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Non-Invasive Foetal Monitoring with Combined ECG - PCG System

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1. Introduction

Although modern ultrasound provides remarkable images and biophysical measures, the technology is expensive and the observations are only available over a short time. Longer term monitoring is achieved in a clinical setting using ultrasonic Doppler cardiotocography (CTG) but this has a number of limitations. Some pathologies and some anomalies of cardiac functioning are not detectable with CTG. Moreover, although frequent and/or long-term foetal heart rate (FHR) monitoring is recommended, mainly in high risk pregnancies, there is a lack of established evidence for safe ultrasound irradiation exposure to the foetus for extended periods (Ang et al., 2006). Finally, high quality ultrasound devices are too expensive and not approved for home care use. In fact, there is a remarkable mismatch between ability to examine a foetus in a clinical setting, and the almost complete absence of technology that permits longer term monitoring of a foetus at home. Therefore, in the last years, many efforts (Hany et al., 1989; Jimenez et al., 1999; Kovacs et al., 2000; Mittra et al., 2008; Moghavvemi et al., 2003; Nagal, 1986; Ruffo et al., 2010; Talbert et al., 1986; Varady et al., 2003) have been attempted by the scientific community to find a suitable alternative.
The development of new electronic systems and sensors now offers the potential of effective monitoring of the foetus using foetal phonocardiography (FPCG) and foetal electrocardiography (FECG) with passive, fully non-invasive low cost digital recording systems that could be suitable for home monitoring. These advances provide the opportunity of extending the recordings of the current commonly used CTG from relative short to long term, and provide new previously unavailable measures of cardiac function.
In this chapter, we present highlights of our research into non-invasive foetal monitoring. We introduce the use of FECG, FPCG and their combination in order to detect the foetal heart rate (FHR) and potential functional anomalies. We present signal processing methodologies, suitable for longer-term assessment, to detect heart beat events, such as first

and second heart sounds and QRS waves, which provide reliable measures of heart rate, and offer the potential of new information about measurement of the systolic time intervals and foetus circulatory impedance.

2. Foetal monitoring

The most important aim of foetal surveillance is to avoid intrauterine death or permanent damage to the foetus. So, in industrialized countries, all pregnant women periodically take pregnancy and foetal well-being checks, which include measuring the pattern of foetal growth and maturation, oxygen availability and cardiac functions.
The foetal heart rate (FHR) is currently monitored for routine ante partum surveillance in clinical practise (Babbitt, 1996) and it is thought to be an indicator of a correctly functioning nervous system (Baser et al. 1992). FHR analysis as a means of monitoring foetal status has become widely accepted and continuous FHR monitoring should be recommended, particularly for high-risk pregnancies (Kovacs et al, 2000; Moghavvemi et al., 2003; Varady et al., 2003).
There are two situations for which FHR provides important information about the condition of the foetus. It is known that FHR monitoring is able to distinguish between the so called *reactive* foetus and the so called *non-reactive* foetus (Bailey et al., 1980). A foetus is considered *reactive* if the FHR will temporarily accelerate in response to stimulation (e.g. during a uterine contraction). Alternatively a foetus is considered *non-reactive* if no accelerations were observed or they did not meet the criteria for a reactive test (Rabinowitz et al., 1983). The above mentioned classification is considered a reasonably reliable indicator of foetal development and well-being (Babbitt, 1996). It is also known that a normal reactive foetus is less likely to suffer foetal distress during labour (Janjarasjitt, 2006).
FHR can be monitored by means of different techniques: CTG, magnetocardiography, electrocardiography (ECG) and phonocardiography (PCG). We describe these techniques in the following sections.

2.1 Ultrasonic Doppler cardiotocography (CTG)

CTG is one of the most commonly used, non-invasive pre-natal diagnostic techniques in clinical practice, both during ante partum and labour (Romano et al., 2006). In some countries, the CTG is considered a medical report with legal value (Williams and Arulkumaran, 2004). Since its introduction in the 1960s, electronic foetal monitoring has considerably reduced the rate of perinatal morbidity and mortality (Shy et al., 1987). It can be used from the 24th week of gestation onwards even if, in clinical routine, it is generally used in the last weeks of gestation only (from the 35th week). During CTG diagnostic monitoring, FHR and uterine contractions (UC) are simultaneously recorded by means of an ultrasound Doppler probe and a pressure transducer (Cesarelli et al., 2009), respectively.
In order to record a FHR signal an ultrasonic beam is aimed at the foetal heart. The ultrasound reflected from the beating heart walls and/or moving valves is slightly Doppler shifted as a result of the movement. After demodulation the Doppler shift signal is used to detect the heart beats in order to extract the FHR. The ultrasonic frequencies used are generally within the range of 1-2 MHz (Karlsson et al., 1996).
The advantage of the Doppler ultrasound technique is that one can be virtually assured that a recording of FHR will be obtained. The disadvantages of such systems are that they require intermittent repositioning of the transducer and are only suitable for use by highly

trained operators. Because the procedure involves aiming a directional beam of a 2 MHz ultrasound at the small target a foetal heart presents, the use of Doppler ultrasound is not suitable for long periods of FHR monitoring. Moreover, as previously mentioned, although frequent and/or long-term FHR monitoring is recommend, mainly in risky pregnancies, it has not been proven that long applications of ultrasound irradiation are absolutely harmless for the foetus (Kieler et al., 2002).

The major limitation of the Doppler ultrasound technique is its sensitivity to maternal movements that result in Doppler-shifted reflected waves, which could be stronger than the foetal cardiac signal (Hasan et al., 2009). Thus the CTG technique is inappropriate for long-term monitoring of FHR, as it requires the subject to remain immobile. Moreover, the detection of the heart beats relies upon a secondary effect (the mechanical movement of the heart and/or the cardiac valves) and it is therefore not as accurate for FHR analysis as detection of the QRS complex from FECG. In addition, FHR is the only parameter obtained by CTG and some pathologies and anomalies of cardiac functionality are not detectable from the FHR alone. Research has shown that a global assessment of morphological and temporal parameters of the FECG or FPCG during gestation can provide further information about the well-being of the foetus (Martenset al, 2007; Varady et al., 2003; Kovacs et al., 2000; Hany & Dripps, 1989).

2.2 Foetal magnetocardiography

Foetal magnetocardiography (FMCG) consists of the measurement of the magnetic fields produced by the electrical activity of the foetal heart muscle (Janjarasjitt, 2006). The recording uses the SQUID (Superconducting Quantum Interference Device) biomagnetometry technique. The FMCG is morphologically and temporally similar to the FECG since the electrical field and the magnetic field are generated in conjunction by the activity of the heart.

Because of the disadvantages of the FMCG such as size, cost, complexity of the required instrumentation, and again the need to minimise subject movement (Wakai, 2004; Zhuravlev et al., 2002; Mantini et al., 2005), FMCG is currently mainly a research tool and little used in clinical practice. However, a considerable advantage over FECG is that FMCG can be recorded reliably from the 20th week onwards, unaffected by the insulating effects of the vernix caseosa, and with virtually no interference from the maternal ECG. Hence, the FMCG result can help to classify arrhythmias, such as heart blocks and atria flutter, and to diagnose a prolonged QT-syndrome (Mantini et al., 2005; Wakay, 2004; Zhuravlev et al., 2002).

2.3 Foetal phonocardiography

The preliminary results obtained by Baskaran and Sivalingam (Tan & Moghavvemi, 2000) have shown that there are significant differences in the characteristics of FPCG signals between intrauterine retarded and normal growth during pregnancy. This preliminary study has further inspired investigations into the possibility to employ FPCG to identify foetuses at risk. This could be a significant contribution to the pressing clinical problem faced by some abortions and preterm babies. FPCG records foetal heart sounds using a passive, non-invasive and low cost acoustic sensor (Varady et al., 2003; Kovacs et al., 2000; Hany & Dripps, 1989). This signal can be captured by placing a small acoustic sensor on mother's abdomen and, if appropriately recorded, is very useful in providing clinical indication. Uterine Contractions (UCs) may be simultaneously recorded by means of a pressure transducer.

Even though the heart it is not fully developed in a foetus, it is still divided into two pairs of chambers and has four valves. During the foetal cardiac cycle, when the ventricles begin to contract, the blood attempts to flow back into the atrial chambers where the pressure is lower: this reverse flow is arrested by the closing of the valves (mitral and tricuspid), which produces the first heart sound (S1). After, the pressure in the ventricular chambers increases until the pulmonary valves open and the pressurized blood is rapidly ejected into the arteries. The pressure of the remaining blood in the ventricles decreases with respect to that in the arteries and this pressure gradient causes the arterial blood to flow back into the ventricles. The closing of the pulmonary valves arrest this reverse flow and this gives rise to the second heart sound (S2) (McDonnell, 1990).
A disadvantage of FPCG is that it is not possible to fully automate the signal processing for detecting the hear sounds because the signal characteristics depend on the relative positioning of the foetus with respect to the sensor. This results in a variable signal intensity and spectrum. Moreover, recordings are heavily affected by a number of acoustic noise sources, such as foetal movements, maternal digestive and breathing movements, maternal heart activity and external noise (Mittra et al., 2008; Ruffo et al., 2010).
Despite the disadvantages mentioned above, FPCG provides valuable information about the physical state of the foetus during pregnancy and has the potential for detection of cardiac functionality anomalies, such as murmur, split effect, extra systole, bigeminal/trigeminal atrial. Such phenomena are not obtainable with the traditional CTG monitoring or other methods (Chen et al, 1997; Moghavvemi & Tan, 2003; Mittra et al., 2008).

2.4 Foetal electrocardiography

FECG (Echeverria et al., 1998; Pieri et al., 2001) has also been extensively studied, but it is difficult to obtain high quality recordings, mainly because of the very poor signal to noise ratio (SNR). Moreover, the automated analysis of FECG is less accurate than that of CTG (Varady et al., 2003).
ECG is a recording of the electrical potentials generated by heart muscle activity. Aristotle first noted electrical phenomena associated with living tissues and Einthoven was the first one demonstrating the measurement of this electrical activity at the surface of the body, which resulted in the birth of electrocardiography (Janjarasjitt, 2006).
Electronic foetal monitoring for acquiring the FECG can be external to the mother, internal, or both. The internal monitoring method is invasive because of the placement of a small plastic device through the cervix. A foetal scalp electrode (a spiral wire) is placed just beneath the skin of the foetal scalp. This electrode then transmits direct FECG signal through a wire to the foetal monitor in order to extract the FHR. Because the internal foetal monitor is attached directly to the scalp of the foetus, the FECG signal is usually much clearer and more consistent than the signal recorded by an external monitoring device. However, the most important problem is a risk of infection which increases significantly in long term recordings (Murray, 2007). Hence, a foetal scalp electrode cannot be used ante partum period (Hasan, 2009). In contrast, external methods utilizing abdominal FECG have a greater prospect for long-term monitoring of FHR (e.g., 24 h) and foetal well-being. We have shown that the FECG can be obtained non-invasively by applying multi-channel electrodes placed on the abdomen of a pregnant woman (Gargiulo et al., 2010).
The detection of FECG signals by means of advanced signal processing methodologies is becoming a very essential requisite for clinical diagnosis. The FECG signal is potentially precious to assist clinicians during labour for more appropriate and timely decisions, but

disadvantages such as low SNR, due to the different noise sources (Hasan et al., 2009), and the necessity of elaborate signal processing have impeded the widespread use of long-term external FECG recordings.

3. Processing of the FPCG Signal

In an adult, the heart (a sound generator) is closer to the transducer than in a foetus, where it may be separated from the probe by a distance of up to ten times the foetal heart diameter (Talbert, 1986). In addition, the foetal heart is a much weaker sound generator than the adult heart. Generally, the foetal heart sounds can be heard in only a small area of the mother's abdomen of usually no more than 3 cm in radius, although sometimes this range can extend to a 12 cm radius (Zuckerwar et al., 1993).

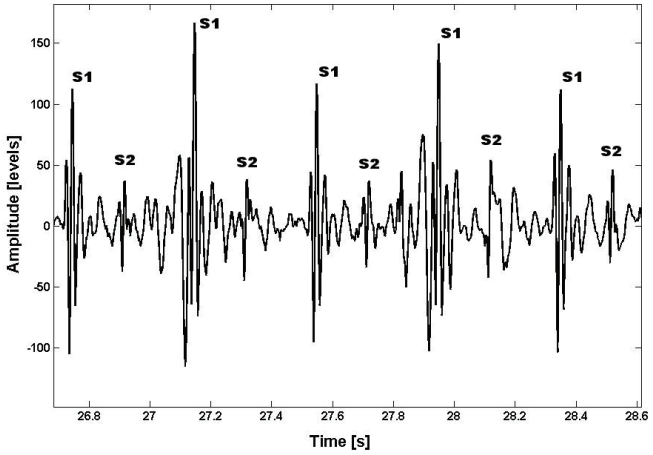

Fig. 1. Example of a FPCG signal (37th gestational week) recorded by a portable phonocardiograph and digitized with a sampling frequency of 333 Hz and 8-bits ADC.

In figure 1 examples of S1 and S2 events are shown. S1 contains a series of low frequency vibrations, and it is usually the longest and loudest heart sound; S2 typically has higher frequency components than S1, and its duration is shorter. In adults a third sound (S3) characterized by low frequency may be heard in correspondence with the beginning of the diastole, during the rapid filling of the ventricles and also a fourth heart sound (S4) in correspondence with the end of the diastole, during atrial contraction (Reed et al, 2004). In FPCG recordings, S3 and S4 sounds are practically undetectable (Mittra et al., 2008) and the power spectral densities and relative intensities of S1 and S2 are a function of foetal gestation age (Nagal, 1986). Whenever the closing of the cardiac valves creates a sound, the acoustic waves travel through a complex system of different tissue layers up to the maternal abdominal surface: amniotic fluid, the muscular wall of the uterus, layers of fat and possibly bony and cartilaginous material. Each layer attenuates the acoustic wave's amplitude due to absorption and reflection arising from the impedance mismatch that occurs at the boundary of two different layers. The result is attenuation of signals and a poor SNR (Jimenez et al., 1999; Mittra et al. 2008).

Recorded FPCG signals are heavily affected by other noise sources (Varady et al., 2003; Bassil & Dripps, 2000; Mitra et al., 2008; zhang et al., 1998), such as:

- acoustic noise produced by foetal movements;
- maternal digestive sounds;
- maternal heart activity sounds (MHAS);
- maternal respiratory sounds;
- movement of measuring sensor during recording – shear noise;
- external noise originating from the environment – ambient noise.

The above interference signals are non-stationary and have to be removed from another non-stationary signal: the foetal heart sound (FHS). Thus, a crucial issue is the correct recognition of FHS associated with each foetal heart beat and the subsequent reconstruction of the FHR signal (Varady et al., 2003; Bassil & Dripps, 2000; Kovacs et al., 2000; Moghavvemi et al., 2003; Mittra et al., 2007).

Most of the early effort in the area of FPCG monitoring was focused on sensor development. More recent studies focused on FHR estimation and different signal processing algorithms have been developed to perform foetal heart beat identification, such as: matched filtering (a technique commonly used to detect recurring time signals corrupted by noise); non-linear operators designed to enhance localised moments of high energy, such as the Teager energy operator proposed by James F. Kaiser (Kaiser, 1990); autocorrelation techniques in order to emphasize the periodic components in the foetal heart signal while reducing the non-periodic components; quadratic energy detectors that incorporate frequency filtering with energy detection (Atlas et al., 1992); neural networks; and linear prediction.

Except for some studies, the proposed methods have mainly aimed at detecting heart sound occurrences, but not their precise location in time. Moreover, no detailed quantitative results assessing the reliability of the proposed methods have been published.

In (Ruffo et al., 2010) we presented a new algorithm for FHR estimation from acoustic FPCG signals. The performance of the algorithm was compared with that of CTG, which is currently considered the gold standard in FHR estimation. The results obtained showed that the algorithm was able to obtain obtains the FHR signal reliably. An example of the comparison is shown in Figure 2.

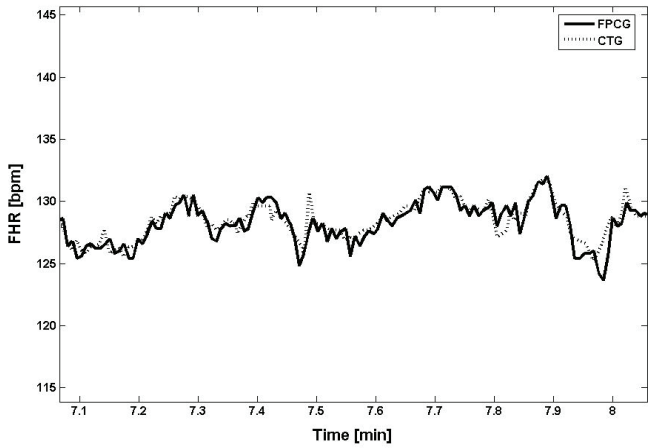

Fig. 2. Comparison between a FHR estimated from FPCG signal and FHR simultaneously recorded by means of CTG

3.1 FHR extraction from FPCG

In FHS extraction, S1 is often considered as a good time marker for the heart beat, because of its high energy with respect to the other portions of the FPCG signal, and its lower morphologic variability (Pieri et al., 2001; Ahlstrom et al., 2008). Thus, once each S1 is detected, the correspondent FHR series can be easily estimated measuring the time between each S1.

A possible algorithm for FHR extraction based on S1 enhancement and detection was presented by Ruffo et al. (Ruffo et al., 2010). A block diagram of this algorithm is shown in figure 3. In addition to the extraction of the FHR, the detected S1 sequence it is also used to identify the fainter S2.

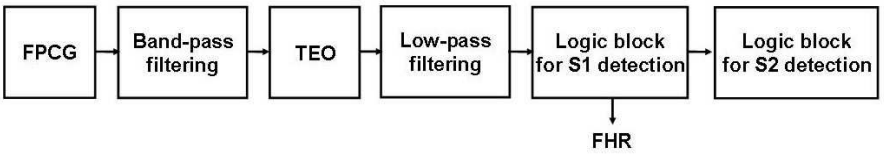

Fig. 3. Block diagram of the FHR from FPCG algorithm

Before entering into the detailed explanation of each block, it is worthwhile to recall that interference in FPCG recording is usually below 20 Hz (mostly internal noise, such as MHAS and digestive sounds) and above 70 Hz (externals noise) (Varady et al., 2003; Bassil & Dripps, 2000; Kovacs et al., 2000; Mittra et al. 2008). Moreover, the frequency content of S1 and S2 partially overlap, so that it may be difficult to distinguish them in the frequency domain. However, in the time domain they are separable since the time correlation between them is known (Varady et al., 2003; Kovacs et al., 2000; Jimenez et al., 1999; Mittra et al. 2008). Thus, the algorithm described in figure 3 has been designed accordingly. Particularly the first filtering block, the band-pass filter, is designed to cut out most of the interference. It is a 100^{th} order digital band-pass filter having 3 dB band equal to 34-54 [Hz] centred at 44 Hz. (Ruffo et al., 2010).

The output of the filter is fed to the Teager Energy Operator (TEO) block (Kaiser, 1990). This non-linear time operator is implemented here for S1 enhancement. It is able to identify signal tracts characterized by local high energy (Kaiser, 1990). The resulting signal will have a further enhanced S1.

Because of the residual noise, the TEO output needs further digital filtering (Kaiser, 1993). In the presented algorithm such a filter is implemented with a 30 Hz cut-off frequency 5^{th} order low-pass filter (Ruffo et al., 2010). The result of the filtering will be an enhancement of the lobes corresponding to the possible locations of S1.

Finally, the signal is sufficiently pre-processed to perform the S1 extraction. Such extraction is performed using a peak by peak analysis with a strategy very close to that reported in (Varady et al., 2003; Bassil & Dripps, 2000; Kovacs et al., 2000; Ahlstrom et al., 2008). After an initial training, peaks within a fixed time interval (based on inter-distance consistency of the previous eight identified beats) are classified as candidate beats. Among them, the peaks with amplitude greater than a fixed threshold (based on the amplitude regularity of the previous eight identified beats) are classified as probable heart beats.

The time interval considered for a candidate beat is set to be equal to T_0 + 0.65*MEAN, T_0 + 1.35*MEAN, where T_0 is the position of the last detected S1 and MEAN is the mean of the

time distance between two consecutive detected S1 events on the previous eight beats. The coefficients 0.65 and 1.35 were heuristically chosen in order to take in consideration acceptable variations of FHR and to reject, at the same time, extreme outliers. The amplitude threshold is half of the mean value of the previous eight detected S1 amplitudes. In the case of detection of multiple peaks with an amplitude higher than the threshold in the same time interval, the algorithm chooses the peak which has position P_i that minimizes the distance $||T_0-P_i|$ - MEAN|. To illustrate how the logic block for S1 detection works, its flow chart is depicted in figure 4.

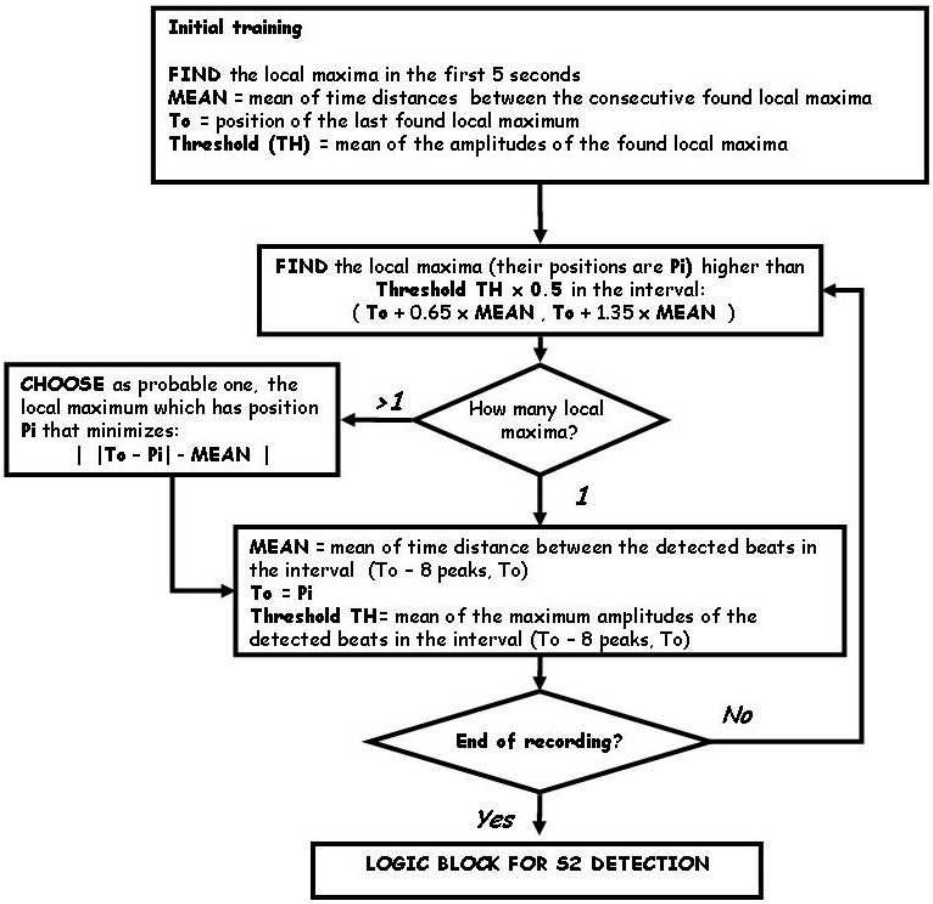

Fig. 4. The logic block for S1 detection

Finally, for each of the detected S1, the timing of the event occurrence is established following an approach similar to the ones used in ECG processing for QRS detection (Kohler et al., 2002; Bailon et al., 2002; Rozentryt et al., 1999): for each identified S1 event, the algorithm chooses the time occurrences of the maximum amplitude of the peak as time markers.

In addition, the algorithm generates a reliability index for each detected S1 event. The value assigned to the reliability index from the algorithm is a function of the local SNR and number of candidates that the logic block has found for the corresponding beat; the index can assume three different values (high, medium, low) in a similar way to some CTG devices used in clinical practise (Ruffo et al., 2010).
Once the S1 detection is complete, the search for S2 events is executed by the next logic block. As for the previous logic block, in order to identify an S2 event, remaining large signal amplitudes are analyzed with regard to the consistency of their distance from the corresponding S1 events and their amplitude regularity. According to Kovacs et al., the time interval between S1 and S2 (SSID) in milliseconds is a function of the corresponding FHR value (Kovacs et al., 2000): SSID = 210 – 0.5 * FHR. If Tn represents the position in milliseconds of the last detected peak S1, the algorithm searches for S2 candidate peaks with a position in a fixed time interval T equal to Tn + SSID – 50 , Tn + SSID + 50. The algorithm deals with multiple peak detection with a strategy similar to the one for multiple S1 detection described above. The flow chart for this logic block is depicted in figure 5, an example of results of the entire algorithm on an excerpt of data is shown in figure 6.

4. Processing of the FECG signal

The FECG can be recorded from the maternal abdominal region using a multi-lead system that covers the entire area. The raw recorded waveform is similar to the maternal one (often recorded with an additional chest lead. However, if the signals are correctly processed it will be possible to recognize three important features that are helpful indicators for foetal well being assessment and diagnosis such as (Peddaneni, 2004):

- Foetal heart rate
- Waveforms amplitudes
- Waveforms duration.

Unfortunately there is a lack of meaningful abdominal FECG recordings mainly because of the very low SNR due to the various interference sources (Hasan et al., 2009). Some of the issues are:
Base-line wander: respiration and body movements can cause electrode-skin impedance changes generating a baseline drift (Janjarasjitt, 2006). The baseline drift due to the respiration presents itself as a large amplitude sinusoidal component at low frequency and can cause amplifier saturation and signal clipping;
Power line interference: induced by the main electrical power source (60 or 50 Hz);
Maternal ECG (mECG): this is likely the main interferer. Since the maternal ECG amplitude is considerably higher than the FECG (in an abdominal recordings, the amplitude of the maternal QRS is typically around 1 mV while the foetal QRS amplitude is around 60 μV), the larger signal may obscure the smaller one. Moreover, the spectra of maternal and foetal signals overlap, so that it is not possible to separate them through conventional selective filtering (Janjarasjitt, 2006);
EMG: generated by muscle contraction and generally associated with movements and uncomfortable positions for the patient. EMG can generate artefacts that are characterized by a relatively large high-frequency content (Janjarasjitt, 2006). The situation is far worse during uterine contractions which add to the FECG some peculiar artefacts due to the uterine EMG (electrohysterogram); however, it is useful to monitor FECG during uterine contractions because the FHR in response to the contractions is an important indicator of the foetal health (Peddaneni, 2004).

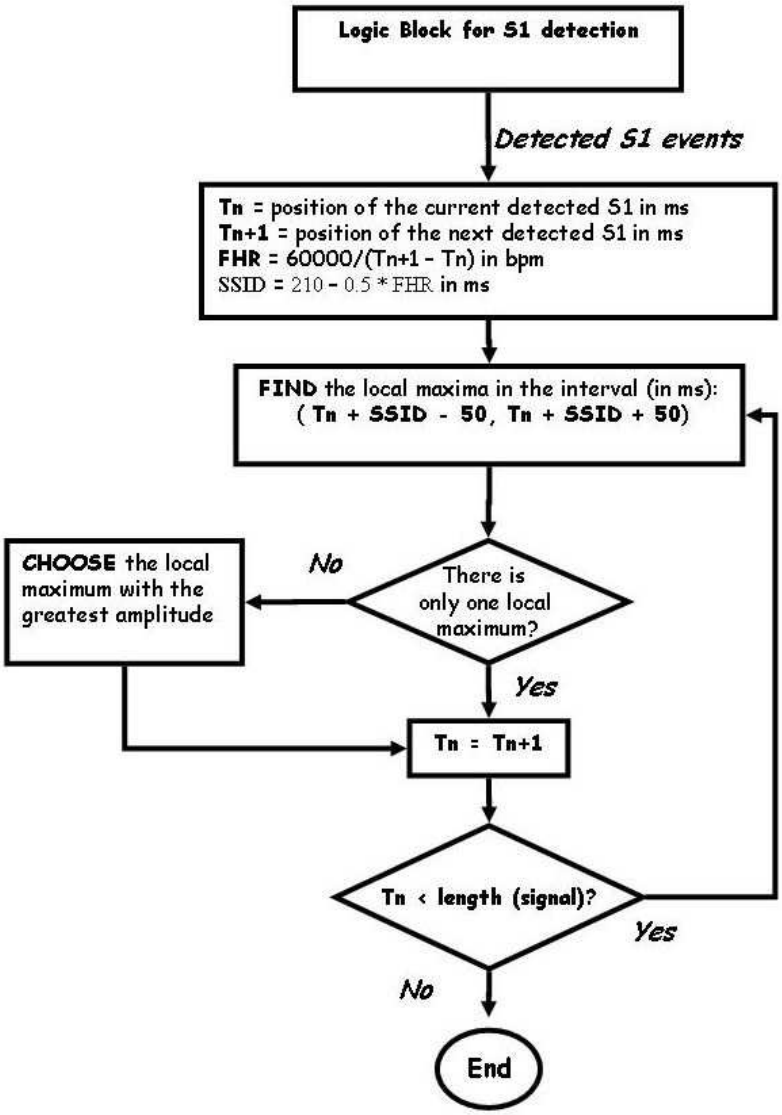

Fig. 5. Flow chart of the logic block for S2 detection

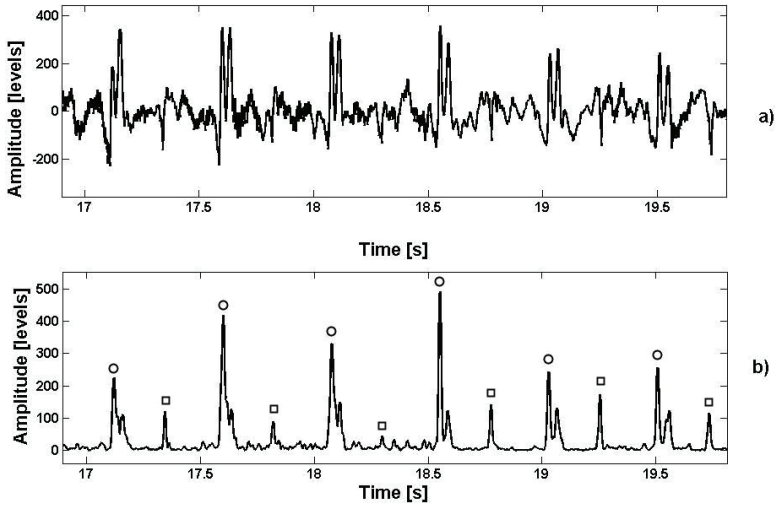

Fig. 6. Examples of detected S1 events (circles) and detected S2 events (squares): a) FPCG signal; b) Low-pass filtering block output

Inherent noise in electronic equipment: all electronic equipment generates noise. This noise cannot be eliminated - even the use of high-quality electronic components can only minimize it.

In addition to all the issues described above, there is an inter- and intra-subject variability related to the gestational age and the position of the electrodes during the acquisition of the signal. Finally, another issue that has to be considered in FECG recording, is the attenuation of the FECG signal due to the electrically insulating properties of the vernix caseosa, which develops around the 28th to 32nd weeks of gestation (Janjarasjitt, 2006). Despite all the above mentioned issues, the FECG is a unique tool to assess foetal well being.

Cardiac events in an ECG are associated with alphabetical labels as shown in figure 7. One cycle of a normal heart beat consists of waves, complexes, intervals, and segments representing as follows:

- P wave: the firing of the sinoatrial node and atrial depolarization;
- PR interval: the atrial depolarization and atrioventricular delay;
- QRS complex: the ventricular depolarization;
- Q wave: the initial negative deflection due to ventricular depolarization;
- R wave: the first positive deflection due to ventricular depolarization;
- RR interval: the time interval between consecutive R waves;
- S wave: a second negative deflection of ventricular depolarization;
- ST segment: a part of the ventricular depolarization process;
- T wave: the ventricular repolarization;
- QT interval: the time interval which ventricular depolarization and repolarization take.

The analysis of FECG permits the evaluation of cardiac parameters in order to identify eventual cardiac pathologies (Symonds et al., 2001), such as acidosis (Janjarasjitt, 2006). It can also give other information about premature ventricular contractions, activity of the autonomic nervous system, cardiac arrhythmia, uterine contraction, etc. It is important to

monitor the ST interval since it reflects the function of the foetal heart muscle during stress tests. Rosen and Kjellmer (Rosen & Kjellmer, 1975) observed progressive changes in the ST interval prior to the bradycardia in the FECG tracings in experimental hypoxia and it is known that oxygen deficiency causes neurological damage. The ST waveform can be assessed qualitatively by its shape but also quantitatively, by the height of the T wave in relation to the amplitude of QRS wave (T/QRS ratio). Greene et al. (Greene et al., 1982) found a correlation between high values of the T/QRS ratio with persistently elevated ST waveforms and anaerobic metabolism in chronically instrumented lambs. In addition, in adults, ST depression with T wave elevation is also seen in myocardial ischemia and may represent an index of myocardial ischemic hypoxia when the myocardium action potential change is not uniform. Finally, it is know that ST waveform monitoring is used to identify myocardial infarction or coronary insufficiency (Braunwald et al., 1976).

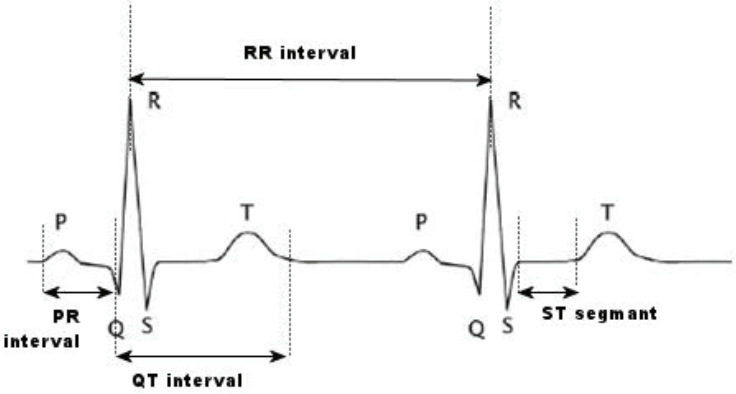

Fig. 7. An example of ECG signal and its components

4.1 FHR extraction from FECG

The extraction of the FHR from FECG is not a trivial signal processing issue. In the literature it is possible to find different techniques to extract FHR from abdominal ECG recordings: Neural Networks (Camps et al., 2001; Kezi et al., 2006), Dynamic Neural Network (Camps et al., 2001; camps et al. 2004), Least Mean Square (Camps et al., 2004; Roberts & Mullis, 1987), Orthogonal Basis Function (Longini et al., 1977), Subtraction of an Average Pattern (Bundin & Abboud, 1994), Wavelet Transform (Hasan, 2009; Mochimaru et al., 2004; Mallat & Hwang, 1992), State Space Projection (Ritcher et al., 1998; Schreiber et al., 1998), Temporal structure (Kardec & Cichocki, 2001; Zhi-Lin & Zhang, 2006), Polynomial networks (Assaleh & Al-Nashash, 2005), and Independent Component Analysis (Stone, 2002; Hyvarinen & Oja, 2000). However, there is no agreement about which one is the best technique. Our method is based on Independent Component Analysis (ICA). ICA is essentially a method for extracting individual signals from mixtures of signals under the physically realistic assumption that different physical processes generate unrelated signals. The simple and generic nature of this assumption ensures that ICA is being successfully applied in a diverse range of research fields (Stone, 2002). In our case it is possible to assume that the foetal and maternal signals are the independent components.

A number of different methods for implementing ICA have been published. Aapo Hyvärinen in 1997 introduced a family of algorithms that are grouped under the epithet fixed-point or FastICA algorithms (Hyvarinen, 1997). In principle, all the FastICA algorithms find independent components by separately maximising the negentropy (negative entropy) of each mixture (Yan et al., 2000). It is also known from the literature that FastICA algorithms usually offer fast and efficient approach for the pre-processing of FECG with multiple signals of interest, in particular when the SNR is low. Moreover, no specific a priori knowledge is required in order to identify components generated from different sources. However, the main disadvantage of this technique is that it requires different ECG leads (Stone, 2002; Hyvarinen & Oja, 2000). These additional leads mean a larger number of electrodes is then required. In addition, because the foetus moves, it is clear that a standard location for the sensors does not exist. Enough electrodes must be used to ensure a good informative content for the foetal extraction, but the number of electrodes should not be excessive because this could be uncomfortable for the mother. As a compromise, we used four electrodes placed on the maternal abdomen and an additional electrode placed on the right leg as the reference.

One of the known limitations of ICA is that the number of the output channels cannot be larger than the number of input signals. However, since the number of independent sources in the recorded signals could be greater than the number of the abdominal leads employed, it is important to reduce, as much as possible, the known sources of noise (such as maternal ECG, baseline wander, power-line interference, and motion artifacts) prior to ICA.

In our case, a bank of sharp notch filters (with Q-factor equal to 30) at 50 Hz and its higher harmonic components (100, 150 and 200 Hz) is used to suppress the power line interference. Next, a 10^{th} order band-pass filter with a bandwidth range of 3 - 40 [Hz] is used because the frequencies of interest for the QRS extraction lie mainly inside this frequency range. This filter reduces high frequency noises coming from motion artefacts and also reduces low frequency baseline wander.

The maternal ECG needs to be reduced as well. In our case, the maternal QRS waves are detected and erased by means of a threshold detection (proportional to the local root mean square value of the signal), and for each detected maternal QRS, the average wave, computed on the previous detected five QRS waves, is then subtracted.

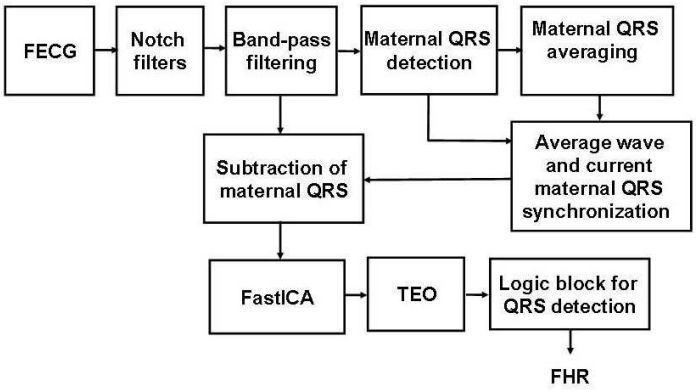

Fig. 8. Flow chart of the algorithm for FHR extraction

The FastICA algorithm described is summarized in the block diagram depicted in figure 8. The independent component that best represented the FECG was chosen manually.
In order to extract FHR, the foetal QRS waves were detected using the same strategy used for the FPCG. Foetal QRS waves were enhanced by means of TEO and then detected using a similar process employed for S1 events detection (Kohler et al., 2002; Bailon et al., 2002; Rozentryt et al., 1999). An excerpt of data showing QRS detection is depicted in figure 9.

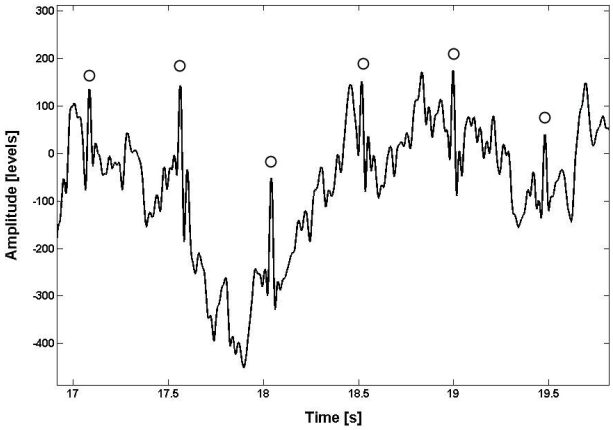

Fig. 9. Examples of detected QRS events (circles)

5. Combined FECG-FPCG monitoring and future development

A longer-term non-invasive assessment to evaluate foetal distress could be achieved by means of the measurement of the systolic time intervals (FSTI) of the foetal heart (Fleming et al., 1986). In the literature, the most satisfactory available technique for FSTI measurement consists of recording simultaneously FECG and valve movements by means of a Doppler ultrasound device (De Vore et al., 1981; Giolardino et al., 1986; Adam et al., 1979; Robinson et al., 1978). However in order to identify foetal cardiac valve movements, FPCG could be a possible alternative to the Doppler ultrasound system (Fleming et al., 1986). This would overcome the problem caused by the directionality of the ultrasound beam and, in addition, it would avoid long term exposure to ultrasound waves.
In order to estimate FSTI from FPCG and FECG signals it is necessary to extract different heart beat events. In particular, from FPCG, it is necessary to detect the vibrations which identify the mitral valve closure, aortic valve closure, aortic valve opening (a lower-frequency component resulting from the ejection recoil) at the commencement of systole. Instead to estimate the FSTI from the FECG, it is necessary to extract the QRS complex, because the pre-ejection period (PEP), can be defined as the time interval from the onset of the Q-wave to the aortic valve opening) (Fleming et al., 1986).
The proposed algorithms provide all the required information; the occurrence of PEP can be estimated by means of the QRS wave detection while the timing of the other events can be estimated by the detection of S1 and S2. In both S1 and S2, the main part of the complex consists of large vibrations, due to the movements of the valves (Luisada et al., 1949). Therefore, division of each S1 and S2 into different phases which correspond to different

valvular events (mitral valve closure and opening and aortic valve closure) is relatively easy (Fleming et al., 1986).

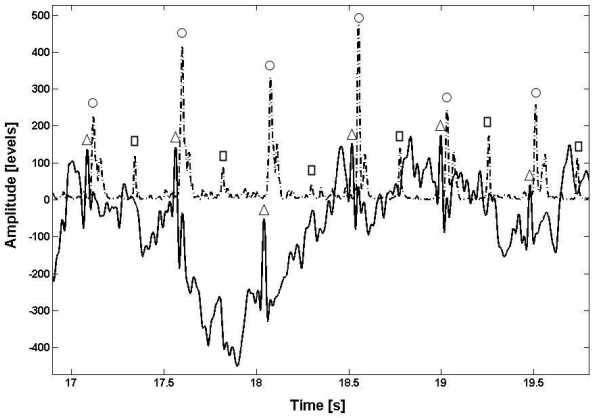

Fig. 10. Examples of detected QRS events (triangles), S1 events (circles) and S2 events (squares) in a combined recording; solid line represents FECG, dashed line represents FPCG (low-pass filtering block output)

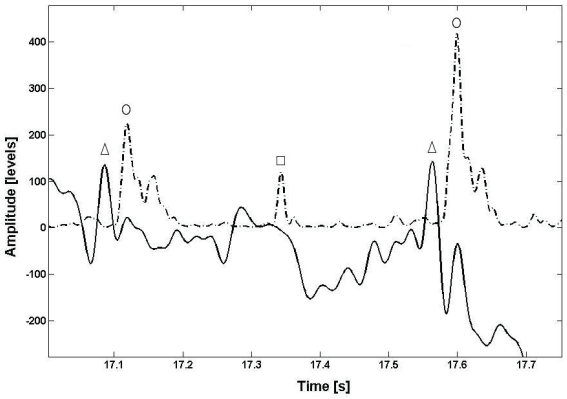

Fig. 11. Magnified section from figure 10

CTG monitoring is limited to the clinical recording duration (typically only 20-30 minutes) and it does not provide information about the foetal circulatory impedance on a continuous basis or over longer periods. Our results will encourage the further development of processing strategies to obtain further information about the foetal circulatory impedance. By monitoring of the time difference between occurrence of particular events on the FECG signal (such as P waves) and the corresponding foetal heart sounds, it is possible to provide information about the circulatory impedance. For example, in the case of placental insufficiency, the placental resistance rises and a larger pressure is generated in the foetal ventricles; this causes a lengthening of the time interval between the P wave and the occurrence of S1. In this way, it would be possible to monitor any increase of this time interval over a long period of time to identify a foetus at risk.

Further information to assess the foetus well-being can be estimated from the FECG and FPCG signals separately. FECG processing allows ST interval analysis. Synchronized averaged FECG can improve the SNR. R-peaks can be detected and aligned in a given time window (e.g. 30 seconds or more). Then all the recognized FECG can be averaged, with the expected improvement in SNR proportional to the square root of the number of FECG considered in the averaging operation. In this way it is possible to reduce the noise and analyze the ST interval which reflects the condition of the heart muscle under load. This could be useful for clinicians when deciding on obstetric interventions (Ross et al., 2004).
Future developments will aim to detect from the FCPG signal cardiac functioning anomalies (such as murmur, split effect, extrasystole, bigeminal/trigeminal atria contraction; phenomena which cannot be studied with the traditional CTG technique).

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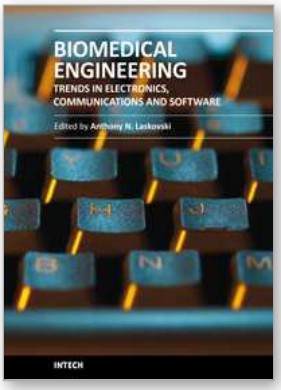

Biomedical Engineering, Trends in Electronics, Communications and Software

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Rapid technological developments in the last century have brought the field of biomedical engineering into a totally new realm. Breakthroughs in materials science, imaging, electronics and, more recently, the information age have improved our understanding of the human body. As a result, the field of biomedical engineering is thriving, with innovations that aim to improve the quality and reduce the cost of medical care. This book is the first in a series of three that will present recent trends in biomedical engineering, with a particular focus on applications in electronics and communications. More specifically: wireless monitoring, sensors, medical imaging and the management of medical information are covered, among other subjects.

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