above all, the system must be easy to use; its application must be as fast as possible. Further, it must not restrict the fireman in action and it must be comfortable. If these requirements were not met, the firemen would probably refuse to use this system.

The heart rates obtained from individual firemen should be constantly sent to the commander who is to evaluate the data and replace the tired fireman if needed. There is no need for showing the heart rates to the actual fireman as he has no time to deal with this when in action.

For firemen – rescuers the special device for heart rate measurement must be developed. None of the commercially available systems for measuring heart rate is fully satisfactory. They do not meet the requirements of speedy usage, as upon alarm the firemen must dress quickly and go to action. On that account it is impossible for firemen to waste time by placing the measuring system and fixing electrodes. Moreover, all devices for heart rate checking require a direct contact with the body of the fireman. One of the possible solutions to this problem is the system being attached to the body constantly. Nevertheless, it must not restrict the fireman at work and it should be comfortable. Also, the system must be capable of transferring the obtained data to the commander who evaluates it, which enables him to deploy firemen into action more effectively.

A. *The heart pulse rate*

The heart pulse rate indicates the number of heartbeats per minute. The following types of heart pulse rates are distinguished:

1) Resting heart rate – in the morning after awakening or

just before going to sleep. The resting heart rate ranges from 65 to 75 pulses per minute; it drops to 50 pulse/min in trained individuals. Therefore, the fitness condition can be assessed based on the resting heart rate. If the resting heart rate corresponds to the above mentioned value or drops, the sportsman is well trained or rested. On the contrary, if the heart rate increases by approximately 10 %, this can indicate insufficient recovery after workouts from the previous day, stress or upcoming illness.

2) Instant heart rate – affects fat burning, muscle building etc. When the rate is too high the strength and stamina increase but no fat burning occurs. Vice versa, too low a heart rate indicates ineffective workout during which nothing virtually happens in the body.

3) Maximum heart rate – HRmax – Its value corresponds to the maximum intensity which the organism of the individual is capable of achieving under load and maintaining for a short time. This value is specific to the individual and it is influenced more by age than by the workout. The value also differs in relation to the type of load. One can obtain different values when functionally tested on a treadmill (the achieved value is usually higher) and then on a bicycle ergometer. [13]

Calculation of maximum heart rate

- For men: 214 - (age x 0.8)
- For women: 209 - (age x 0.7)

B. Factors affecting the pulse rate

Factors affecting the pulse rate are, for instance, age, gender, physical exertion, respiratory deficiency, body temperature, bleeding, fluid overload, disease, or stress.

When measuring the heart rate one monitors the frequency of the pulse: tachycardia – over 90‘; bradycardia – less than 60‘. Further, regularity – rhythm: regularis (regular) or iregularis (irregular) as a result of extrasystoles, atrial fibrillation. Pulse deficiency – when the central pulse is higher than the peripheral. Quality – the quality of the heart rate – it can be either full, well palpable or thready, nonpalpable and soft. [13]

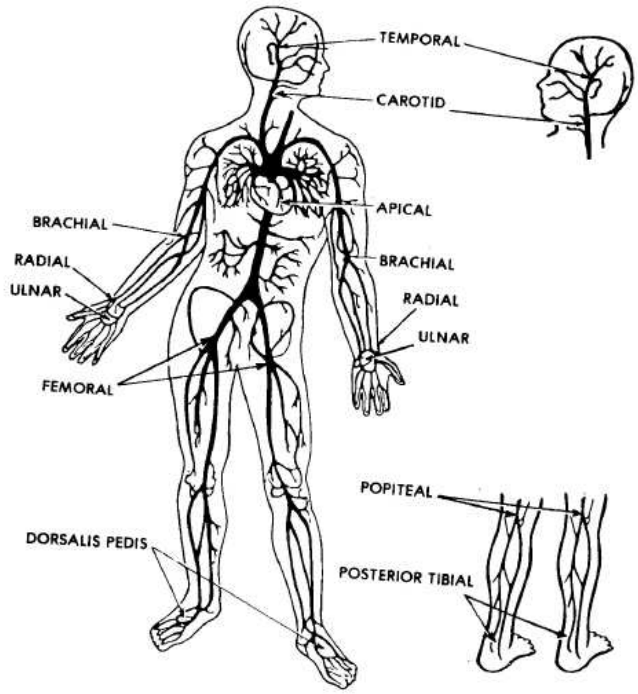

Fig. 1 Points for measuring the heart rate [13]

III. Problem Solution

Individual methods of measurement differ only in the way the heart rate is converted on the electrical impulses which are consequently processed and displayed. Generally, it can be stated that a block diagram, see Fig. 2, consists of sensor, amplifier, converter of scanned quantities on pulses, microprocessors for signal processing and display units or chart recorders. [6]

The main task of the amplifier is to increase the input level of a biosignal to the level at which other circuits can process this signal. These are, predominantly, voltage amplifiers. The next task of the amplifier is the impedance matching of the device’s input and the impedance of a patient. Furthermore, the input amplifier is capable of filtering unwanted signals, for instance 50 Hz from the power supply. It is, in other words, an active filter. Last but not least, it also separates the patient from the device.

Another part of the diagram is a converter of the scanned value to pulses indicating a change in the measured value (indication of a single pulse). Depending on this part of the diagram all hereafter described methods differ.

The fourth part of the diagram deals with processing the pulse. In most cases it is a microprocessor whose main task is a conversion of pulses to a number. This conversion can be accomplished by several means. For instance, an instantaneous value based on only two consecutive pulses can be displayed or the so-called running average based on several consecutive pulses (for example 5 or 10) can be calculated. The higher the number of averaged values, the lower the dynamics of the change in the displayed value. Furthermore, it is possible to calculate the so-called weighted average where individual “older” values lose their importance when calculating the displayed number. Undoubtedly, other algorithms for calculations can be used as well.

The last part of the diagram is a data output. The most commonly used is a display, for instance a seven-segment display or a monitor screen. Another method is a record on an electronic storage medium which can be a part of a holter, sports tracker of the heart rate, or patient monitor at the hospital. [6]

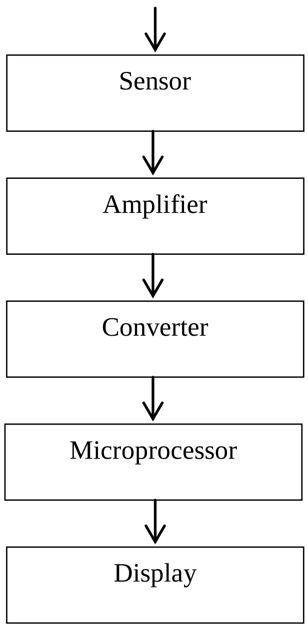

Fig. 2 General block diagram of the heart rate measurement

A. *The method of optical scanning of the heart rate*

This method uses variations in light transmission of the tissue when the blood pressure changes. Well perfused tissue absorbs light differently from the tissue that is not perfused. This change is then dependent on the heart rate. Measurements are performed on fingertips.

This method is very sensitive to movements of the patient. Therefore, it is necessary to have a precisely produced clip on the finger that can remain securely in the same place. Another measure against interference is to include only those impulses that reach the microprocessor in a pre-set period of time. The pre-set time period does not remove all disturbing effects but it is capable of filtering out those effects that would come too early or too late.

Another interference that may occur is the parasitic light that reaches a photodetector of a sensor. Again, this interference can be removed by a precise design of the clip and its thorough shielding from light sources. [6]

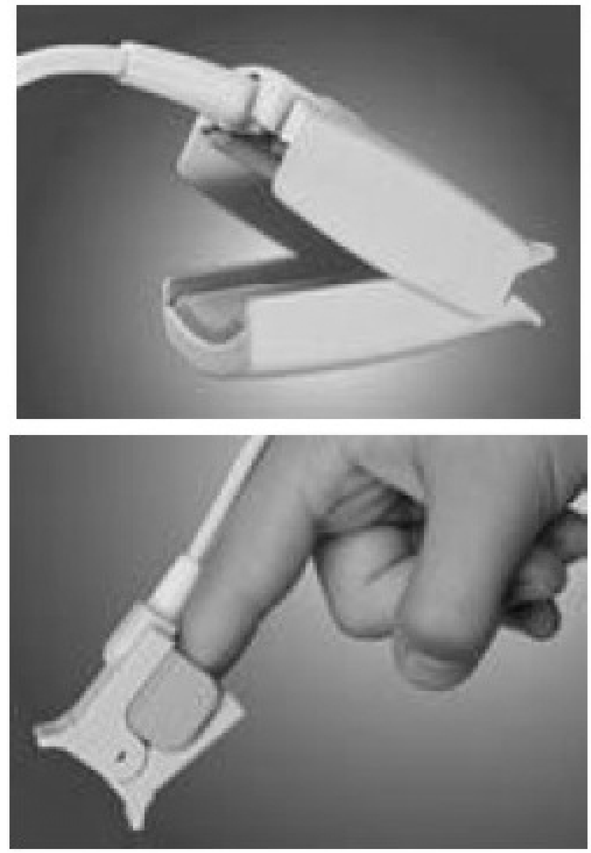

Fig. 3 Optical sensor of heart rate [16]

It is possible to use a transmissive method in which there is a source of light from one side of the finger, most frequently in the infrared range of 940 nm of wavelengths, and a photodetector that detects infrared radiation from the other side (usually, it is a photoresistor or phototransistor). Another method that can be used is a reflexion method where there is the source of light and a photodetector placed next to each other on the same side of the finger. [6]

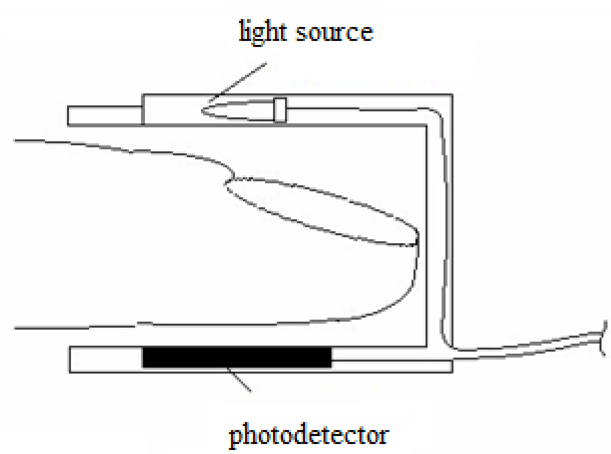

Fig. 4 Translucent method of heart rate scanning [3]

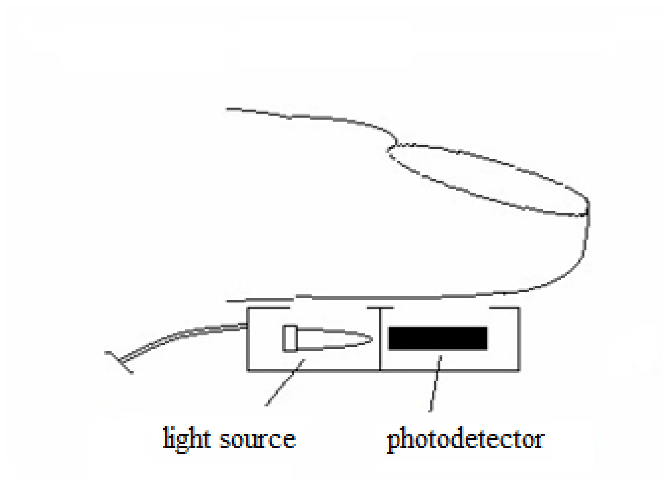

Fig. 5 Reflexion method of scanning [3]

B. The method of capacitive scanning of the heart rate

The sensor is in the shape of a ring which is fitted on the finger. This method uses a flexible dielectric capacitor placed inside the ring. The change in the volume tissue causes resizing of flexible dielectrics, which changes the capacity of the capacitor. With the change in the capacity also comes the change in voltage. Based on the voltage it is then possible to determine the frequency of the heart rate. [3]

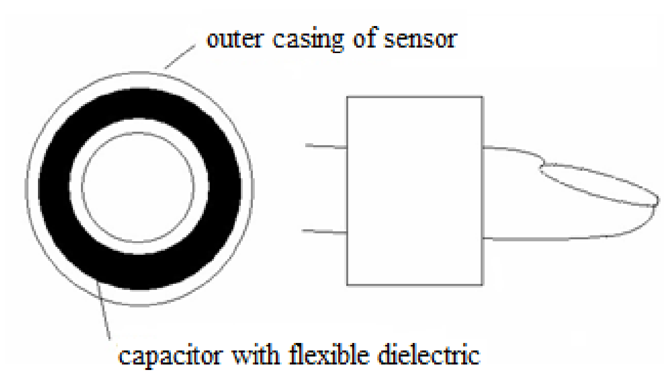

Fig. 6 The method of capacitive scanning of the heart rate [3]

C. The method of the R wave measurement

In order to measure using this method, an R wave detector and an ECG signal are required. The detector signals the QRS complex in the ECG signal. The frequency of the heart rate is then calculated from the R-R interval.

However, interferences which occur in daily life, cause problems. For instance, the interference caused by breathing occurs at frequencies ranging from 0.15 to 0.6 Hz. The electrode potentials caused by motion of the scanned person range from 0.6 to 1.5 Hz. Interference of power supply networks are of 50 Hz while interference by myopotentials ranges from 20 to 500 Hz. When measuring the heart rate the majority of such interferences can be suppressed by a suitable filtration. QRS complex lies at the frequencies of around 12 Hz where the interference is low. [4]

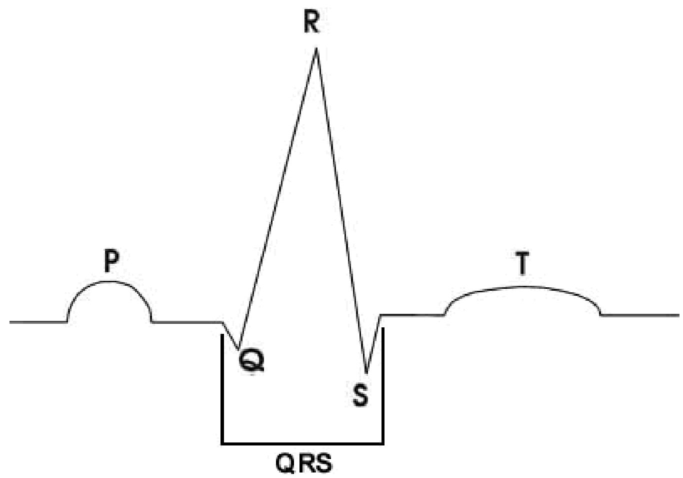

Fig. 7 The QRS complex [9]

D. The method of acoustic scanning of the heart rate

The acoustic manifestations of the heart are referred to as heart sounds generated by the activity of the heart. It is a very simple method in principle. A microphone is placed on the body of the scanned person and the acoustic signal is converted into an electrical signal. After processing the signal it is converted into pulses. The complex processing of the signal is a disadvantage as there are many interferences, such as breathing, heart murmurs and predominantly movements of the scanned person. [3]

A heart sound occurs through a change of flow rate (or by changing the character of the flow) as well as through opening and closing of valves. There are two types of flow – the laminar flow that occurs under standard conditions, and the turbulent flow. The laminar flow of blood has a parabolic flow profile with the fastest flow in the middle of blood vessels; vice versa, during the turbulent flow vortices are generated and thus the flow slows down.

During the cardiac cycle 4 types of heart sounds are distinguished:

- First sound – Systolic. It is longer and broader. It is created by the closure of mitral and tricuspid valves. The beginning of the first sound corresponds to the peak of the R wave.
- Second sound – Diastolic. This shorter and clearer sound is created by the closure of semilunar aortic and pulmonary valves. The beginning of the second sounds usually corresponds to the end of the T wave; the end of an ejection phase.
- Third sound – Protodiastolic. At the beginning of the filling phase, when rapid blood flow vibrates a ventricular wall, the third sound is being created; this sound is audible only in children. It occurs about 0.10 s after the T wave.
- Fourth sound – Presystolic. An atrial systole induces

the fourth sound which is not audible but which can be found at a phonocardiogram at the end of the P wave. [17]

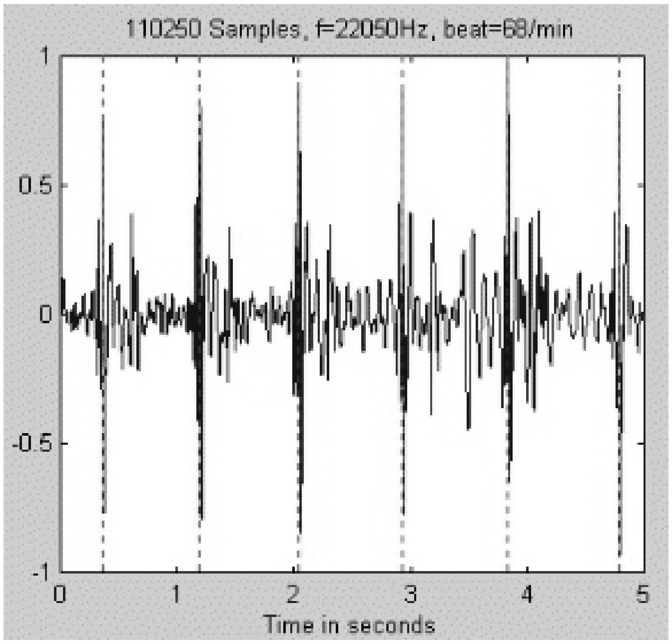

Fig. 8 Signal at the output of the microphone [6]

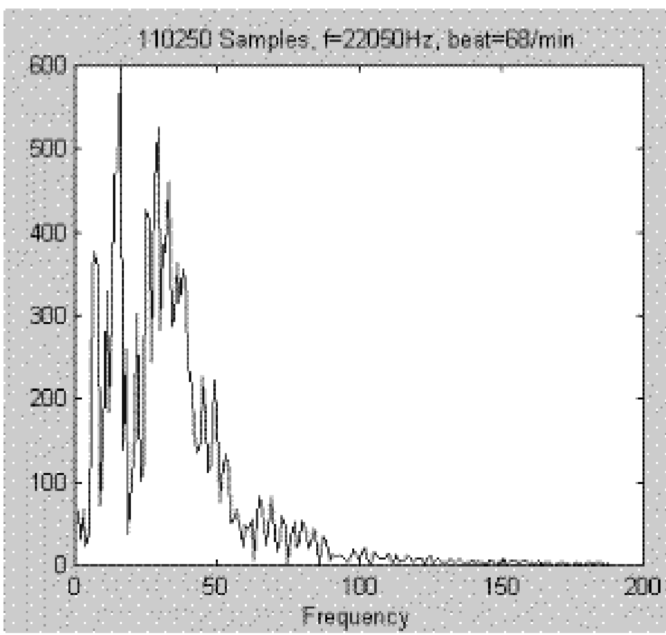

Fig. 9 Spectrum of the signal from the Fig. 8 [6]

E. The method of impedance scanning

During this method changes of impedance induced by the change in blood volume in between two electrodes or by electrical impedance of the chest caused by the heart activity, are recorded.

This method uses several electrodes which are always placed in symmetric positions. This technique allows monitoring of the heart rate, respiratory rate, blood flow in the given section of the tissue, minute volume of the heart and other quantities. The reaction time of changes in electrical resistance or electrical impedance of the chest induced by cardiac activity are being evaluated. The blood flow through heart cavities and large vessels together with changes in blood filling and air in the lungs are recorded in a typical course. Modern devices do not measure the electrical resistance but the absolute value of electrical impedance for alternating current at the frequency of several tens of kHz. Thus, it is possible to subtract the resting value and reaction time of the variable component. Two or four electrodes are used for the measurement.

However, the disadvantage of this method is that during physical activity when the stroke volume increases the results of measurement differ noticeably when compared to invasive monitoring. [3]

F. The use of individual methods

For firemen – rescuers the measurement of the R wave by means of the ECG signal obtained by electrodes seems to be the most suitable. Both optical and pressure sensors would obstruct during the action as they are usually attached to the finger. The fireman needs both hands free to do the job. Impedance scanning is inappropriate due to its inaccuracy during physical activity.

G. The location of sensors

There are several possibilities where to place the sensors. There is no need to scan the entire ECG by means of 12 electrodes. The electrodes located in a chest belt near the heart are enough. One of first such systems was developed by Finish company Polar. Their product Sporttester was intended for sportsmen who wanted to increase the effectiveness of workouts (see Fig. 10). It comprises of the chest belt and a wristwatch. Information is transferred wirelessly from the chest belt to the watch, which enables the user to see the maximum and average heart rate, training time, burnt calories and proportion of fat per exerted energy.

Nowadays, there exist chest belts which do not send information to the watch but to the smart phones using Bluetooth wireless technology. [8]

Fig. 10 Chest belt by Polar [8]

IV. The design of the heart rate sensor

The heart rate sensor intended specifically for the firemen - rescuers of the future, could have similar parameters as the chest belt made by the Polar company. However, it will be necessary to make the device as small as possible so it is comfortable and light while putting no restrictions on firemen and their other equipment. One of the possibilities of how to speed attaching the chest belt up is to sew it into the clothing that is worn by the fireman that comes in direct contact with the body. Furthermore, this device should be waterproof; if sewn in the cloth it must withstand washing. Another reason for water resistance is the relatively high level of perspiration of firemen in action.

A. The block diagram of the heart rate sensor

The ECG signal obtained from the sensors must be filtered out first; for this a band pass filter with marginal frequencies of 14 to 25 Hz is used in which the most significant spectral components of the R wave are included. The medium frequency of the band-pass filter should therefore be approximately of 12 to 15 Hz with a bandwidth of around 10 Hz. The signal amplification is performed in order to achieve positive values of the signal as well as further enhancement of R waves. The value that is to detect the required R wave is set in the threshold detector. According to [7], the size of the threshold value is usually set at 40 % of the maximum of the QRS complex.

The peak detector represents an algorithm for searching R wave peaks. The algorithm goes through the signal, component by component and the result is a vector that contains only peaks of the R wave, as isolated points. The microprocessor then calculates the interval among these isolated points and recalculates the distance to the time domain. The signal that is processed in such a way is then sent by a transmitter to the commander who evaluates the data. Fig. 11 depicts the block diagram of the designed sensor for the heart rate using the R wave detector. [1]

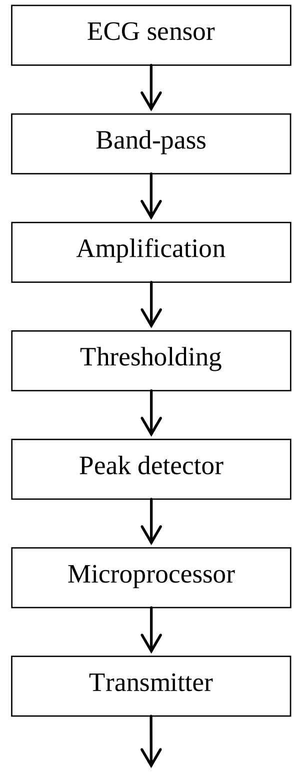

Fig. 11 Block diagram of the R wave detector

For the detection of the wave R the detection of the whole QRS complex in the ECG signal is used. This procedure is necessary during the whole processing of the ECG signal as the QRS complex is the basis for the determination of R-R intervals from which the crucial heart rate is induced. The QRS complex occurs in the frequency range of 8 to 22 Hz. [10,11]

B. Preprocessing

At this point the unwanted signal in the form of the unused remainder of the ECG signal (P wave and T wave) together with drift, main hums and myopotentials are filtered out. These issues are usually resolved by a band pass filter in the range of 10 to 20 Hz. Noise occurs sporadically in the form of random blips or regularly during ergometry testing. Consequently, the signal is enhanced by squaring followed by filtering dependent on the selected method.

C. Decision rule

The decision rule is a set of criteria which the signal must meet in order to be chosen as a wanted area - the R wave. Generally, the rules vary based on different detection methods.

Among the basic decision thresholds are:

- Learning phase
- The first threshold to 40 % of maximum, the next threshold to 40 % from the last maximum.
- If there are two extrema separated by less than 200 ms, only the greater extremum is retained.

- If the distance between the two extrema is in the range of 200 ms to 300 ms then only the first extremum is considered as the new QRS complex provided the value of the second extremum lies within the range ± 40 % of the value of the first one.
- If the distance between the two extrema is in the range of 200 ms to 300 ms and 60 % of the value of the second extremum is greater than the value of the first extremum, then the first extremum is excluded.
- If there is no extremum exceeding limits of detection in an interval which equals to a multiple of 1.66 of the preceding R-R interval, then the greatest extremum within this interval is considered as the new QRS complex. [20]

After detection of the QRS complex the so-called refractory period, which lasts approximately 0.15 s, must be taken into consideration. In this time span no other QRS complex is expected. After the refractory period the threshold drops to a certain limit. If the QRS complex could not be found using the multiple of 1.66 of the preceding R-R interval, the back-testing of the lower threshold is applied (in the reverse direction).

In summary, the whole process is referred to as an adaptive threshold criterion.

D. Detection of the QRS complex

The QRS complex emerges in the band of 8 to 22 Hz with a maximum between 10 – 15 Hz [19]. It is, therefore, necessary to remove other useless signal components. As components useless for the detection of the R wave are considered P waves and T waves which can be suppressed in this case.

In the first part of Fig. 12 the band pass filter with a bandwidth of 8 – 22 Hz is used. The filtered signal is further squared, which highlights the area where the QRS complex occurs. The polarity of the negative wave changes while the positive wave escalates. Subsequently, the signal is smoothed by means a low-pass filter with rectangular pulse characteristic and one smooth peak is created. The value that is required to detect the R wave after exceeding is set in the threshold detector. The threshold is usually set to 40 % of the maximum specified in the learning phase during the detection of the QRS complex. The last part contains the R wave detector where operations to the output signal are processed. [18]

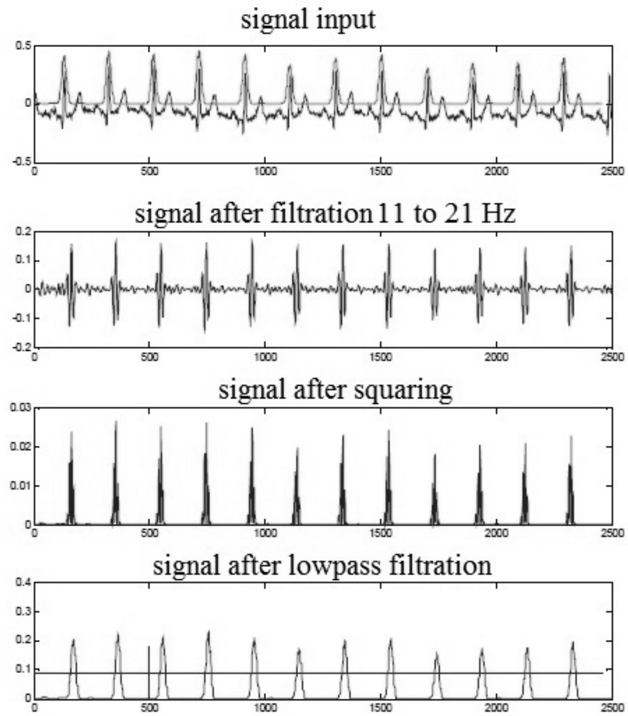

Fig. 12 Detection of the QRS complex [1]

V. Conclusion

The objective of this paper was to design a device for the measurement of the heart rate during physical activities. Such a device would find its application both with sportsmen in optimizing their training plans as well as in the project of the fireman – rescuer of the future. In latter case, the device would be a part of the smart clothing which is to monitor physiological functions of the fireman in action. Having examined possible methods of measuring of the heart rate, the detection of the R wave out of the ECG signal was evaluated as the most applicable because all other methods were prone to interference or restricted the fireman at his work. From the perspective of the sensors, the chest belt was chosen as it is less likely to limit the fireman in comparison with other methods. Also, the chest belt meets the requirements of simplicity of use as no electrodes must be attached to the body prior to dressing for action. Following further research of the implementation of the designed device is expected.

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