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Screening of Congenital Heart Diseases with Fetal Phonocardiography

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***Abstract*—**The paper presents a novel screening method to indicate congenital heart diseases (CHD), which otherwise could remain undetected because of their low level. Therefore, not belonging to the high-risk population, the pregnancies are not subject to the regular fetal monitoring with ultrasound echocardiography. Based on the fact that CHD is a morphological defect of the heart causing turbulent blood flow, the turbulence appears as a murmur, which can be detected by fetal phonocardiography (fPCG). The proposed method applies measurements on the maternal abdomen and from the recorded sound signal a sophisticated processing determines the fetal heart murmur. The paper describes the problems and the additional advantages of the fPCG method including the possibility of measurements at home and its combination with the prescribed regular cardiotocographic (CTG) monitoring. The proposed screening process implemented on a telemedicine system provides an enhanced safety against hidden cardiac diseases.

***Keywords*—**Cardiac murmurs, fetal phonocardiography, screening of CHDs, telemedicine system.

I. Introduction

CONGENITAL heart decease (CHD) is the most crucial factor of fetal well-being. Its detection is of great importance. However, there is ongoing debate about the utility of prenatal fetal diagnosis [1], [2]. In order to accomplish a cost-effective and reliable fetal screening a well-organized classification system has been established based on the risk level of pregnancies. The pregnancies are classified into the high-risk and low-risk population. The screening of the latter is the main topic of this paper.

High-risk population means that at least one of the following risk factors exists: her advanced age, a positive family history of CHD, pregnancies with chromosomal defect of parents or second-degree relatives. Mothers can easily be selected on these conditions for potentially facing a high-risk pregnancy and then be continuously surveyed during the gestation and also after the birth if necessary. So the chance of latent diseases might be excluded. The main examination in this case is the ultrasound 3D echocardiography [3], but its costs and need of application expertise exclude its use for widespread CHD screening. Therefore, it is now practically limited to the *a priori* selected mothers.

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The situation with the low-risk population is quite different, especially if the symptom of the CHD is not significant and, therefore hard to discover. As a consequence, it may happen that a fetus escapes all examination and its lesion, having no chance to be detected remains hidden. After birth or during the following years this latent disease may totally disappear, but in serious cases, may cause a threat or even have tragic consequences. The most critical situations are obviously at sport activities, which involve high physical load. The only possibility to avoid these threats would be a screening test carried out later at the age of 6-8 years. A number of such screenings have shown that a significant rate of students has some heart morphological defect as they escaped all former examinations [4].

Because of the limitations mentioned above another method should be found to discover the low level morphological disease. An opportunity for this purpose may be the fetal phonocardiography (fPCG) carried out non-invasively on the maternal abdomen [5], [6]. A further advantage is that it can be combined with the prescribed cardiotocography (CTG) test. The principle of this screening is that most of the morphological defects generate an internal turbulent blood flow producing a characteristic sound signal. Some types of the CHDs can indicate this signal, after which the mothers can be sent to the 3D echocardiography for detailed examination [7].

Although the fPCG seems to be an appropriate method for CHD detection, it has strong limitations. The first one is the high noise level, which sometimes blocks getting usable fetal heart signals. This noise comes partly from the fetus itself (trunk- and limb-motions, breathing), partly from the mother (maternal heart sounds, breathing and bowel activities). Several methods have been implemented for eliminating this noise [8], [9] making the low intensity heart sound possible to evaluate. Due to this limitation the fPCG can be applied only after the 28th week of gestation and, in addition, it depends on the fetal position and the obesity of the mother.

II. Method

A. Measurement and Data Collection

The prescribed standard 20-minute CTG measurements were applied on a large number of mothers after the 28th week of gestation using the Fetaphon^{TM} fPCG telemonitoring device. At the digitalization of the received sound signal 1ms sampling time and 8 bit resolution were used in order to keep the quantity of data at an acceptable level. Most of the pregnancies were measured with the telemedicine system at home, simultaneously with the prescribed CTG test, usually 3

to 4 times per week on the third trimester. The record measured by the home unit was sent to the evaluation center by the mobile phone network where they were analyzed off-line. The analysis was done by a sophisticated evaluation program that produced both the conventional data as FHR and its variability and the cardiac murmur parameters. Finding any irregular sound or timing abnormality of beats the mother was sent to a 3D echocardiographic examination to the Hungarian State Institute of Cardiology.

The flow diagram of the combined test is shown in Fig. 1. The first block determines a list of the raw timings of the detected S1 sounds and provides information about the noise level of the record. A noisy record will be excluded from the further investigations. Getting a usable record with relatively noiseless S1 sounds the second block improves the timings fitting an appropriate mathematical model to the measured acoustic S1 signals.

The third block is the main part of the whole program. Here the cardiac murmur is searched by repeated comparisons of the systolic and diastolic time intervals with step-by-step selected references applied as murmur sound candidates.

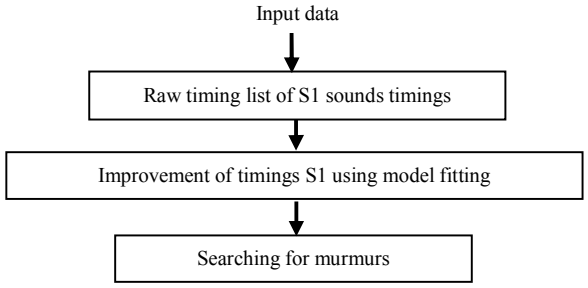

Fig. 1 Flow diagram of the extended fPCG-based CTG monitoring for searching of fetal heart murmurs

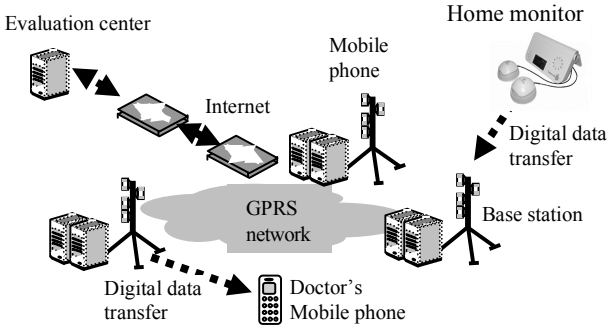

Fig. 2 Architecture of the fPCG telemedicine system applied for cardiac murmur screening

In order to derive further features according to the heart activity one should have relatively noiseless signals. One can achieve these by repeating the measurements many times, that can be easily solved by a home measurement capability. This can be realized by the unique, fully passive fPCG-based telemonitoring system (shown in Fig. 2), developed originally for the standard CTG measurements [10]. The system consists of a sensor to record the fetal heart signals on the maternal abdomen completed with a second sensor for uterine contractions. The measured data will be transferred to the mobile phone network and through the Internet to the Evaluation center, but direct Internet communication is also possible using laptops, iPADs or tablets.

Finally, having a very accurate timing list of the heart rate variability it can be utilized to get data about further parameters of the heart activity such as the supervision of the intrauterine growth restriction (IUGR) and the right development of the fetal autonomic nervous system.

B. Improvements of Timing Using Model Fitting

The exact time position of the S1 sound will be determined by a multistep searching process applying a prepared analytical model, which is theoretically a sinusoidal signal with decreasing amplitude. However, because of the left and right side of the heart there are two discrete sounds of the mitral and tricuspidal valve, which always have the systematic (physiologic) time difference and in case of some kind of heart diseases an excess delay. This time delay between the two sinusoids is characteristic for some CHDs and, therefore, its value is an important data of the screening procedure. The resulting double signal is shown in Fig. 3 with the mitral (M) and tricuspidal (T) valve sound components and the time delay t_d of the second component called split. At very high values of the split the two sounds may be fully separated.

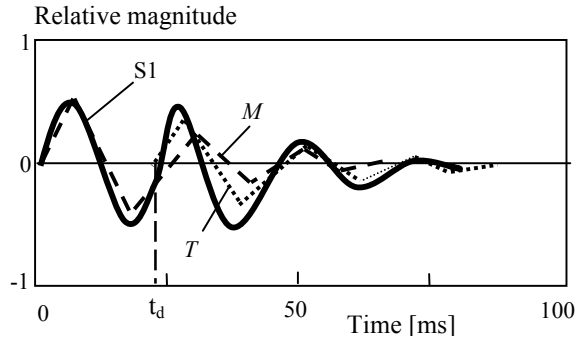

Fig. 3 The split S1 sound with the two overlapping mitral (M) and tricuspidal (T) components

Due to the split the resulting sound signal $f_{S1}(t)$ is composed by the superposition of two sinusoids with decreasing amplitude and oscillation frequency. It is described by the modified expression (1) of [11].

$$s_M(t) = A_M \sin(\omega_M t - \Delta\omega_M(t)) \cdot \exp(-t/\tau_M)$$
$$s_T(t) = A_T \sin((\omega_T t^* - \Delta\omega_T(t^*)) \cdot \exp\left(-t^*/\tau_T\right) \quad (1)$$
$$t^* = t - t_d$$
$$f_{S1}(t) = s_M(t) + s_T(t).$$

where A and ω are the mean frequency and amplitude of the vibration, respectively, $\Delta\omega$ is the frequency change with linear slowing in time, and τ is the time constant of the decay. At the superposition of the two analytical functions the second one is shifted by the delay t_d (called split). This complex waveform is fitted to the measured curve, searching the optimal values of

the parameters A_M, ω_M, $\Delta\omega_M$, τ_M and A_T ω_T, $\Delta\omega_T$, τ_T of the two valve sounds, respectively, and the time delay t_d. The optimization of the model parameters is carried out using the Guided Monte Carlo method where the averages of the three previous S1 sounds are utilized as starting parameters. The resulting S1 sound serves as time basis for the searched cardiac murmur.

C. Searching for Murmur

The principle of murmur search is that if an unexpected signal shape exists systematically in the systolic or diastolic intervals then this abnormal sound should be originated from the fetus. Accordingly, the process of systolic murmur search consists of a systematic scan of the systolic (or diastolic) intervals comparing these with different candidates of murmur shapes as references. These references will be selected step by step along the record and at each comparison the examined signal is shifted, stretched and shrunk for better matching with the reference (Fig. 4).

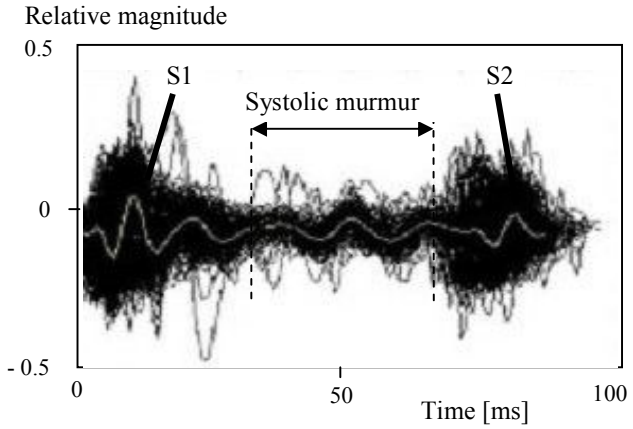

Fig. 4 Measured noisy signal and the extracted murmur in the systolic interval

The results of the comparisons between the selected references and the scanned systolic time intervals will be compared always rejecting the reference with lower correlation. After this evaluation the actual reference signal will be selected as the moving average of the analyzed periods. The reference signal segment which yields the highest correlation over a given limit for a given number of systolic intervals provides the real murmur shape for the given fPCG record. A similar procedure is applied for diastolic murmurs using the S2 sound as time base for murmur search.

From the identified murmur signal, completed with both split data groups (mitral and tricuspidal), nine parameters are extracted characterizing the signal's intensity, position, dominant frequency and shape, which are applied to identify the causing CHD.

D. Discovering the Relation of Measured Murmur and CHDs

Having the heart murmur parameters and the split a question arises, what type of CHDs is the cause of these. This approach started despite the fact that the amount of available data is low due to the very few incidences documented. As a first step some types of CHDs have been chosen, namely (*i*) the ventricular septal defect (VSD) with a ventricular shunt as the most frequent CHD with well distinguishable features, (*ii*) the atrial septal defect (ASD) forming a hole between the two atriums, (*iii*) the mitral stenosis (MS) with its valve narrowing, (*iv*) the pulmonary stenosis (PS) on the pulmonary side, and (*v*) the mitral valve prolapse (MVP) causing a backward blood flow from the left ventricle into the left atrium. All defects mentioned above cause a turbulent blood flow producing thus more or less characteristic murmur and a split in one of the sounds. Using these data it is theoretically possible to identify these CHD types. The work could utilize partly the searched relations known from pediatrics, however, only with strong restrictions because of the quite different pulmonary branch, and the different internal pressure values.

III. Results

For the last eight years fetuses of more than 1000 pregnant women being in the 28^{th} – 40^{th} week of gestation have been examined by fPCG. In the course of this, more than 4800 acoustic curves were recorded with the telemedicine fetal monitor at home, combined with the prescribed 20-minute CTG test which was also recorded and completed with murmur search. The evaluation of the records utilized the timing list of the S1 signals delivered by the program to the FHR determination. The discovered murmurs were classified regarding their characteristic features.

From this population 45 patients were selected having well detectable murmur and in some cases extremely large split as well. In the following, using the conventional time-frequency map three examples illustrate some detected murmurs verified by ultrasound echocardiographic examinations.

The first example (Fig. 5) displays a systolic murmur due to a ventricular septal defect (VSD) where between the S1 and S2 valve sounds a systolic murmur (SM) has been detected caused by the turbulent flow through the small, <0.8 mm size hole between the two ventricles.

TABLE I
The Selected Murmur Parameters Completed with Split Data

	Parameter	Sign	Dimension
p_1	Type, appearance in the systolic or diastolic region	S/D	-
p_2	Volume, amplitude rated to maximum level of S1	V	%
p_3	Dominant frequency	f_D	Hz
p_4	Bandwidth of the well detectable segment of the signal	BW	Hz
p_5	Position as the time of beginning measured from the S1 or S2 peak		ms
p_6	Duration, length of the signal	D	ms
p_7	Shape, characteristic signal form as holo-, increasing, triangle, etc.	form	name
p_8	S1 split, time delay of tricuspid valve sound to mitral valve sound	SP_1	ms
p_9	S2 split, time delay of pulmonary valve sound to aortic valve sound	SP_2	ms

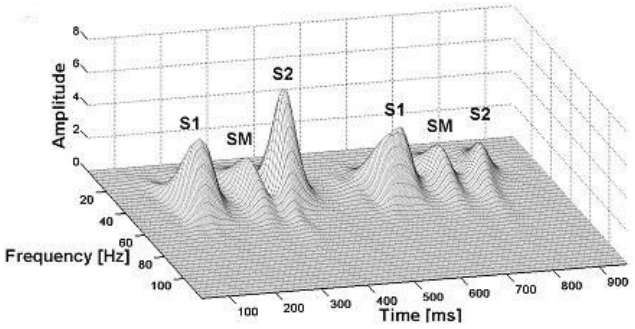

Fig. 5 Time-frequency map of a systolic murmur (SM) due to ventricular septal defect

The second example (Fig. 6) shows a record with extremely large split Due to the large time delay between the mitral (M) and the tricuspidal (T) valve components, the two waveforms are fully separated. In addition, a small level mound can be observed at the end of the systolic period near to the S2 sound, indicating a small level turbulent flow somewhere in the heart.

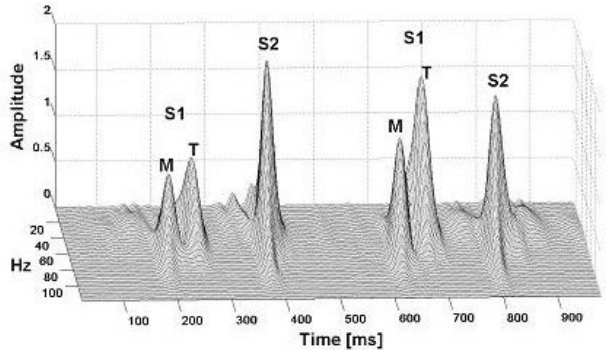

Fig. 6 Time-frequency map of two beats with large split of the mitral (M) and tricuspidal (T) components

A time-frequency map of a heavy ventricular septal defect (VSD) on the middle of the systolic interval is shown in Fig. 7 verified by echocardiography. One can also see the split on the high frequency region of the S1 sound.

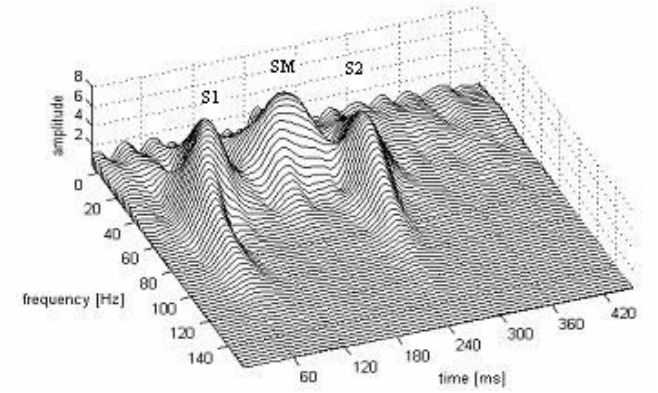

Fig. 7 Time-frequency map of beat with large systolic murmur and a light HF S1split

In order to find relationships between the CHD types and the murmurs they cause a numerical description of the measured sound signals is necessary. In the present stage of research the most important nine parameters have been selected for the characterization of the fetal heart murmurs, which are displayed in Table I. The nine parameters $p_1..p_9$ seem to provide a sufficient description of the examined signal.

In some cases a slight change of the murmur waveform along the record was observed. This deviation, however, was less pronounced. A more noticeable change has been found between the records measured at different dates of the gestation. The appearance of two different murmur types is very rare and, therefore, a very large number of tests should be carried out to find the nature of this defect.

IV. Conclusion

It was demonstrated that with fetal phonocardiography measured after the 28th week of gestation on the maternal abdomen it is possible to discover the fetal heart murmur as well as the split of the S1 and S2 sounds. The main tool for this is a sophisticated signal processing that uses mathematical modeling for all types of fetal heart sounds. Moreover, it was shown that with this method even very low heart murmurs can be detected, sometimes even lower than it could be revealed by ultrasound echocardiography. It was also clear that to achieve this, the telemedicine system can be a suitable device. By means of it pregnant women can carry out the measurements in the most convenient manner, even repeatedly, without any time limitation, in order to find the most noiseless records of heart sounds.

The examinations of the records have shown that, due its simplicity, fetal phonocardiography is remarkably suitable for screening of congenital heart diseases carried out on the low-risk population, even using it as some kind of pre-screening before the postnatal or pediatric heart lesions screening. It was demonstrated, too, that this proposed PCG based screen test could appropriately be combined with the conventional CTG test prescribed for the trimester when the PCG method was also applied for CTG.

It was demonstrated that with the chosen nine-parameter characterization of the identified fetal heart murmur and the related splits it would be possible to determine the relationship of these to the different heart defects, in order to indicate possible postnatal difficulties. However, the results of this should be accepted with restraint regarding that there are also innocent murmurs and because of the spontaneous disappearing of some murmurs after birth or even later.

Last but not least, from the response of large number of mothers it was clear that the negative result on the prenatal screening test for their baby's heart murmur produced a welcome reassurance for the parents.

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