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EPIC SENSORS IN ELECTROCARDIOGRAM MEASUREMENT

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ABSTRACT

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The aim of this Master's thesis was to give basic knowledge of the different electrodes that are used for electrocardiogram measurements without going too deep into medical or physiological details. The main focus was on a new Electric Potential Integrated Circuit sensor that has some very unique features, such as feasibility to also measure many physiological signals through the clothing.

To achieve that aim Electric Potential Integrated Circuit sensors were tested in practise to see if they really can fulfil all the expectations that sensor's developer has given. For this thesis only electrocardiogram measurements were done, even these same sensors can be used for recovering other physiological signals too. Electrocardiogram measurements were done from patient's bare skin and also through two different shirt combinations.

The testing results were very promising even some small drawbacks were faced with the testing equipment. In-contact measurements show clearly that EPIC sensors can reach the diagnostic level signal quality in the electrocardiogram measurement. These sensors may offer a more comfortable measurement for the patients, but the most important thing, the reliability of the measurement, definitely still needs more studying.

Keywords: Electrocardiogram, ECG electrodes, Electric Potential Integrated Circuit, EPIC sensor

CONTENTS

1 INTRODUCTION

This thesis work will give the basic knowledge of an EPIC sensor (Electric Potential Integrated Circuit) and test how well do these new sensors work in an electrocardiogram (ECG) measurement. Beside the theoretical background, many things will be introduced and tested through practical examples. The main aim of this thesis was to test how well EPIC sensors work in practice; how a good signal quality can be achieved and what are possible measuring places are. A very unique feature of EPIC sensors, an ECG measuring through clothing, will also be tested in practise.

The electrocardiogram (ECG) measurement is a quite commonly known method to measure and analyse the functionality of the heart. It is used in medical operations and also in heart rate monitors that many athletics and fitness people use around the world. The ECG measurement is normally done by measuring small electrical changes which are caused by the heart muscle depolarizing during each heartbeat. This is detected as a tiny rise in the voltage between electrodes that are on the skin at thorax area. The electrodes are normally either spot electrodes (disposable wet electrodes that are used in hospitals) or dry electrodes that ambulatory heart rate monitors commonly use.

Unlike traditional electrodes, an EPIC sensor is a non-contact electrometer, meaning that there is no direct ohmic path from the outside world to the sensor input. The electrode is protected by a capping layer of dielectric material to ensure that the electrode is isolated from the body being measured. Since the EPIC sensor makes a high impedance contact to the skin, any contact-enhancing substances, such as gel, paste or water, are not needed.

The aim of this thesis was to give a good base knowledge about different electrodes used in electrocardiogram measurement without going too deep into medical or physiological details. The main interest of this thesis was on the ECG measurement, even though EPIC sensors can also be used for some other applications and for recovering other physiological signals, too.

2 LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
ECG or EKG	ElectroCardioGram (electrical activity of heart)
EEG	ElectroEncephaloGram (Brain spontaneous electrical activity)
EMG	ElectroMyoGraphy (electrical activity produced by muscles)
EOG	ElectroOculoGraphy (Eye movement monitoring)
EPIC	Electric Potential Integrated Circuit
HR	Heart Rate
SW	Software

3 ELECTROGARDIOGRAM

3.1 Introduction to an electrocardiogram

An electrocardiograph, often shortened as an ECG or an EKG, comes from Greek words: *electro*, because it is related to electrical activity, *kardia*, meaning heart and *graph* meaning "to write". Thus, as shortly described an electrocardiograph can be said to record the heart activity through electrical signals generated naturally by a human body. These electrical signals are detected by using electrodes attached to the surface of the skin, or in the near distance from the skin as described later on in this document.

ECG devices were developed to detect and record the ECG signal. This ECG signal can be then used to analyse heart functionality and health in an objective way. The ECG signal is the most important tool when making a diagnosis for the heart disease. The first devices to detect an ECG signal were built already in late 19th century. Understanding the meaning of an ECG signal and finding ways to analyse it were developed fast during the next decades, thanks to more advanced measuring devices that could more accurately measure very small voltages produced by the human heart. A breakthrough for these measurements was the discovering of a string galvanometer by Willem Einthoven in the year 1901. Einthoven used this new invention to study how a human heart works by analysing an ECG signal. He assigned the letters to describe various deflections of an ECG signal and described the changes that a number of cardiovascular disorders cause to the ECG signal. Thanks to Einthoven's discoveries, he was awarded the Nobel Prize in Medicine in 1924. (Heikkilä, 1991; Beardsmore-Rust, 2010)

3.2 Measuring an ECG

An ECG signal is presented by using a graph, where the y-axis represents voltage and the x-axis represents time. An ECG signal can be either shown on the screen of the ECG device or printed out on paper. Since both, the scale of the signal and time are very important when doing a clinical diagnosis, a special ECG graph paper is with a background pattern of squares is used when the ECG signal is printed. A standard paper speed must specified to unify the analysis. The speed of 50 mm/s is usually used (Heikkilä, 1991). Since in most cases the timing of an ECG signal is even more important than its amplitude, the used paper speed must always be checked before doing any medical analysis.

From the diagnostic mode ECG signal we should find five different waves that are assigned with letters P, Q, R, S and T. There are also some other named waves, for example U and J waves, but under normal conditions these waves have a very low amplitude and thus they are hard to find. On the other hand a clear presence of these U and J waves indicates some heart diseases more often than a normal functionality of the heart.

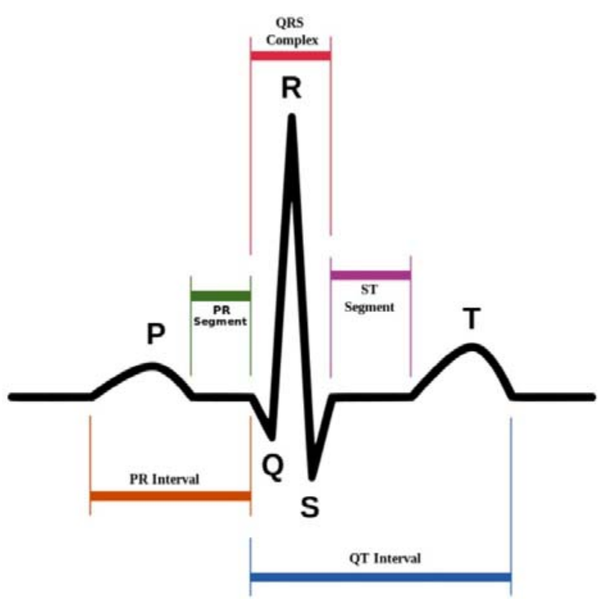

FIGURE 1. Human heart ECG signal (Atkielski, 2007)

Each of these waves represents a certain phase of heart beat. On a normal ECG signal the first wave is P, where both atriums of the heart, left and right are activated. During a PR segment followed the P wave, the heart muscle does not do anything causing the flat line seen on the signal. The QRS complex that includes the waves Q, R and S, reflects a depolarization of left and right ventricles. ST segment represents the moment where ventricle muscles stay activated. The last wave, the T wave represents a recovery of the ventricles. The recovery of atriums cannot be seen from an ECG signal normally, since it has a low amplitude and the recovery happens during the QRS complex. The ECG signal level from the end of the T wave to the beginning of the next P wave is defined to be the baseline of the signal. (Heikkilä, 1991)

The normal human ECG is non-stationary and nonlinear and since the unamplified signal has a very low amplitude, it also has a low signal to noise ratio. Environment, measuring equipment and many individual human factors are affecting the ECG signal quality. Beside the heart, all muscle activity produce an electrical signal and this might affect the ECG measurement by increasing interfering signals. Even breathing causes low frequency movement signals and thus makes the ECG measuring more difficult. The electrical activity produced by muscles is called an ElectroMyoGraphy, which is often shortened as an EMG.

The interference that muscle activity is causing for the ECG measurement can be reduced by using simple signal filtering techniques, such as narrowing the effective measuring bandwidth. This might be a working solution for some health applications, where the main interest is just to detect the heart beating rate. Because the R wave has clearly the highest amplitude of all five waves, health applications such as training computers (also known as heart rate monitors or sports watches) are built to detect the timing of this one precise wave only from the ECG signal. Diagnostic mode measurements need a much wider frequency range, usually from 0,05 Hz to 150 Hz, to give accurate enough information to analyse heart diseases and other abnormal activity of the heart (ECG using wrist-mounted EPIC sensors, 2010). So for the diagnostic measurements narrowing the bandwidth is not an option.

4 Different electrode types

4.1 Introduction for electrodes

Different electrodes and electrode placing might be used depending on the wanted application. The application also defines how many electrodes are needed. Sometimes two electrodes are enough, but for some applications ten or even more electrodes are needed.

The simplest ECG measurement can be done by using two electrodes, usually placed on the chest of the patient, one on each side of the heart where ECG signal has the strongest amplitude. Two electrodes are enough for a basic measurement, such as measuring a heart beat rate with a training computer. For most medical purposes more than two electrodes are used at the time. A different combination of electrode pairs, often called leads, around the body helps to “see” the heart from the different angles. This helps to detect cardiovascular disorders better, for example to know which region of the heart is affected to the disorder.

4.2 Wet gel electrodes

Patient diagnostic measurements are usually done by using conventional disposable Silver – Silver chlorite (Ag/AgCl) electrodes, as shown in figure 2. These electrodes provide an excellent signal quality for the demanding ECG measurements, but they also have some disadvantages. One is the need of skin preparation, such as shaving and cleaning the electrode spots with alcohol before attaching. Wet electrodes are irritating for a long-term use, so the electrodes and their places need be changed at least daily to avoid skin reactions. The changing of electrodes is also needed because the gel material dries during the usage and may finally even stop working. Mostly because of the used gel, these electrodes might also cause allergic reactions, but they are not common in modern electrodes. (Meziane, Webster, Attari & Nimunkar, 2013)

Because these wet electrodes are attached to skin with an adhesive tape, also the tape can cause some mechanical or chemical irritation, but the main irritation may be caused by tearing off a thin layer of skin when removing the electrodes.

FIGURE 2: Example picture of spot electrodes the size of which is 35 x 52 mm

4.3 Dry electrodes

The electrodes that operate without gel, adhesive and skin preparation are called dry electrodes. They are used in research and physical exercise applications for a long period of time, but still they have not achieved acceptance for medical use (Meziane etc. 2013).

The biggest problem of dry electrodes is motion artifacts that are significantly higher than those for wet electrodes. Motion artifacts decrease with time because the electrode and skin beneath it become moisturized by a perspiration after few minutes. The perspiration also works as an electrolyte and it fills the small pores of the skin making it more conductive.

There are many possible materials for dry electrodes:

- Stiff materials, such as metal or ceramic material plates
- Flexible materials, such as rubber, foam or fabrics

Numerous metals have been tried to use as dry electrodes, such as stainless steel, silver and aluminium. After testing some materials are rejected because of their properties, for example aluminium has problems because of oxidation that is caused by the perspiration in the long term usage. Many studies have proven stainless steel as the best material, not only because of its performance, but also because of the availability and price concerns. One common problem of stiff electrodes is that they can easily slip over the skin, which causes a loss of contact and some charging effects between electrodes (Gruetzmann, Hansen and Müller, 2007).

A stable contact between an electrode and a skin is important for all traditional electrodes. Stiff material electrodes suffer from motion artifact mainly because of two reasons; the absence of the gel and the unwanted movement of the electrodes on the skin. A flexible and soft electrode adapts to the body shape during the movement and thus reduces motion artifacts. Softness and better adhesion can also increase the relative contact area of the electrode resulting to a lower impedance and thus reducing motion artifacts. Figure 3 shows one flexible material dry electrode that is used for health application.

FIGURE 3: Example of a dry electrode (heart rate monitor's chest strap)

Flexible dry electrodes can be made for example from foam that is coated with a conductive material, a conductive rubber or a conductive material that is integrated to the textile. This textile can be on clothing, for example on a tight sports T-shirt, or it can be a separate strap with a transmitter that most training computers use. Because of the more complex structure of flexible electrodes some mechanical problems may happen more often than with the stiff electrodes.

4.4 Summary of traditional electrodes

Both gel and dry electrodes suffer from noise, interference and motion artifacts, but partly at different levels. Dry electrodes are more affected by motion artifacts right after application, but when perspiration takes place and fills the electrode-skin gap, there is no big difference between these two electrodes (Searle and Kirkup, 2000). To understand why wet and dry electrodes behave differently, we have to understand the original reasons that are causing noise, interference and motion artifacts.

One of the biggest problems with both sensors is mains interference. This interference comes from AC power lines and has a frequency of 50 or 60 Hz. Because of its source, this interference is unavoidably present in any clinical application. A Driven Right Leg (DRL) circuit can be used to reduce a common mode interference as later described in this document. According to some studies, a manual matching of the contact impedances can reduce the power-line interference down to about 1% of the initial value (Adli and Yamamoto, 1998).

Dry and insulating electrodes suffer from a charge sensitivity, meaning that electrodes are acting as an electrometer. Since the charge sensitivity is consequence of high input impedance of an electrode, insulating electrodes suffer the most. The same effect can be seen on wet electrodes, but there this effect is irrelevantly low (Searle etc. 2000).

A motion artifact is a result from two things. The first is the potential skin changes during the mechanical deformation, and the second one is changes on the mechanical contact between the electrode and the skin. Even an EMG artifact can often be reduced by a proper electrode placement and signal filtering, it still remains one of the greatest source of motion artifact together with skin stretching. Motion artifact are increased when there is a patient movement, a mechanical adherence of electrodes to the skin is poor, a gel or other electrolyte is drying or when wrong type of electrodes are used or they are misplaced.

The lack of standard measurement methods combined with a human variability, for example the skin impedance changes by many factors such as season, time and circumstances, makes an objective comparison of different electrodes difficult. When comparing different electrodes to each other, all measuring system specifications need to be considered instead of the electrode itself. As an example of this standard amplifiers are mostly made for gel-based wet electrode systems and thus they might not be optimal to be used with dry electrodes. (Meziane etc. 2013)

4.5 EPIC sensors

An electric potential sensor (EPS) was developed at the University of Sussex in England. An electric Potential Integrated Circuit (EPIC), which is an advanced version of the previous studies and the main focus of this thesis, is developed by Plessey Semiconductors Ltd. The EPIC sensor has all electric potential sensor parts integrated to one component.

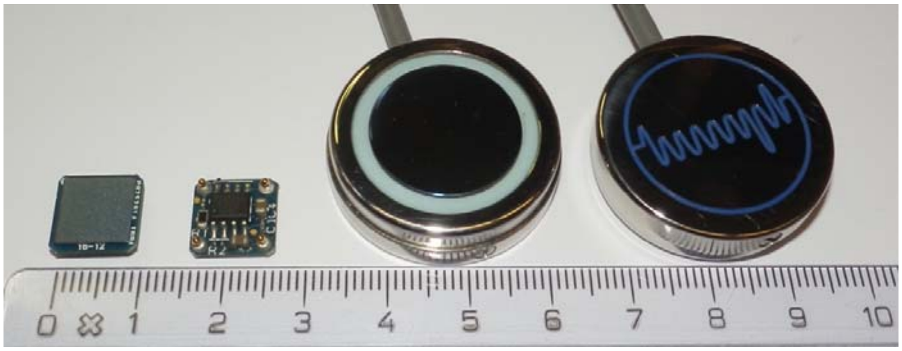

FIGURE 4: EPIC sensors (PS25201B and PS25100; top and bottom views)

The basic idea of capacitive electrodes to be used in electrocardiograph purposes is quite old, since the first working devices were introduced already in the year 1968 (Lopez, 1969). Even though many common problems associated with capacitive, non-contact electrodes have been solved during the last decades, any design has not really progressed beyond the lab prototype stage.

EPIC sensors can be applied to a range of applications such as electrophysiology including monitoring the electrical activity of heart (ECG), -brain (an ElectroEncephaloGraph, an EEG), -muscles (an EMG) or eye movement (an ElectroOcularGraph, an EOG). EPIC sensors can also be applied to a proximity- and movement sensing, a non-destructive testing of composite materials and in nuclear magnetic resonance probes. Some microscopy applications have also been introduced (Plessey Semiconductors, 2013).

The EPIC sensor can be used either in a contact or non-contact mode. The contact mode is used to measure for example bio-electric signals such as an ECG or an EEG from the human body, and the non-contact mode is used to measure the disruption of an electric field caused by a human body movement.

In this thesis work the main interest is in Electrocardiogram (ECG) measurements. For this purpose the EPIC sensor has very unique properties. The EPIC is a capacitive sensor that does not rely on a direct, ohmic contact to the body, so no gels or other contact-enhancing substances are needed. Since the EPIC sensors do not require a direct skin contact, they are capable of measuring an ECG or other bio-electrical signals through the clothing, too. (Plessey Semiconductors, 2013)

EPIC sensors can be used for both simple heart rate analyses as well as making more exact clinical diagnostic measurements, such as a replacement of the traditional twelve-lead ECG. The twelve-lead ECG is used to measure the electrical activity of the heart from many, slightly different perspectives to achieve a clearer picture of how the patient's heart is working.

EPIC sensors can be used for recovering other physiological signals than the ECG, for example those signals that are caused by the electrical activity of an eye muscle when looking in different directions. Since different muscles are activated when looking up, down, left or right, each direction has its own unique signature on an EPIC sensor output signal. These sensors can also be used for an electroencephalography (an EEG), where the electrical activity of the brain is recorded (Harland, Clark & Prance, 2002). Since EEG signals can be recovered from near the proximity to the patient, EPIC sensors have a significant benefit compared to traditional sensors when there is no need to prepare a direct connection to the skin.

5 HOW DOES AN EPIC SENSOR WORK

An EPIC is an acronym for "an Electric Potential Integrated Circuit" but the term has also become synonymous with the sensor itself. An EPIC is a non-contact electrometer, so there is no direct DC path from the outside world to the sensor input. The input is protected by a capping layer of dielectric material to ensure that the electrode is isolated from the body being measured.

The device is AC coupled with a frequency spectrum of a few tens of mHz to above 200 MHz. Accurate frequencies depend on the wanted application and also vary between different types of EPIC sensors. The wanted application also defines the size of the electrode, since it corresponds strongly to the input capacitance. The right input capacitance is important for the accurate contact mode measurements, such as measuring a medical level ECG signal.

A single EPIC sensor can be used to read the electric potential and when using many sensors together in a differential mode, it can measure the local electric field. Anyway, the local electric field is quite relative term in this context, since EPIC sensors can be used to detect any disturbance of the electric field at distances up to several meters. The human body contains a large amount of conducting material and thus causes a large perturbation in the electric field. Since EPIC sensors detect these perturbations in the electric field, a human body is an easily detectable target for the sensor. For example, rising one foot while sitting a few meters away from the sensor creates a strong signal on the sensor output. (Beardsmore-Rust, 2010; Plessey Semiconductors, 2013)

Figure 5 shows a basic block diagram of the EPIC sensor. The size of the electrode depends on the input capacitance required for a particular application. For contact mode measurements where sensors are placed on or in close the proximity to the patient’s skin, the electrode's size is very important, since the device operation can be understood in terms of capacitive coupling. For devices that are several meters away, the coupling capacitance is defined only by the self-capacitance of the electrode. As the EPIC sensor takes only a very small amount of energy from the electric field, the device's response is largely a function of the input impedance as it interacts with the field. (Beardsmore-Rust, 2010)

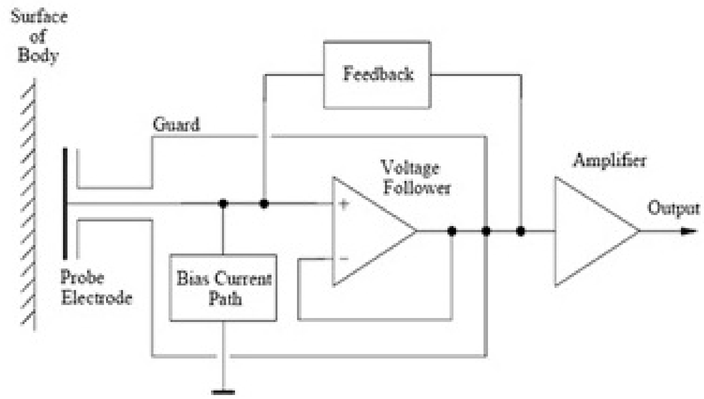

FIGURE 5. Block diagram of the EPIC sensor (Plessey Semiconductors, 2013)

5.1 Introduction and background for electric potential sensors

Measuring electric fields in an accurate and repeatable way is a very challenging task do to even nowadays, even there are all kinds of modern measuring technologies available. Electrostatic measurements, where the interest is in the presence of the charge, rather than in the movement of some quantity of the charge can be done in many ways: to measure the charge directly, to measure the electric field strength or to measure the actual spatial distribution of the charge. There is no standard way to do this measurement; there is just a range of common and less common ways to do it. Anyway there is some similarity between all the measurements, and this gives us a good basis to also understand how electric potential sensors work. (Beardsmore-Rust, 2010)

The charge Q induced on a surface, with area A [m^2] at which the electric field E [Vm^{-1}] is

EQUATION 1: $$Q = \varepsilon_0 \varepsilon_r E A$$

where ε_0 = permittivity of free space and ε_r = relative permittivity of the medium. This relationship combined with the fact that the capacitance C is defined as the quotient of the charge on a capacitor which with the voltage present on the capacitor plates creates a measurable quantity.

EQUATION 2: $$C = \frac{Q}{V} \;\; => \;\; V = \frac{Q}{C}$$

If a known capacitance of the value C is allowed to charge in the field strength E, it creates a voltage V which can ideally be measured in some way without affecting the quantity of charge on the capacitor. Since this is possible only in an ideal situation, some kind of calibration factor needs to be used to compensate the measurement circuit properties:

EQUATION 3: $$V_{sensor} = S * \frac{\epsilon_0 \epsilon_r A E}{C}$$

Where S is set (or measured) calibration factor, which varies with the sensitivity and gain of the measurement circuit.

When we take this theory to practise, we get the simplest of all electric field measurement circuits, induced charge electric field meter. In this application the strength of the field causes a directly proportional output voltage on an amplifier output.

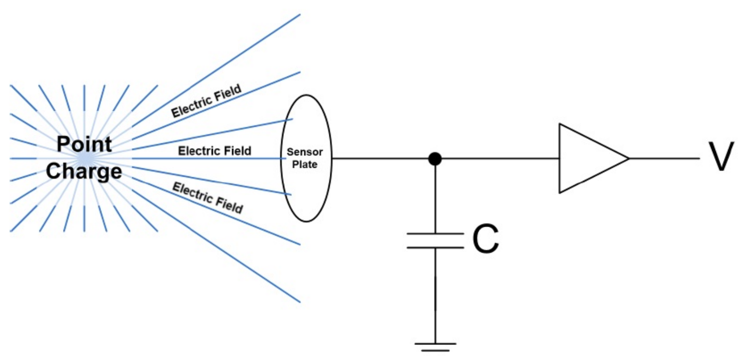

FIGURE 6. Induced charge electric field meter (Beardsmore-Rust, 2010)

On this circuit the electric field charges the capacitor that has a well-defined capacitance. The voltage on this capacitor is then amplified to the level that is easier to be measured with traditional measuring equipment. When measuring very low electric fields, the amplifier has to be designed so that it provides the minimal discharging of the front end input capacitor. Finding or designing this kind of extremely high input impedance amplifier is the most difficult part of building this electric field charge meter. If the actual level of the electric field is needed to know instead just the absence of field, the charge meter must be calibrated in the well-known electric field before the measurement.

5.2 Feedback techniques

When doing practical measurements outside the laboratory screened environments, the interference type of noise can be a big problem. When measuring equipment, an electric potential sensor in this case, saturates at the time it is measuring a signal of interest, some information will be lost and it cannot be recovered afterwards. However, if the sensor does not saturate, it might be possible to recover even very small signals from large noisy ones by using post processing techniques. For this reason it is crucial that these sensors have a sufficient dynamic range to prevent the saturation under any potential operating condition.

There are many solutions for this problem, such as filtering out the unwanted noise signal or reducing the gain of amplifier, if it is possible without compromising the signal to noise ratio. Even if these techniques provide a solution in some cases, there is no one general solution for all applications and circumstances. Since electric potential sensors might be very weakly coupled to a signal and thus causing a poor signal to noise ratio, some special techniques are used to enhance the input characteristics of the sensor. Three positive feedback techniques, Bootstrapping, Neutralization and Guarding are defined in the following chapters.

5.2.1 Bootstrapping

Bootstrapping is a technique where amplifiers input impedance is tried to be changed, usually increased, by feeding part of amplifiers output signal back to the input. If the feedback is adjusted so that the signal voltage across the component connected to the input is zero, the component does not draw any current from the input and thus the component can be seen to have an effectively infinite resistance. If the feedback signal is increased from this level, the amplifier will lose its stability. For this reason an infinite resistance cannot be archived, thus the input impedance can increase significantly when compared to the situation where Bootstrapping techniques are not used. (Beardsmore-Rust, 2010)

5.2.2 Neutralization

Neutralization is a similar technique than Bootstrapping, but instead of input impedance the input capacitance is now altered. In Neutralization the current is fed back from the output to the amplifiers input through a feedback capacitor. Neutralization feedback compensates for the input current which is shunted by the input capacitance and thus nulls its effect. Quite similar to bootstrap, on neutralization the feedback is possible to be set so that the input capacitance is completely cancelled, but there is a risk of amplifiers instability also in this case. (Beardsmore-Rust, 2010)

5.2.3 Guarding

To protect the input of an amplifier or an electrometer against the interference type of noise, the input is often surrounded by an earthed layer. This is a common situation especially when coaxial type cables are used, but the same thing can be seen on printed circuit boards, too. Because these cables and boards have a dielectric spacer between the input and grounding shield, there is always some leakage- resistance and -capacitance. When this leakage resistance is large enough it will also affect to the input impedance of very high impedance circuits. This can be avoided by using a technique named Guarding. On Guarding a voltage essentially equal to the input voltage is driven to the shielding, thus making a leakage resistance extremely large. The effect is thus quite similar to bootstrapping, but now the feedback is lead to a shielding instead of an amplifier input. Guarding also reduces a common-mode capacitance and improves a common-mode rejection. (Beardsmore-Rust, 2010)

5.3 Feedback techniques in an EPIC sensor

Advanced feedback techniques such as bootstrapping and guarding are actually the key factors to make the EPIC sensors even possible to work. The input resistance of sensors can be boosted up to values around 10^{15} Ω by using bootstrapping techniques while the input capacitance can be reduced down to 10^{-17} F, thanks to guarding techniques (Plessey Semiconductors, 2013).

To understand better how the previously introduced feedback techniques work in the case of an EPIC sensor, the feedback mechanism can be obtained by looking figure 7.

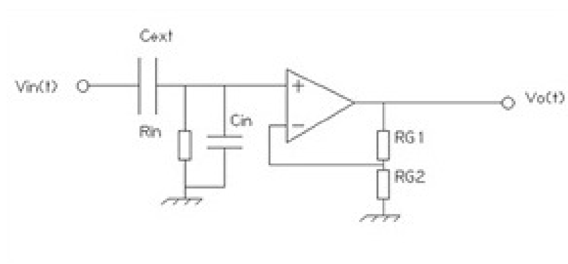

FIGURE 7. Input buffer of the amplifier (Plessey Semiconductors, 2013)

The first stage gain is set with the resistors RG1 and RG2. The input capacitance is represented with Cin, and Rin represents amplifiers input resistance. As this is a simplified example, all parasitic components that are present in a real life (for example due to the layout or substrate issues) are included to Cin and Rin. The capacitor Cext models the capacitive coupling to the measurement target.

As mentioned earlier, EPIC sensors can be used in two different modes; in a contact mode and a non-contact mode. Considering this through figure 7, a contact mode means situation where Cext >> Cin, and a non-contact mode means situation where Cext << Cin.

Figure 8 shows an example of an EPIC sensors frequency response. Corner frequencies (Fc1 and Fc2) that are marked into the figure can be calculated by using the equation 4.

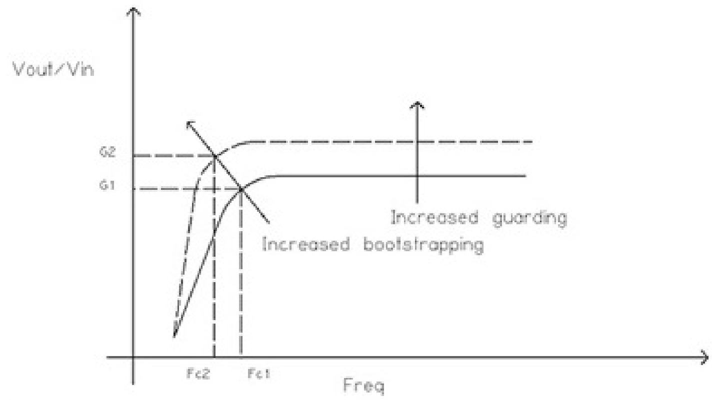

FIGURE 8. EPIC sensor frequency response example (Plessey Semiconductors, 2013)

EQUATION 4: $$Fc = \frac{1}{2\pi(Cext+Cin)Rin}$$

Because the values for Cin and Rin can be controlled by applying the bootstrapping, both the gain and corner frequency will be changed accordingly.

The response of the sensor can be controlled even more when applying the other positive feedback loops discussed earlier. This makes an EPIC sensor to be versatile tailored for many applications without changing any physical properties of the sensor, such as sensors dimensions that affect directly the input capacitance.

6 DRL, Driven Right Leg

A Signal measured from the human body does always include a large amount of noise. As mentioned in chapter 4.4 “Summary of traditional electrodes”, one major component is the power line noise that is capacitively coupled to the body. Driven Right Leg is a technique where an inversed common-mode noise component is driven back to the body to reduce noise and to improve the signal stability. The name for this technique comes from a conventional ECG application where an inversed noise component is usually driven to the right leg of the patient.

6.1 Introduction and theory for DRL

ECG measurements are usually done by using a differential measurement method. Because of the used method common mode noise should not be a problem, at least at a theory level. In practise an impedance difference between electrodes might cause a large asymmetry in two different signal paths and thus cause a differential voltage which is proportional to a common-mode noise (Lim, Chung & Park, 2010). Figure 9 helps to understand this asymmetry situation.

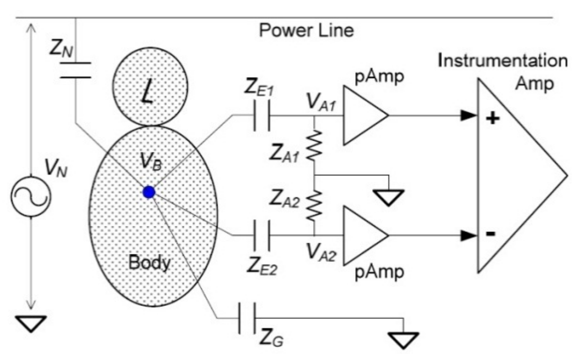

FIGURE 9: Non-contact ECG measurement model including capacitive coupling to power line (Lim etc. 2010)

Where:

Z_{E1}, Z_{E2} = electrode impedance,
Z_{A1}, Z_{A2} = input impedance of pre-amplifier
Z_N = impedance between the body and the power line
Z_G = impedance between the body and ground
V_B = body potential
V_N = power line voltage

The differential voltage V_D is transformed from the common mode interference V_B by the asymmetry in the electrode impedances, as shown in equation 5.

EQUATION 5:

$$V_D = V_{A1} - V_{A2} = \left(\frac{Z_{A1}}{Z_{E1}+Z_{A1}} - \frac{Z_{A2}}{Z_{E2}+Z_{A2}}\right) V_B$$

The transformed differential voltage V_D is proportional to the difference between electrode impedances and the common-mode noise V_B. In a case where the electrode impedance is much less than the input impedance of the pre-amplifier, the differential voltage is inversely proportional to the input impedance Z_A of the preamplifier, as shown in equation 6. (Lim etc. 2010)

EQUATION 6:

$$V_D = V_B \frac{\Delta Z_E}{Z_A}$$

Where:

$$Z_A = \frac{Z_{A1}+Z_{A2}}{2}$$

$$\Delta Z = Z_{E1} - Z_{E2}$$

When using the DRL, or in other words, driving the inverse common mode noise component to the body, the impedance between the body and the instrument is reduced at the viewpoint of the common-mode noise (Lim etc. 2010). Figure 10 shows the common-mode noise model that includes the DRL circuit.

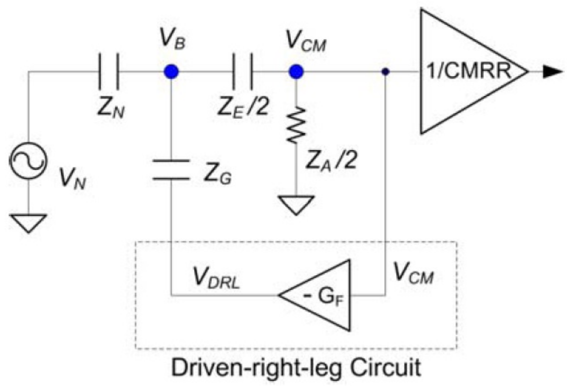

FIGURE 10: Common-mode noise model including DRL circuit (Lim etc. 2010)

The common-mode noise is reduced proportional to the increase of feedback gain G_F, as shown in equation 7. This equation is valid only to the point where the system will become unstable.

EQUATION 7:

$$V_{CM} = \frac{Z_A Z_G V_N}{(Z_A+Z_E)Z_G+((1+G_F)Z_A+Z_E+2Z_G)Z_N}$$

6.2 DRL system design and implementation in case of a non-contact ECG measurement

When using the EPIC sensor in a contact mode and when a patient touches the measuring system ground directly with the skin, the removing of a common mode noise is not a problem. In the non-contact ECG measurement there is no direct contact from the system ground to the patient's skin, and some other method for reducing the power line noise is needed. (Non-contact ECG measurement using EPIC, 2012)

In the conventional ECG applications the DRL signal is coupled directly to the patient's skin. Since this is not possible in a real non-contact measurement, the DRL signal needs to be coupled capacitively to the body. This can be done for example through clothing by using a conductive material that is placed on the seat or back of chair, as shown in figure 11. A conductive material can also be built in to a mattress or clothing. Despite the name, the DRL can also be connected to other parts of body than only the right leg.

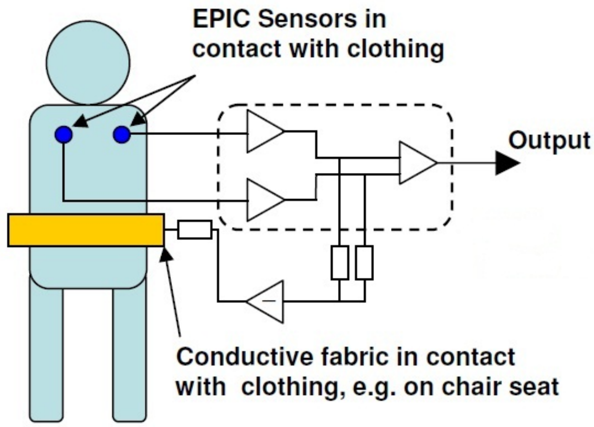

FIGURE 11: Non-contact ECG measurement including a capacitively-coupled DRL circuit (Non-contact ECG measurement using EPIC, 2012)

A DRL circuit can be built using a standard summing amplifier that generates an amplified and inverted signal, which is an average of the individual signals from two different EPIC sensors. The optimal level of feedback gain depends on many factors such as the type of used sensors, the amount of common-mode noise and clothing that is used by the patient. If the gain is at a too low level, all the noise cannot be cancelled and if the gain is too high, the system will become unstable. For this reason the gain of an DRL loop can be adjustable, as in the EPIC Demonstration Set that is used in the Measurements chapter.

7 MEASUREMENTS

One of the main interests of this thesis was to find out how well EPIC sensors work in practice. Since these sensors can be used in many different ways, there are two different levels that are evaluated. At the first level the signal quality is estimated to be good enough for diagnostic measurements. To reach this level, all five different waves must be found from the ECG signal clearly. If this level is not reached, only the R-wave is tried to find from the signal. This level presents a health application level, where the main interest is to find R-waves and thus to be able to measure the heart beat rate.

7.1 Used equipment and measuring methods

All the measurements were done by using the Plessey PS25000 EPIC Demonstration set which was connected to a battery powered laptop computer (HP EliteBook 8540w). This EPIC Demonstration Set is commercially available from the Plessey Semiconductors Ltd. The demonstration set includes two active EPIC sensors (type PS25100) and one control and interface box for connecting the system to the computer. The set also includes the needed computer software, a USB cable for connecting the interface box to the computer and a user guide. This demonstration set can be used to explore electrophysiological signals such as an ECG or an EEG but also to test electric field detection applications such as a motion sensing.

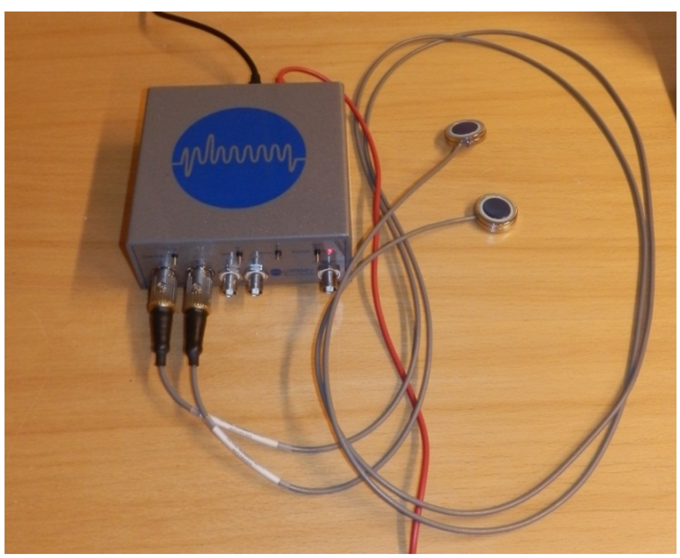

FIGURE 12: Plessey PS25000 Demonstration set

The control and interface box was used, as the name says, to provide an easy interface for the sensors. This box requires a connection to a computer that has the associated software installed for the two reasons; the interface box is powered only through a USB connector, and results can be seen either on the display of the computer or on the separate oscilloscope. The box provides the following functions:

- Power and signal socket for two PS25100 sensors (channel A and B)
- Switchable gain of x1 and x10
- Switchable low pass filtering
- Switchable notch filtering
- Analogue outputs for each sensor (channel A and B)
- Analogue difference output for the two sensors (channel A -channel B)
- A data acquisition (DAQ) card
- A USB 2.0 interface
- DRL circuit with adjustable gain

The user interface of the control and interface box can be seen in figure 13. This software provides the needed drivers for a data acquisition card and shows the measuring results on the oscillogram. The software makes it possible to post process the measuring data by using many filters included in the software. The recording of the measuring data for the later use is also possible.

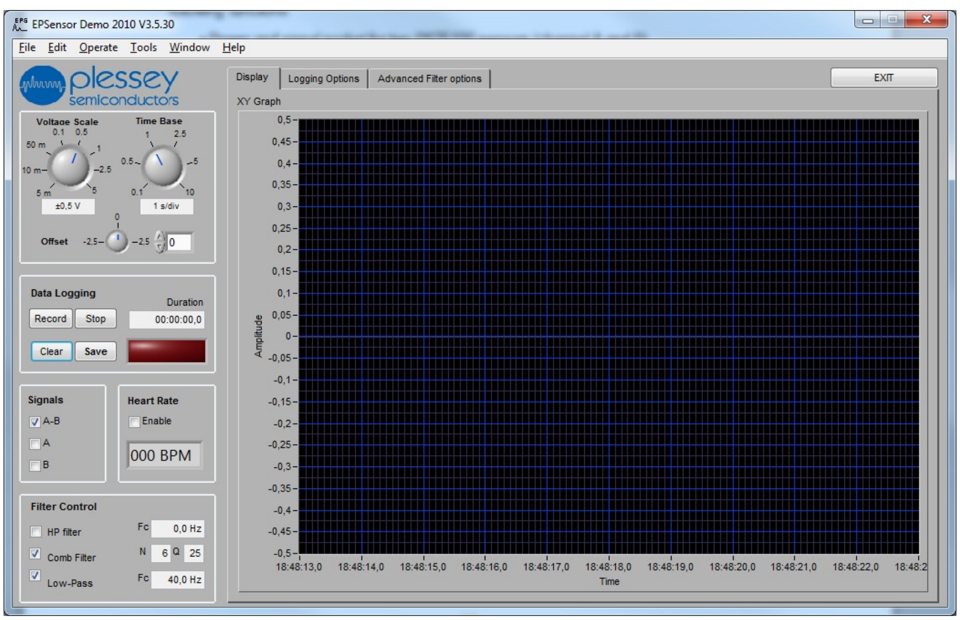

FIGURE 13: User interface control and interface boxes software

To get familiar with the new measuring system, the testing was started with in contact mode measurements from the bare skin. On this mode sensors should be able to provide a very good level ECG signal and all interference and unwanted noise is at as low level as possible. For this reason it should be easy to explore how a different filtering setting affects the measuring result. When the effect of different settings in the software and in the interface box have been tested, the testing will continue with non-contact measurements.

7.2 In contact measurements

Contact measurements were performed by placing the EPIC sensors to the bare skin on chest. For all measurements, the control and interface box setting were done according to the user guide recommendations (low pass filter: in, gain: x10 and notch filter: in). To attach the sensors firmly, the training computer's flexible chest strap was used, as shown in figure 14.

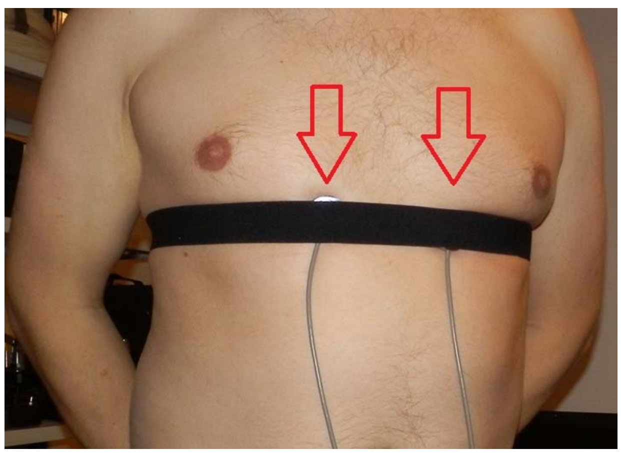

FIGURE 14: EPIC sensor placing on in-contact measurement

The signal quality was surprisingly good even without any software filter and without an DRL feedback, as seen from chart 1 on the measuring results (Appendix 1). When different software filter settings were tested, it was clear that a wrong filtering setting can easily spoil the signal quality. For this reason recommended filtering setting from the user guide was used for all measurements, if not otherwise noted. These settings are:

- High pass filter: 50 mHz
- Low pass filter: 150 Hz
- Comb filter: enable, N=6, Q=25

Enabling both the Driven Right Leg and the filtering on software to improve the signal quality a little bit, but the effect was not significant in the case of in contact measurement. The main difference comes from the signal's baseline change when filters are not enabled. The effect can be seen in charts 2 and 3 in Appendix 1.

Chart 4 presents what happens when a subject is moving during the measurement. The movement in this case is just rising both hands above the head and dropping them back to the sides while sitting on place. EMG signals are dominating the ECG curve during the movement, and a baseline will wander up and down for a while before settling back to the same level as it was before the movement. When studying more disturbs that are caused by the movement, it was found that some part of movements is caused by the moving of EPIC sensor's cables. The cable shielding seems to be insufficient for these kinds of measurements. For this reason a movement effect was tried to be eliminated on the rest of the measurements.

The last in contact mode test was done to explore how reducing the distance between two EPIC sensors will affect the results. Normally, the used distance between the sensors was 12 centimetres, and it was first reduced to six centimetres and then down to two centimetres. The results are shown in charts 5 and 6. The results show clearly that a shorter distance leads to a lower amplitude on a measured signal. For this reason the signal will suffer more easily from all interferences, as seen from the baseline that starts to drift. This is because of a small movement that happens when the patient is breathing, and thus the EMG signal starts to modulate the ECG signal.

7.3 Non-contact mode measurements

Non-contact mode measurements were performed similarly than in contact measurements, except this time electrodes are placed over the shirt instead of bare skin. Two different shirts were used in measurements, a thin T-shirt and a thicker woollen shirt. Both shirts were made from 100% cotton. Beside different shirts, tests were performed with different combinations of software filtering and DRL.

Non-contact measurements were done without any software filtering and without an DRL are shown in charts 7 and 10. As seen from the overview charts, the ECG signal is useless since not even the R-waves can be clearly identified from noise. When measuring the signal through a T-shirt and using only software filters, the R-waves can be identified quite clearly as shown in chart 8. The used filter settings in this precise case were 8 – 25 Hz and a comb filter was enabled with settings N=6 and Q=25. This gives much better results than the normally used 50 mHz – 150 Hz range, because it filters a lot of noise that is caused by moving. In this case moving comes from breathing since all other movement was avoided.

Chart 9 is showing non-contact measuring results through a T-shirt. In these measurements both the DRL and software filters are used. As can be seen from chart 9, a non-contact measurement through the T-shirt gives a surprisingly good signal. With optimal filtering settings the signal quality could be even better. Finding better filter settings and thus seeing how a good signal can be reached would definitely need more studying of ECG filtering techniques. More measurements would also be needed to verify that filters do not distort the signal, so that a filtered ECG signal can still be used for the diagnostic purposes.

Chart 11 is showing a non-contact measurement through two shirts, a T-shirt and a woollen shirt. Even when using two shirts the R-waves can be found easily. Since the amplitude of the signal is at a very low level, discovering the diagnostic level ECG signal looks impossible. A much better signal quality can definitely be achieved for a health application use by changing filtering settings and doing some post processing for the signal.

7.4 Summary of measurements

The overall signal quality that was achieved in these measurements was quite good. In contact measurements showed clearly that the EPIC sensors can reach the ECG quality that is at the diagnostic level, as the manufacturer of the sensor claims. Non-contact measurement results were also surprisingly good, especially when measuring through the thin T-shirt.

Partly because of the used equipment, any measurements that included any moving could not be done. The EPIC demonstration set included sensors with very long cables that were unfortunately quite sensitive for the moving effect. Just moving the cables caused so much noise to the measurement that any testing could not be executed in a repeatable way.

Based on these test results, it is impossible to say what is the real potential of these sensors for health applications, where the measurements must be done during the subject's movement. Testing this would definitely need building an ambulatory device that could record the ECG signal from the EPIC sensor independently during the exercise. Also, more study should be done to understand the possibilities of signal filtering and post processing in the case of processing the heart beat or when doing the ECG measurement.

9 CONCLUSION

The aim of this thesis was to give basic knowledge of the different electrodes that are used for electrocardiogram measurements without going too deep into medical or physiological details. The main focus was on a new Electric Potential Integrated Circuit sensor that has some very unique features. Beside the theory, the EPIC sensor was tested in practise to see if it really can fulfil all the expectations that sensor's developer has given.

The theoretical part for wet and dry electrodes was tried to be selected so that it supports and helps to understand why the Electric Potential Sensor is so special compared to the other sensors, and on the other hand what are the biggest challenges in the ECG measurements. Hopefully, this theory also helps the reader to understand why these different electrodes are used.

Because the subject of this thesis work is very specific, in some parts of this document it was hard to draw a clear line when the reader will have enough information and on the other hand when the information goes too deep into the details. Some sacrifices were needed to keep the given schedule, so all the measurements that were originally planned could not be completed. Beside the time, the used measuring equipment also limited the testing, since the measurements with the patient movement could not be completed because of an unreliable cable shielding.

Since the testing results so far are very promising, studying the EPIC sensor possibilities in a field of the ECG measurement should be continued. The current testing equipment should be either modified or replaced so that it could be used for measurements that also include patient movement. Also, the signal filtering and post processing of the ECG signal should be studied more to know the real limitations of this new interesting sensor.

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All the measurements are done by using Plessey PS25000 EPIC Demonstration set which is connected to laptop computer. Results are recorded using software which was delivered with the Demonstration set. On all charts x-axis presents time in seconds and y-axis presents voltage in volts. Each page has two charts; first presents overall view, and the second chart presents detailed view of the same measurement. All the measurements with related settings are listed in figure 15.

Meas/chart number	Page number	Measurement type	Measurement place	SW filters	DRL	Notes
1	37	In contact	Chest			
2	38	In contact	Chest	X		
3	39	In contact	Chest	X	X	
4	40	In contact	Chest	X	X	Movement
5	41	In contact	Chest	X	X	Sensor distance 6 cm
6	42	In contact	Chest	X	X	Sensor distance 2 cm
7	43	Non-contact	Chest			T-shirt
8	44	Non-contact	Chest	X		T-shirt
9	45	Non-contact	Chest	X	X	T-shirt
10	46	Non-contact	Chest			T-shirt + wool shirt
11	47	Non-contact	Chest	X	X	T-shirt + wool shirt

FIGURE 15: List of measurement and settings

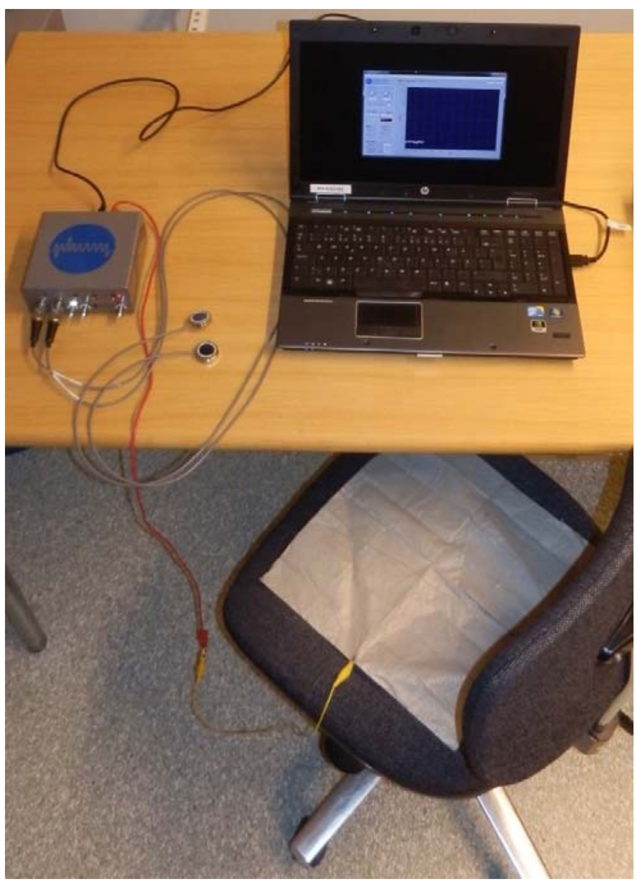


FIGURE 16: Used measureing equipment including DRL sheet on the chair

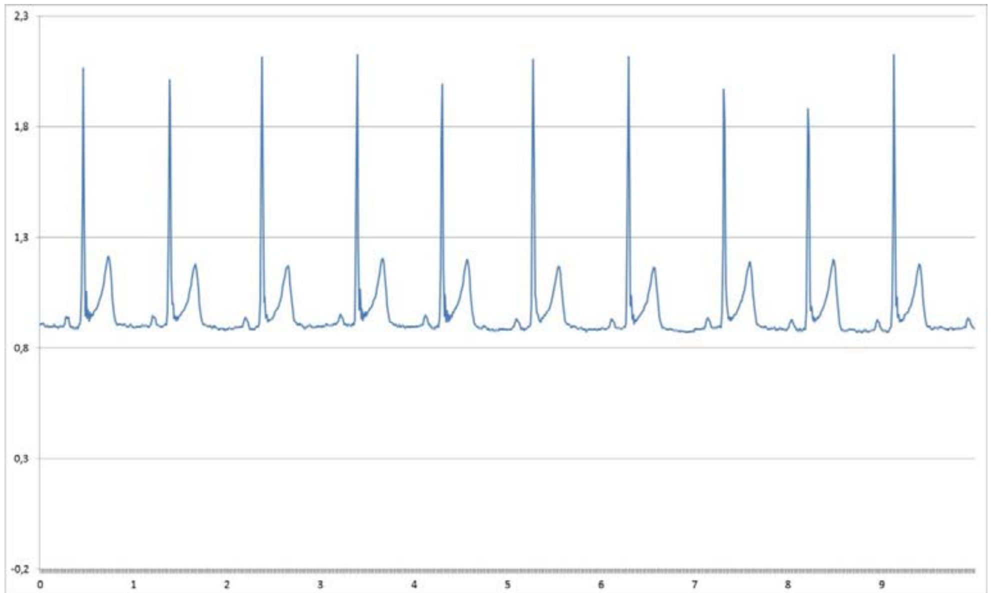


CHART 1. Overview

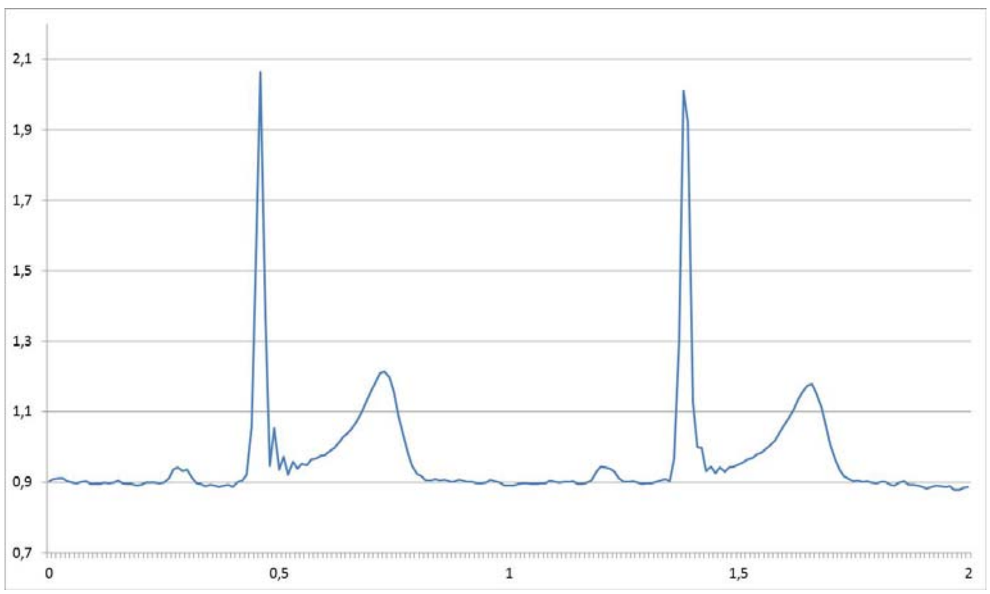
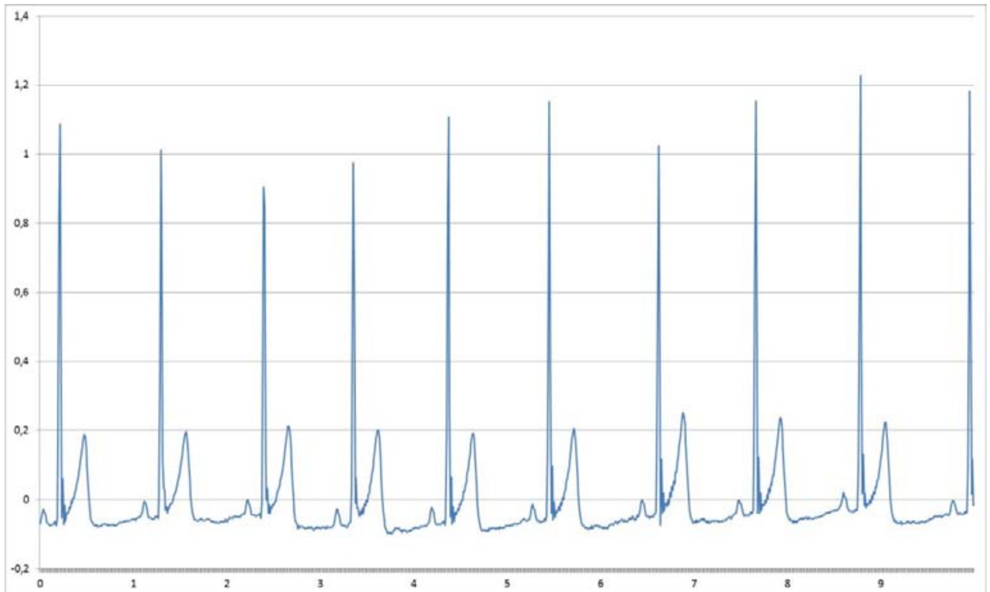


CHART 1. Details



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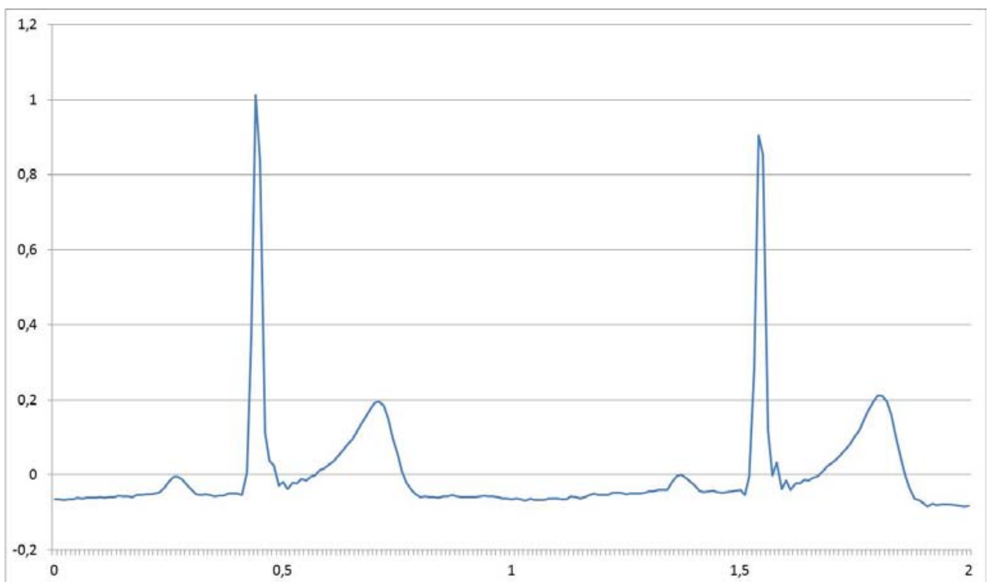

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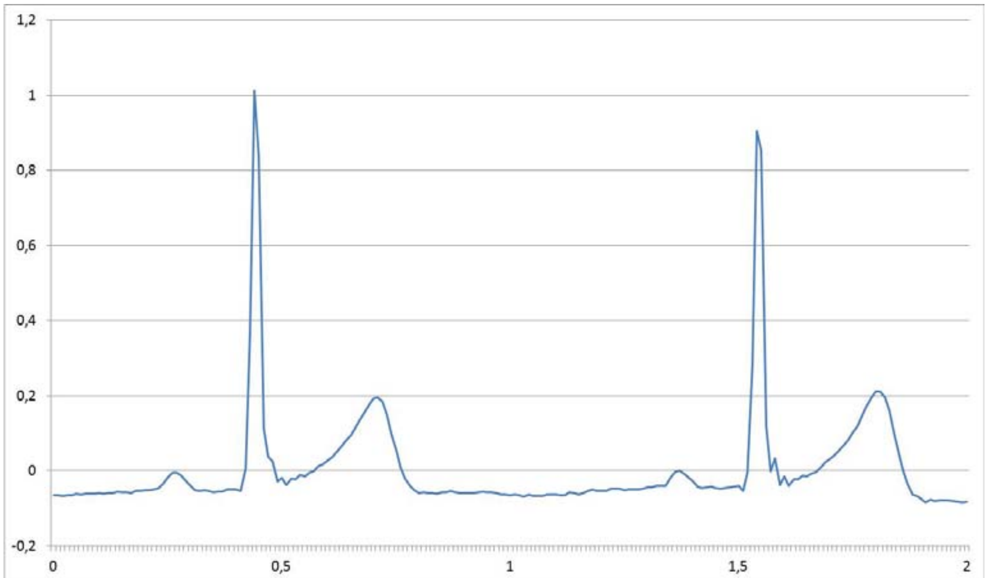

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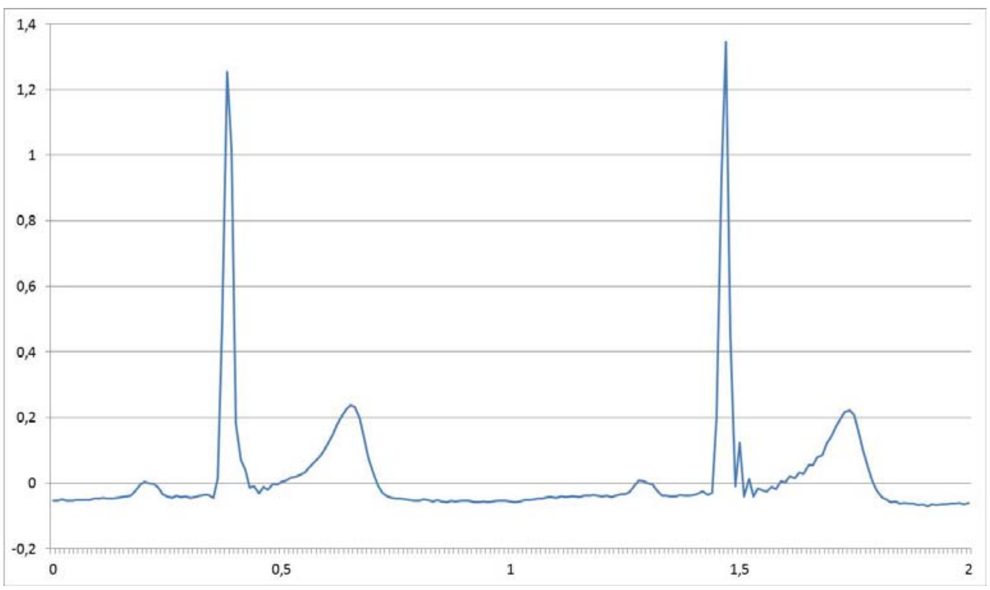
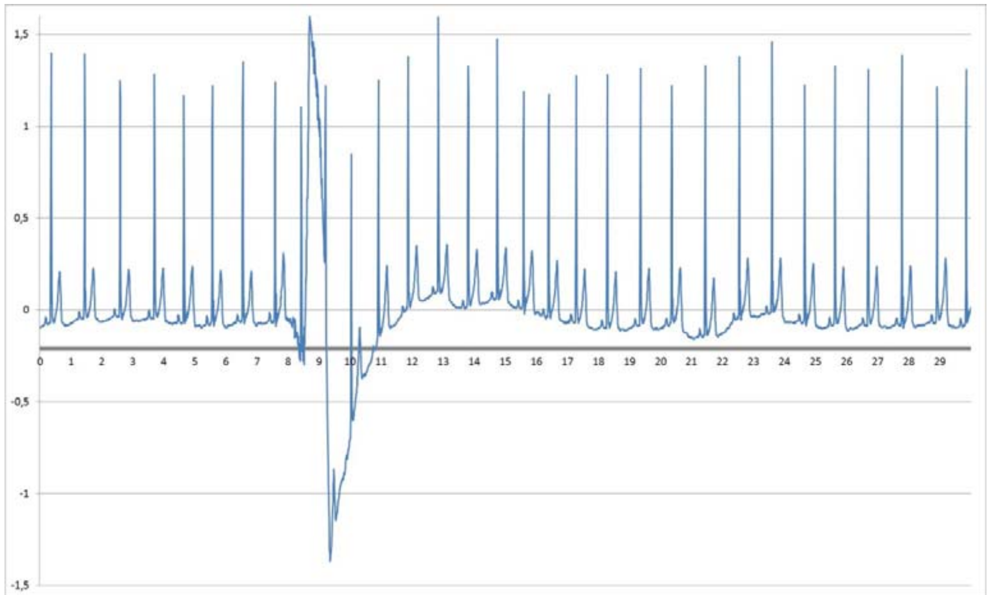


CHART 3. Details



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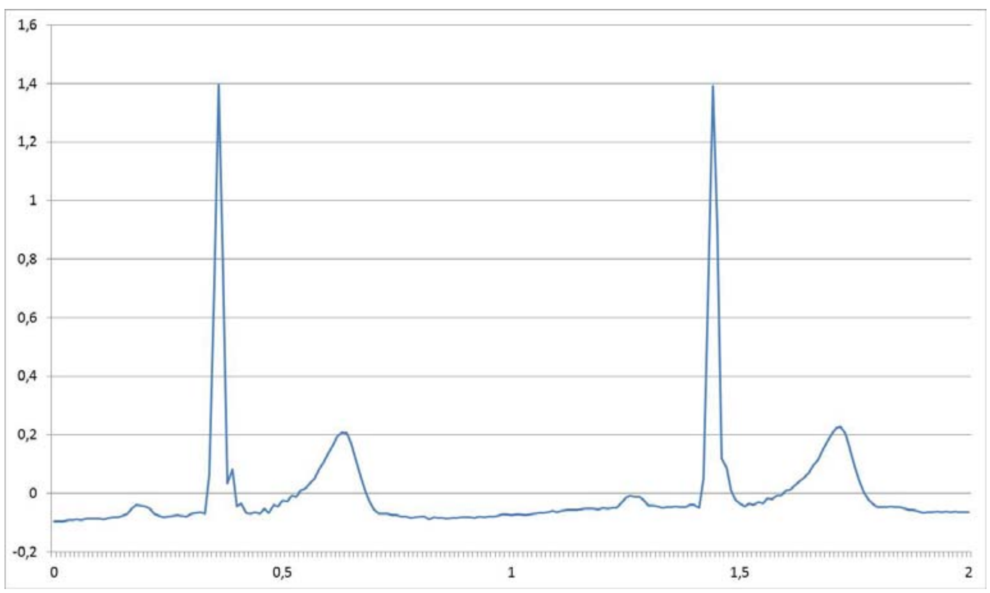

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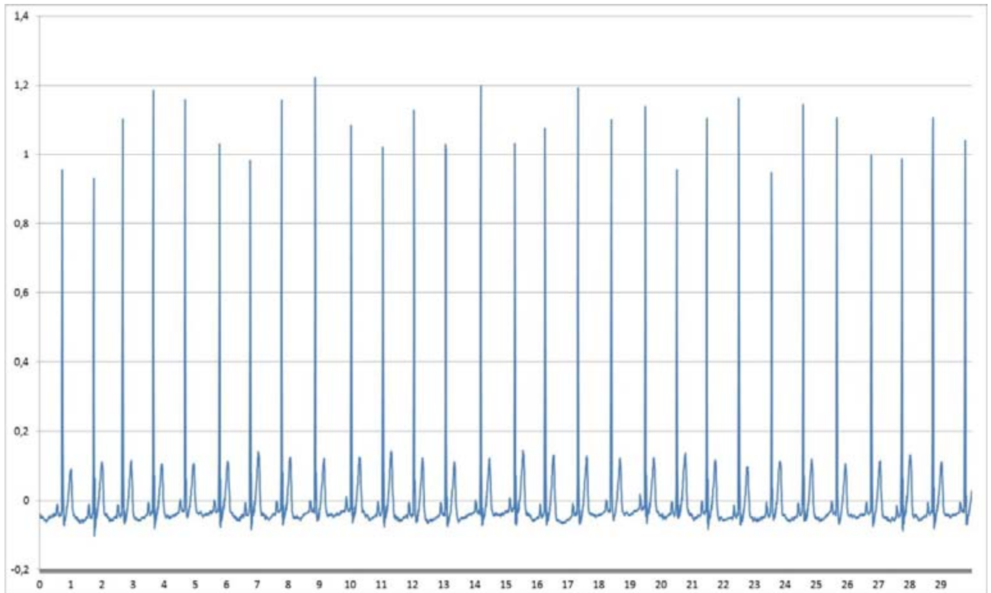
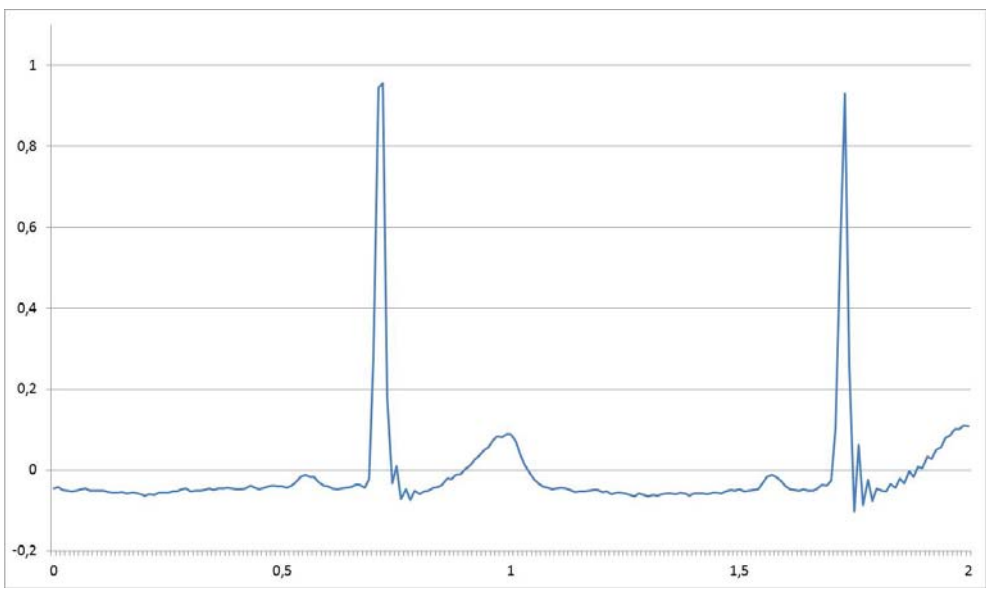


CHART 5. Overview



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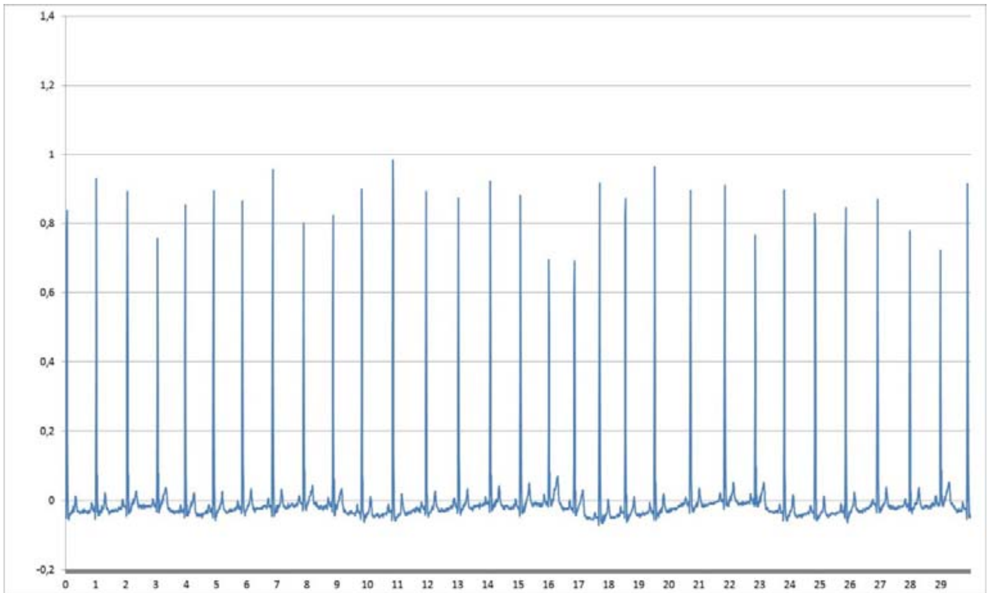

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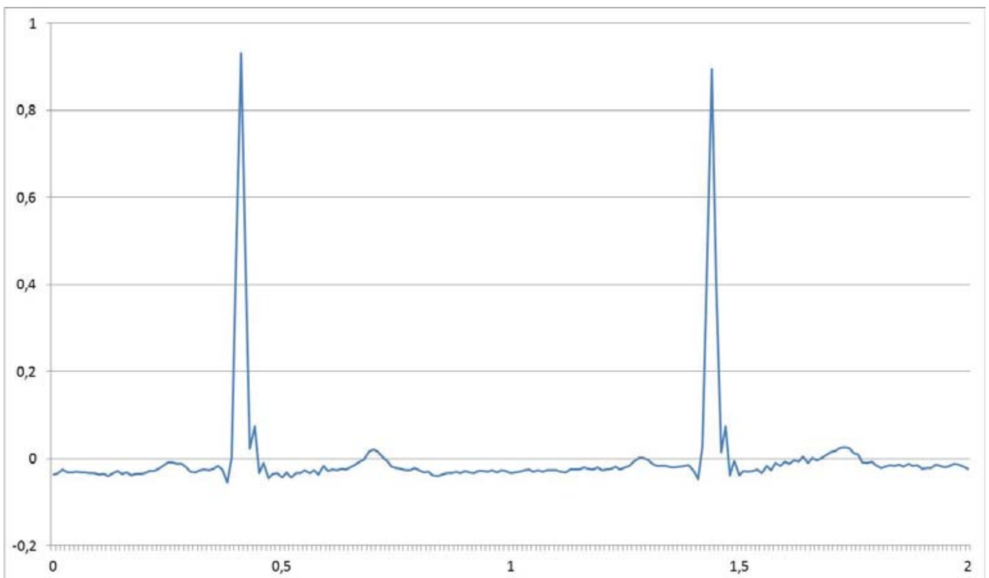

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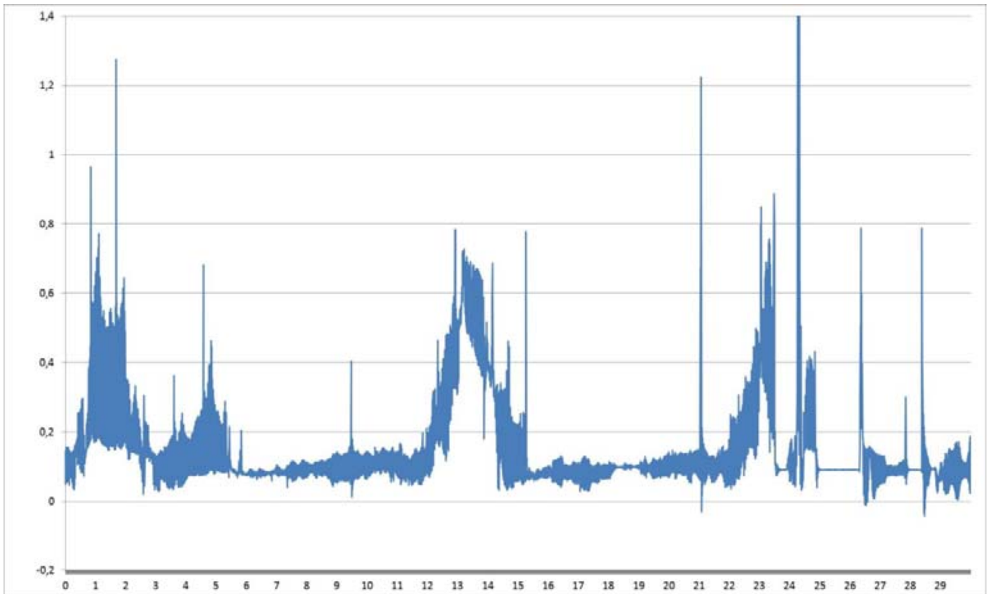

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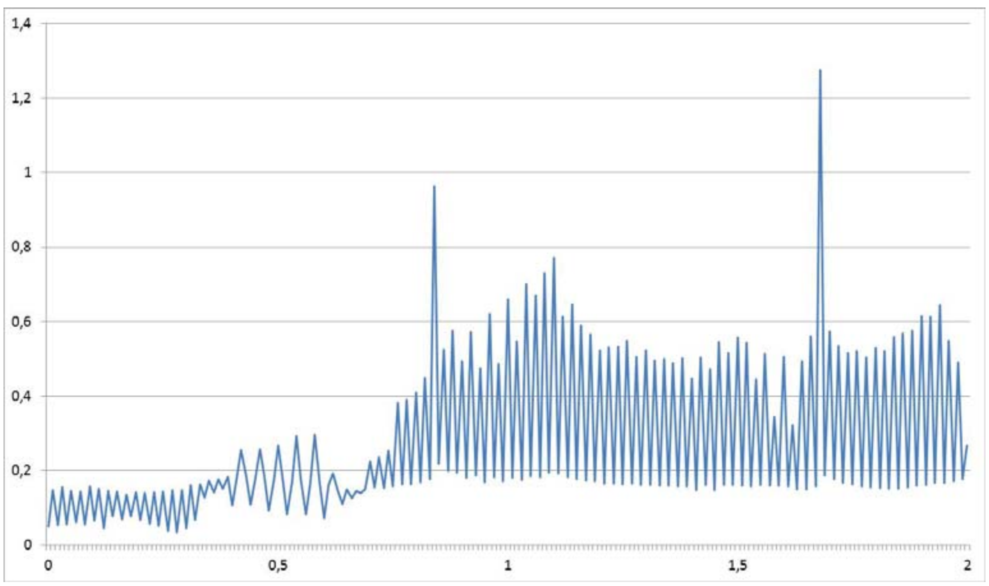

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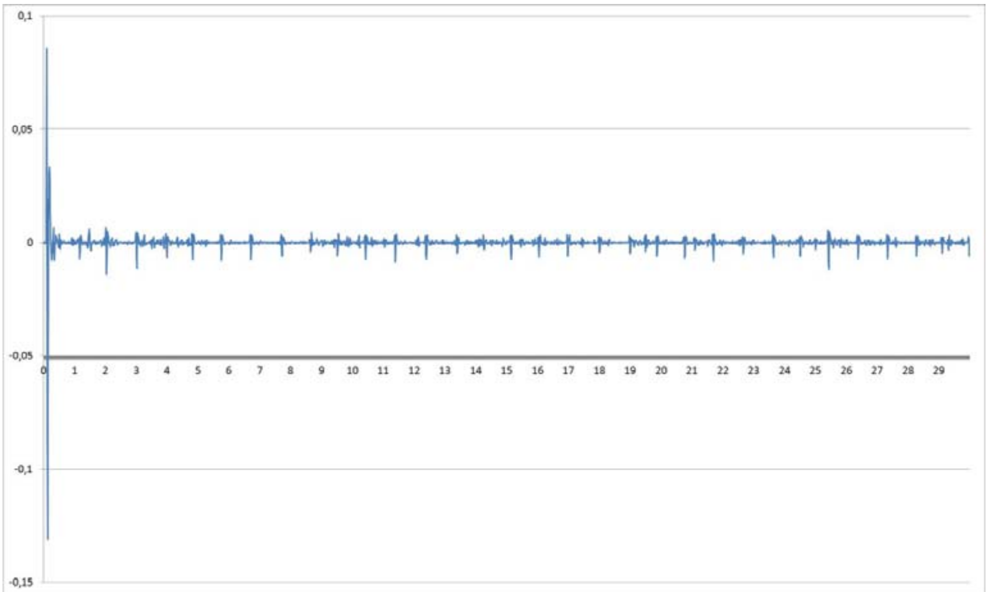

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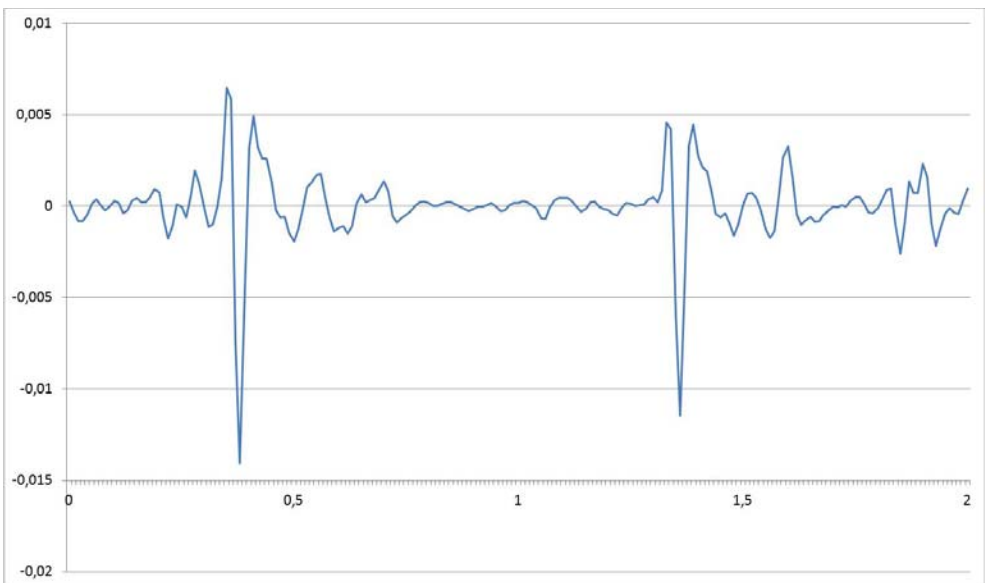

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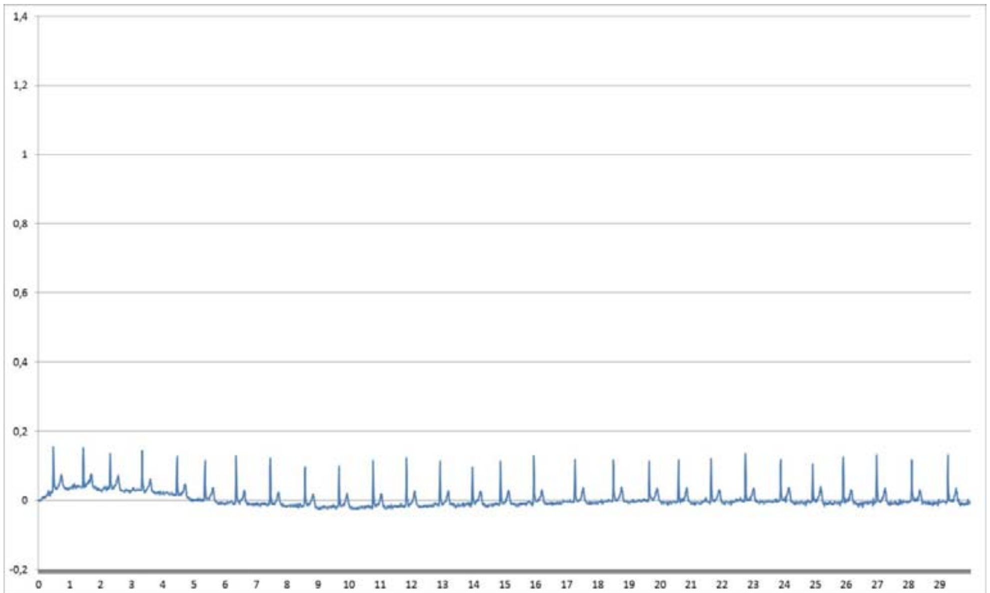

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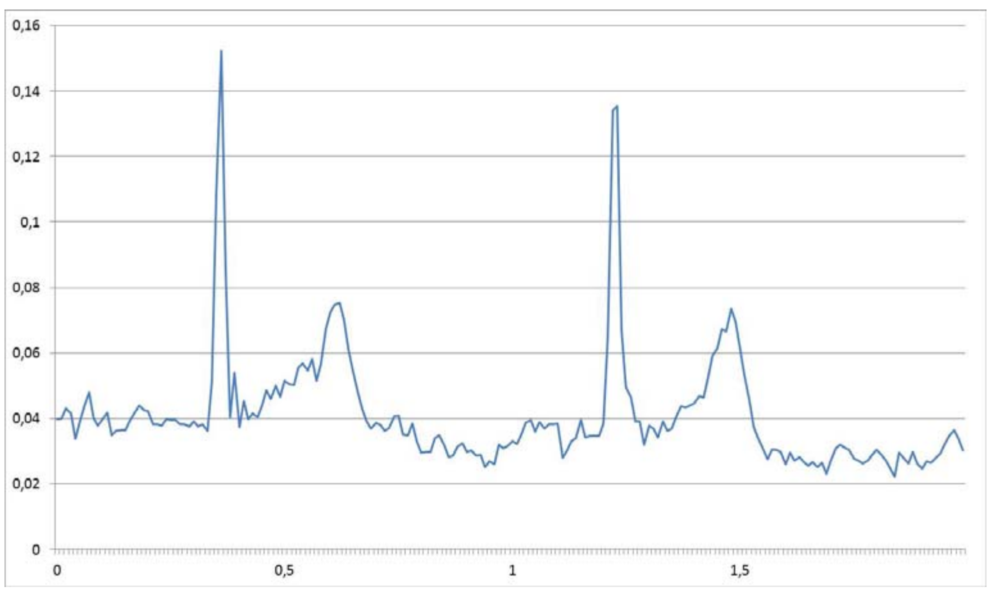

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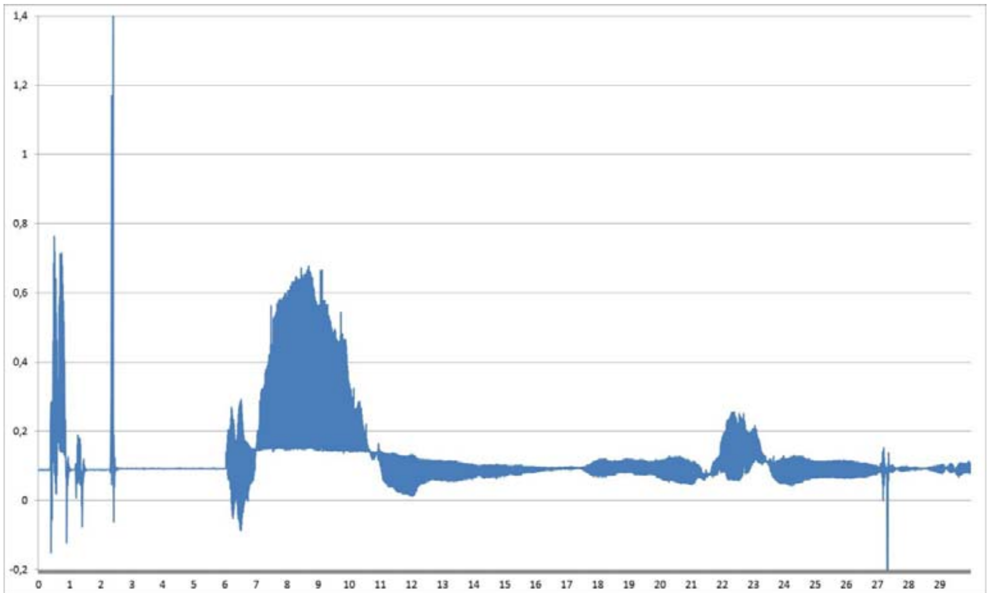

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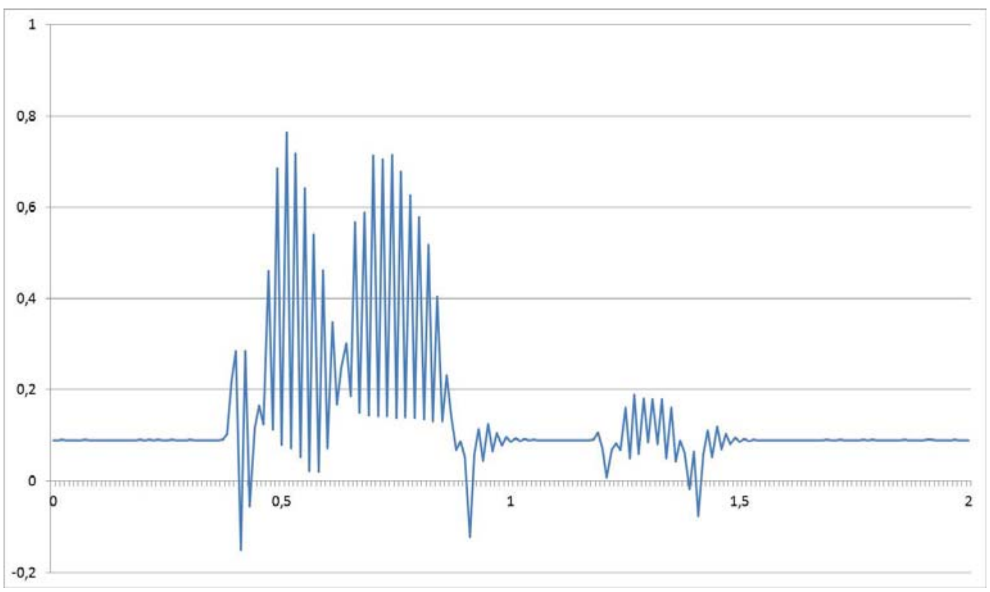

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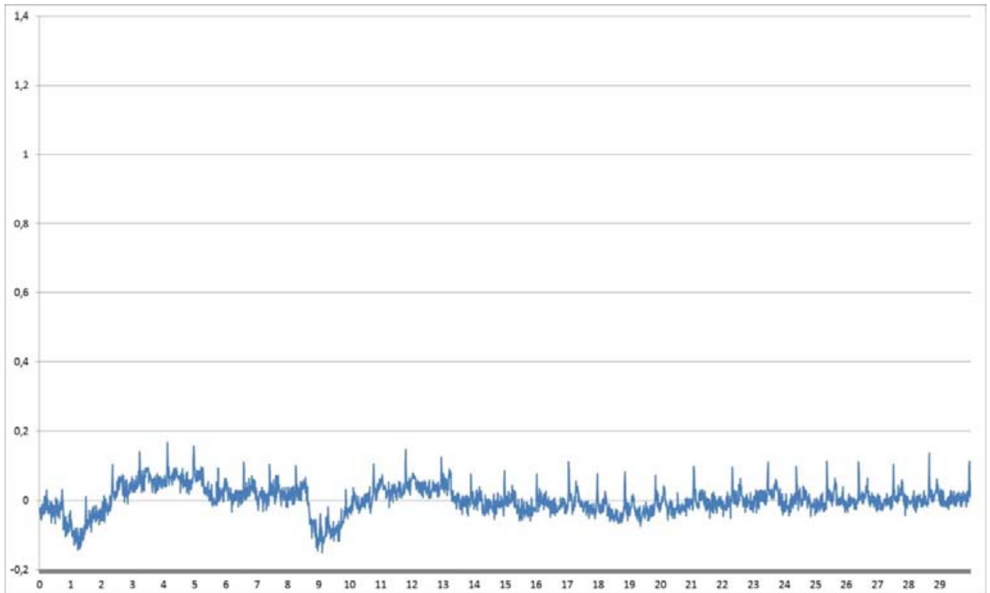

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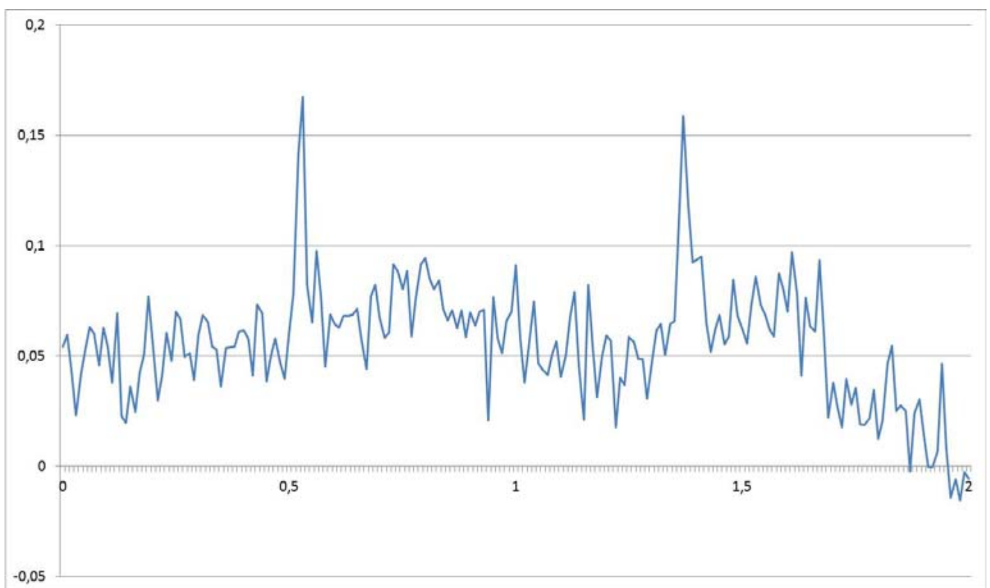

CHART 11. Details