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Screening for Congenital Heart Diseases by Murmurs Using Telemedical Phonocardiography*

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Abstract— **A large proportion of congenital heart diseases (CHD) remain undetected during pregnancy or even after birth. Many of them generate turbulent blood flow, resulting heart murmur. Doppler ultrasound cardiotocography (CTG) is suitable for the assessment of the fetal heart rate and some derived parameters, but it is inadequate for detecting heart murmurs. Although comprehensive examination can be carried out with echocardiography, it is expensive and requires expertise; therefore, it is not applicable for widespread screening. This paper presents a new possibility for screening for some CHDs using phonocardiography, which can be combined with Doppler ultrasound CTG as an extension of it. Furthermore it can be carried out at home allowing repeated measurements, which increases also the reliability of filtering out innocent murmurs. The diagnostic capability of this screening method is supported by a large number of evaluated fetal heart sound records. Moreover, according to experiences pregnant women prefer this reliable, easy to use method, which facilitates their examination.**

I. Introduction

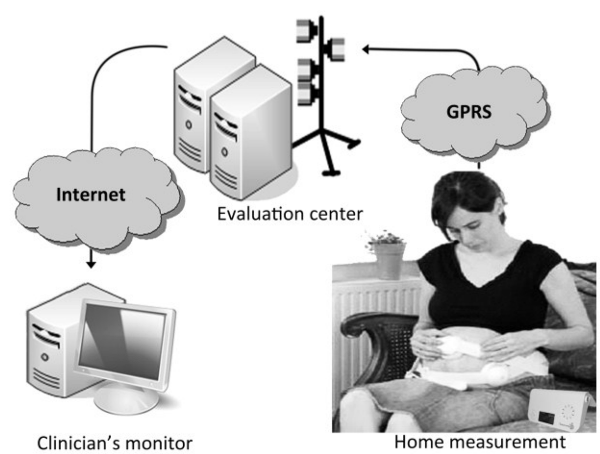
Antenatal monitoring and assessment of fetal well-being has crucial importance for obstetrics. Therefore there is a growing demand for assessment of fetal heart during the conventional routine screening for abnormalities. In fact the screening of the high-risk population is solved, taking into account pregnancies with maternal disease, positive family history of CHD, pregnancies with chromosomal defect of parents or second-degree relatives, twin gestation or advanced maternal age. In contrast, the low-risk population is problematic because moderate symptoms of an anomaly do not appear frequently and noticeably resulting in undetected CHDs in case of considerable part of pregnancies [1]. Thus, they won't be examined intensively with echocardiography and neither classified as high-risk cases.

The most exact method for the assessment of the fetal well-being is ultrasound echocardiography [2]. This examination is expensive and needs expertise. Thus, its widespread usage is limited. The traditional way of fetal monitoring in the third trimester is the ultrasound CTG measured regularly to assess the fetal heart rate (FHR) and some derived features, such as the baseline, the short-term variability (STV) and the number of accelerations and decelerations [3].

Electrocardiography (ECG) gives a particular insight into the operation of the fetal heart, and can also indicate some types of CHDs. Moreover telemedical systems are available based on this technique, however, some limitations exist, e.g. due to the very low signal to noise ratio, especially in the presences of the vernix caseosa. The same assumptions can be made to fetal magnetocardiography (fMCG) where telemedical operation is not feasible.

Whereas ultrasound echocardiography provides the most accurate results and can be used even in the early state of the pregnancy it is not a suitable tool for wide-range prenatal screening of low-risk population, but being necessary for the detailed examination in case of a risky pregnancy. Besides in certain circumstances the results of the Doppler ultrasound based CTG measurements can differ from the values derived from fetal ECG [4]. The main reason is that the ultrasound pulse is not reflected from a constant, well-defined location of the heart, which impairs the accuracy of timing measurements.

A useful phonocardiographic method (PCG) for fetal monitoring was discussed by a previous study [5]. It uses a special acoustic sensor to record trans-abdominally the acoustic signals of the fetal cardiac system. Based on its passive, non-invasive nature it is suitable for extremely long-term CTG measurements. Moreover it is easy to use and completely harmless that makes it applicable to perform home measurements as part of a telemedicine system (Fig. 1) [6].



1. Figure. Measurement with the fetal telemedicine system carried out at home after the 28th week of gestation.

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The acoustic signal measured on the maternal abdomen is first preprocessed for data transmission, and then sent to the evaluation center via mobile phone network, where the measured data is stored and the computationally expensive algorithms are performed. Finally, a summary is made available to the clinician aiding in clinical decision making. The processed data is available through an Internet portal to authorized members.

The phonocardiography-based CTG measurement combined with murmur inspection gains the capabilities of the screening process. The early identification of a cardiac anomaly is very important because echocardiographic measurement can be carried out to identify the severity and the type of the anomaly. In severe cases prompt postnatal operation can be prepared for. PCG enables the indication of prenatal diseases, intrauterine growth retardation (IUGR) and the balance of the fetal autonomous nervous system [7]. These can be suitably monitored by the repeated long-term home measurements using the telemedicine system. Moreover, the regularly performed screening lowers the maternal distress level especially in the last trimester.

Follow-up care after birth should be provided to confirm a diagnosis made during pregnancy and also to help the early detection of a hidden disease in the early phase of life, but unfortunately it is generally difficult because of human factors.

The phonocardiographic method is capable of displaying additional symptoms of the fetal heart activity. Based on the several CTG measurements carried out during the last decade it appears that some additional features of the fetal activity can be detected, such as the waveforms of the closing valves or the sound of the turbulent blood flow, which may contain indications of congenital heart diseases.

The diagnosed heart murmur as CHD can be classified according to their severity as follows:

- Innocent murmurs caused by defects that close after birth by themselves within 1 to 1.5 years. (e.g. tiny muscular septal defect between the two ventricle)
- In mild cases it requires surveillance and supervision.
- In severe cases regular echocardiographic measurements should be carried out and usually pharmacological or surgical intervention is needed.

It would be a great advance if a detected heart murmur could be referred to one or more corresponding heart defects. Currently this feature is not available, and a perfect identification may hardly be achieved. However some typical morphological disorders cause very characteristic murmurs and cooperation with echocardiographic measurements can lead to a more accurate diagnosis. To be able to set up a reliable database a large number of PCG measurements must be carried out because these heart defects are rare (appearance is lower than 1.5%), thus it can only be achieved by a phonocardiology expert system.

This paper describes a highly reliable and compact method based on a telemedical system applied for fetal screening with long-term home monitoring.

II. Method

A. General

Several studies investigated the circulatory system and heart diseases for children, adolescents and adults [8, 9] but the knowledge of the fetal heart murmurs is poor. The knowledge database about the children's morphological defects helps to distinguish the various types of murmurs but must be handled with doubt as there are basic differences in the circulation therefore they are not suitable for direct exploitation.

Recording the heart sounds of an adult or children the waveforms produced by the heart operation can be easily observed as it is not influenced by the maternal heart sounds, neither by additional bowel movements (peristalsis, intestinal activity). However several methods were implemented for denoising [10, 11], because the fetal heart as a tiny sound source generates a very low intensity signal and especially in the early state of the pregnancy the SNR is too low due to maternal and external noises what makes the record un-evaluable. Previous fetal PCG studies showed that the precision is highly influenced by the presence of noise [12]. Further difficulties are the shorter beat-to-beat lengths and the narrower bandwidth.

B. Data collection

More than 2000 fetal CTG measurements have been carried out during the last few years using the Fetaphon PCG device. Each one is a standard 20-minute CTG test carried out after the 28th week of gestation and recorded on individual patients. The data was collected remotely as part of the telemedicine system. The measurements applied a sampling frequency of 333 Hz and a resolution of 8 bits in order to achieve a low data bandwidth on the mobile phone network. One part of the pregnancies was measured by the telemedicine fetal monitor at home on a regular basis (3 to 4 times per week) the other part of the data is from the in situ measurements just after the echocardiographic examination of risky pregnancies in the hospitals and at the Institute of Cardiology. After preprocessing the recorded signals the measuring unit transfers the data to the evaluation centers using mobile phone network where off-line analysis is performed. Data transmitted to the evaluation centers will be analyzed by complex evaluation program with murmur detection. As a result a diagnostic aid is made available to the physician. Records containing symptoms suggesting critical fetal status can be forwarded even to the responsible clinician's mobile phone, consequently resulting in near-constant surveillance. Data collected and evaluated in the medical centers is also available through an Internet portal to authorized clinicians.

C. Murmur extraction

Automatic screening for murmurs [13] requires a complex algorithm that can be divided into sub-functions:

- The extremely noisy parts of the record, where the SNR is insufficient for further processing must be eliminated.
- Practically every measured acoustic signal needs an individual processing method to recover the largest number of beats. To achieve that requirement, complex first (S1) and second (S2) heart sound detection algorithm is used for segmenting the record, which is the combination of the Wavelet transform, the autocorrelation and the Matching Pursuit methods. The use of this combined method is necessary because in irregular cases an extra systole can ruin such methods which lean on the periodic nature of the heart operation. Simultaneously, the FHR computation is performed based on S1 timing.
- The positions of the systolic and diastolic intervals are determined based on the timing of the S1 and S2 signals. Unfortunately, some types of murmurs overlap the S1 and S2 sounds, resulting in a more complex waveform. Similarly, the existence of split makes the separation more difficult.
- The identification of a murmur requires a scanning algorithm that inspects every heart cycle of the recorded signal to find a consecutively repeating signal component at the same position in the cardiac cycle.
- If a murmur was found, a mathematical model is fitted in order to extract the parameters as follows: distance from S1 and S2 sounds, shape, duration, level according to the maximum amplitude of S1, dominant frequency and bandwidth. Additionally the S1 and S2 split are also stored in the database.

In order to calculate the split, mathematical model is fitted to the heart sounds using a simplified version of the model of Xu et al. [14]. Both components (S_c) of the complex valve sound have been approximated by the following form [6]:

$$S_C(t) = A_C \sin\left(\omega_C - \Delta\omega_C \frac{t}{T_S}\right) t \cdot \exp\left(-\frac{t}{\tau_C}\right), \qquad (1)$$

where A_c is the amplitude, ω_c is the frequency and $\Delta\omega_c$ is related to the frequency decrease of the vibration, τ_c is the time constant of the decay, and T_S is the duration of the valve sound. Index c refers to the given component. It should be taken into account that there is a time delay between the closure of the two valves which forms a split.

III. Results

Applying these methods to the records in our database containing 2000 fetal CTG measurements 45 of them were filtered out as irregular cases including several murmurs and extremely large split as well.

Two records are selected for presentation purposes which contain heart murmurs. Each has been verified by ultrasound echocardiographic examination.

Fig. 2 (a) shows two beats of an acoustic signal with systolic murmur (SM). The most common reason for this symptom is either an abnormal leaflet string or a small shunt between the two chambers (septal defect).

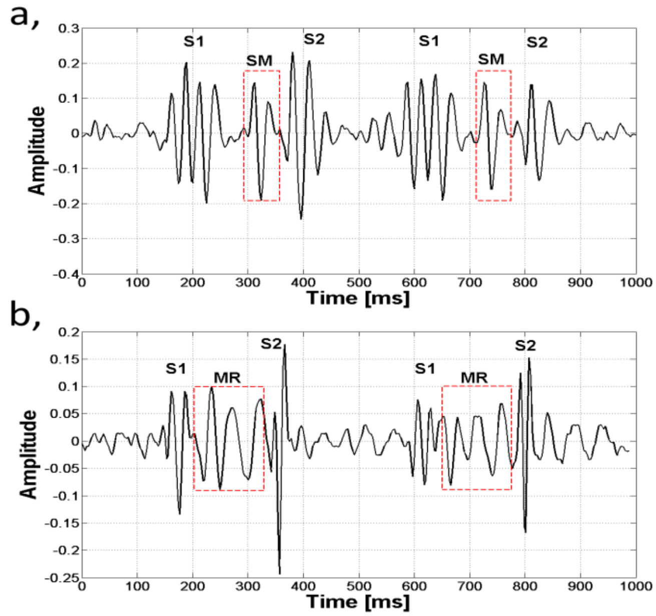

Figure 2. Typical acoustic curve showing two periods of heart cycles. The first (S1), the second (S2) heart sounds, the systolic murmur (SM) and the mitral regurgitation (MR) are marked.

The characteristic acoustic signal of mitral regurgitation (MR) is presented in Fig. 2 (b), where due to dysfunction of the mitral valve blood leaks back into the atrium during contraction of the left ventricle causing turbulent blood flow.

The heart murmurs are more visible in the time-frequency map (Fig. 3) because the overlapping sound components make the separation difficult in the time domain.

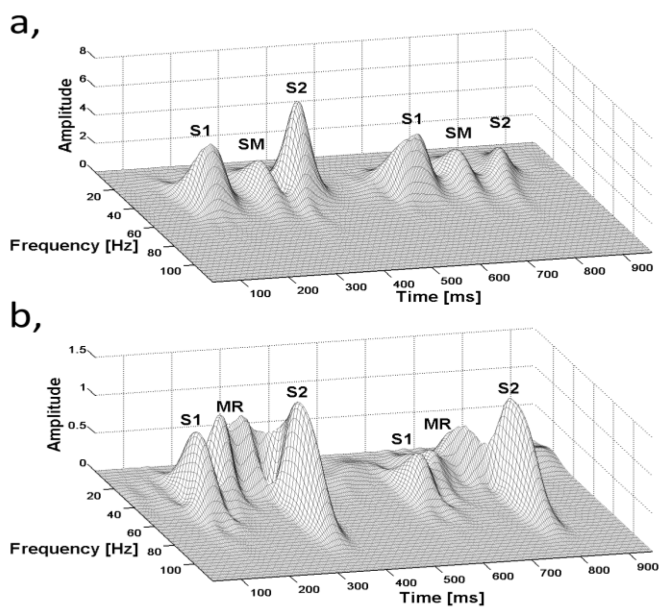

Figure 3. Time-frequency maps of two heart cycles with additional systolic cardiac murmur according to Fig 2.

The short time intervals between the two heart sounds and additional noise especially in the early phase of the pregnancy ruin the visibility of the murmurs.

The two types of murmurs shown on Fig. 2 are displayed in the time-frequency map. On Fig. 3 (a) a third peak appears between the valve sounds because of the turbulent blood flow in the systolic period. On Fig 3 (b) due to mitral regurgitation the murmur consists of two peaks which significantly differ in the two consecutive heartbeats as displayed on the map.

The searching algorithm was calibrated for detecting characteristic murmurs produced by typical morphological disorders. Besides their successful identification the detection of multiple or complex cases are difficult. The different morphological disorders can cause various types of heart murmurs which makes the identification of the underlying disease very complicated. Therefore the specificity and selectivity of the algorithm is not yet applicable for the whole database.

In addition the classification of doubtful cases especially in the early phase of pregnancy is a great challenge for obstetricians as well.

IV. Conclusion

Based on the large number of evaluated fetal heart sound records, the paper demonstrated that phonocardiography can be a suitable tool for testing fetal well-being noninvasively and for the detection of heart murmurs. As it was proved, the phonocardiography-based method can indicate several congenital heart diseases; however, further measurements must be carried out to improve our knowledge base.

The presented way of investigation is based on a telemedicine system, where processing of measured data is performed at evaluation centers linked together through the Internet. It means that the calculated results are available after a few seconds due to data transfer, which can be confusing for the clinician participating in the measurement.

To overcome this problem the evaluation functions should be integrated into an ASIC chip resulting real-time measurement capabilities, using the developed method by [15] to implement Wavelet analysis into VLSI for neural implants.

The widespread dissemination of this technique is a large challenge. It offers a new method for fetal examination besides the well-established ultrasound Doppler CTG method. Moreover, this technique would make it possible to create a fetal screening expert system and would support the certainty of a decision about cardiac anomalies.

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