Robust estimation of fetal heart rate from US Doppler signals

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Abstract— **In utero, Monitoring of fetal wellbeing or suffering is today an open challenge, due to the high number of clinical parameters to be considered. An automatic monitoring of fetal activity, dedicated for quantifying fetal wellbeing, becomes necessary. For this purpose and in a view to supply an alternative for the Manning test, we used an ultrasound multitransducer muligate Doppler system. One important issue (and first step in our investigation) is the accurate estimation of fetal heart rate (FHR). An estimation of the FHR is obtained by evaluating the autocorrelation function of the Doppler signals for ills and healthiness foetus. However, this estimator is not enough robust since about 20% of FHR are not detected in comparison to a reference system. These non detections are principally due to the fact that the Doppler signal generated by the fetal moving is strongly disturbed by the presence of others several Doppler sources (mother' s moving, pseudo breathing, etc.). By modifying the existing method (autocorrelation method) and by proposing new time and frequency estimators used in the audio' s domain, we reduce to 5% the probability of non-detection of the fetal heart rate. These results are really encouraging and they enable us to plan the use of automatic classification techniques in order to discriminate between healthy and in suffering foetus.**

Keywords— **fetal monitoring, fetal heart rate, Doppler**

I. INTRODUCTION

THE present paper proposes two algorithms for computing the fetal heart rate. Section II shortly presents our system developed in a view of realizing this task. Having multiple Doppler signals, the problem of estimating the fetal heart rate reduces to two separate problems. Section III.A proposes an algorithm for solving the first problem that is to find correctly the FHR on each Doppler signal, which is not always easy because of the complex nature of signals. For the second problem, two algorithms for fusioning multiple estimates are presented in section III.B. The experimental results together with our conclusion are reported in section IV. Finaly, in the last section we shortly discuss some future trends in our project.

II. EQUIPEMENT

As we can see in figure 1, our Doppler system (the Actifoetus system) contains three groups of four ultrasound transducers each, with sensors working at five depths between 1.88 cm and 15 cm. One group is used for lower members, another one for upper members while the third group is for detecting the FHR. The caracteristics of transducers used in detection of FHR are: bandpass 2.2 MHz - 2.5 MHz, emission frequency of 2.25 MHz, acoustic driving power 1 mW/cm^2, pulse repetition frequency 1 KHz.

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Fig. 1. *The Actifoetus System*

III. FETAL HEART RATE ESTIMATION

A. SLIDING WINDOW ALGORITHM

The first problem that we solve is to estimate the FHR for a given Doppler signal at some depth. For this, we split up the Doppler signal in two directional signals. This task consists in distinguish between the positives and negatives frequencies. We achieve this separation operation by filtering the Doppler signal with an analytic passband filter and it conjugate. An analytic filter eliminates the negative frequencies while the conjugate filter do the same thing for the positives frequencies. It remains only to take the absolute value of filtered signals to obtain the "positives amplitudes" for the signals that get close to the sensor, respective "negative amplitudes" for the signals that move away. Next step is to filter the "positives amplitudes" and "negatives amplitudes" at 4 Hz. This frequency is set to respect the maximum physiological heart rate (as is reported in [1] of a foetus it's 240 beats/minute).

The cardiac rhythm will be estimated from peaks of functions which enhance some patterns in the signal. These functions, autocorrelation (1), crosscorrelation (2), correlation coefficient (3) and YIN estimator (4) [2] are widely used in voice signal processing domain. We mention that in case of YIN estimator we look for minimums of the function and not for the maximums. Below we note these functions with I_i, i=1,...,4 and we present their expressions:

$$I_1(t,k) = \frac{1}{W} \sum_{n=1}^{W-|k|-1} x(t,n) \cdot x(t,n+k) \tag{1}$$

$$I_2(t,k) = \frac{1}{W} \sum_{n=1}^{W} x(t,n) \cdot x(t,n+k) \tag{2}$$

$$I_3(t,k) = \frac{\sum_{n=1}^{W} x(t,n) \cdot x(t,n+k)}{\sum_{n=1}^{W} x(t,n) \cdot x(t,n)} \tag{3}$$

$$I_4(t,k) = \begin{cases} 1, & if\ k = 0 \\ d(t,k) / \left[\frac{1}{k} \sum_{j=1}^{k} d(t,j) \right] \\ W \end{cases}$$

$$d(t,k) = \sum_{n=1} (x(t,n) - x(t,n+k))^2 \qquad (4)$$

Here, we noted with W the size of slidding window, t the time at witch we compute the function and k the lag. First step is to find the positions of maximums or minimums M_n, $n = 0, ..., N-1$, of the used function I_i, with N the number of extrema. Having M_n, we compute the time distances $D_n = M_n - M_{n-1}$ between positions of two consecutives maximums where $n = 1, ..., N-1$. Further, we will label with $\Delta_n = |D_n - D_{n-1}|$, $n = 1, ..., N-1$ the absolute difference of two consecutives distances and with $\Delta = \{\Delta_1, ..., \Delta_n\}$ the vector of differences. For a true fetal cardiac rhythm it is necessary that Δ vector be lower than a threshold value. We note ϵ the threshold value (in beats/minute). The threshold establishs the time interval where we expect a new maximum value of the function. If all the Δ vector's values are lower than ϵ, the fetal cardiac rhythm is considered as the average value of D, while in the other case is decided a non-detection decision of the fetal cardiac rhythm.

Figure 2 illustrates the calcul of vector Δ. For the autocorrelation function of a synthetic signal of 2048 samples we have found position's maximums M_0,...,M_5 and the distances D_1,...,D_5. If the threshold condition is satisfied then the cardiac rhythm is the average of D_1,...,D_5, else we decide that there is no cardiac fetal rhythm. We tested the same algorithm for each defition (1)-(4) and for several patients. An example of FHR computed for a patient coded 19-SAB-CA and for all techniques is presented in the figure 3. Autocorrelation in the upper left corner of the figure, crosscorrelation in the lower left corner, correlation coefficient in the upper right corner and YIN estimator in the lower left corner are presented. Our calculus show that the technique which gives the best trade-off in terms of precision and computation is the autocorrelation function. It performs better than the other techniques I_2, I_3, I_4, and it gives more estimations of FHR on the Doppler signal at a given depth and a given sensor. This is a major advantage comparing with the others techniques. Also, another advantage of the autocorrelation technique is the fewer number of operations used. We also point out that the inconvenience for the same autocorrelation technique

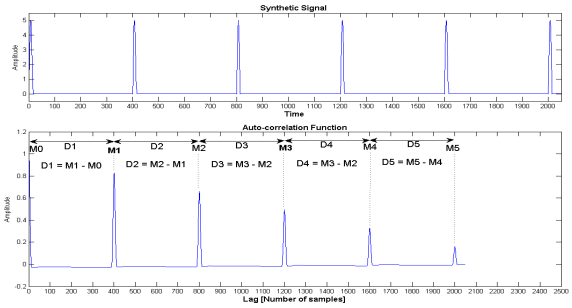

Fig. 2. *Exemple of FHR computation*

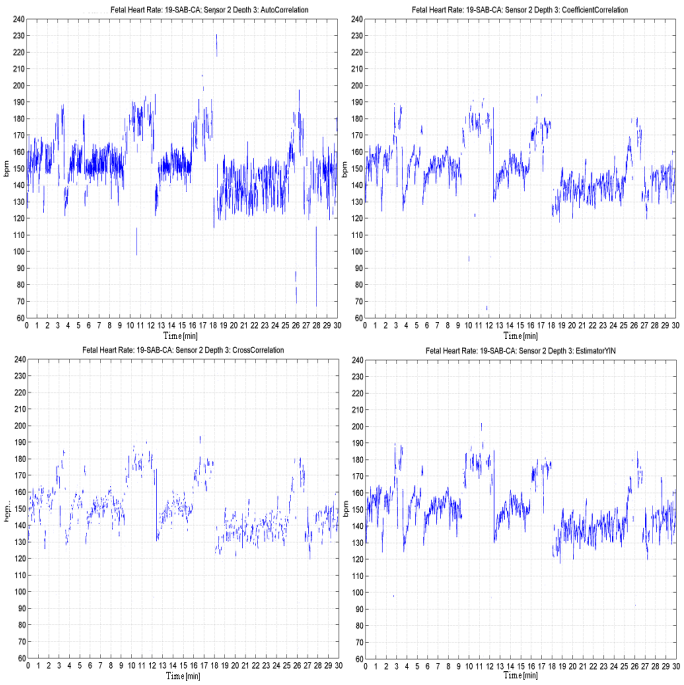

Fig. 3. *Patient 19-SAB-CA. Fetal heart rate detection on the Doppler signal acquired with Sensor 2 at Depth 3 with: a) upper-right corner: Autocorrelation function I_1; b) lower-right corner: Crosscorrelation I_2; c) upper-left corner: Correlation coefficient, I_3; d) lower-left corner: YIN estimator*

is an increased ratio comparing with the others methods of the untrusted reported values of FHR. Anyway, these incorrect estimates are eliminated by the fusion algorithm who dones the final FHR of the foetus. This fusion part of several estimates of the FHR is described below.

B. FUSION FETAL HEART RATES ALGORITHM

Applying the algorithm described in previous section to all received Doppler signals leads to multiple estimates of the same physiological parameter, the FHR. The questions that we adresse at this point is how to choose the best estimate through all estimates? For solving this problem, we propose two algorithms. First of them is based on the maximum of the autocorrelation function and on the detection probability, while the second is based on the statistical properties of the FHR on each channel and on the final fusioned FHR.

B.1 ALGORITHM 1

The first algorithm that we tested takes into account the value of autocorrelation function utilized in the analyse of Doppler signals. The reasons of choosing this function have been ennumerated in the previous section. As we can see in the figure 4 the algorithm supposes a temporal window during the analyze is made. We note this window with t_0,...,t_n. Also, the Doppler signals are labeled S_iD_j, with S from sensor, D for depth, i=1,...,4 and j=2,...,5. The fact that j is starting from 2 means that we ignored the first depth of exploration where a high probability of untrusted value of fetal cardiac rhythm was observed.

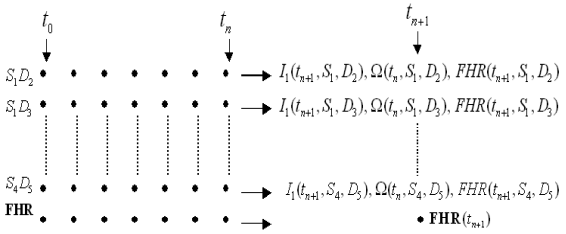

Fig. 4. *Principle of algorithm 1: The fetal heart rate at time instant t_{n+1} is function of the value of the autocorrelation function $I_1(t_{n+1}, S_i, D_j)$ and of detection probability $\Omega(t_n, S_i, D_j)$*

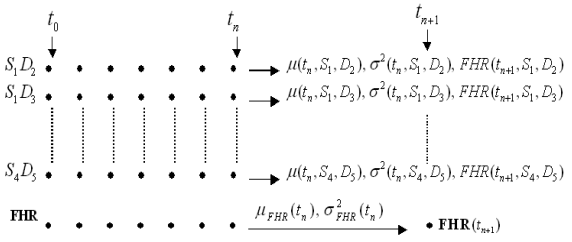

Fig. 5. *Principle of algorithm 2: The fetal heart rate at time instant t_{n+1} is function of the statistics properties on each Doppler signal $\mu(t_n, S_i, D_j)$, $\sigma^2(t_n, S_i, D_j)$ and of statistic properties of final fusioned fetal heart rate $\mu_{FHR}(t_n, S_i, D_j)$, $\sigma^2_{FHR}(t_n, S_i, D_j)$*

Assume now that for a given instant t_{n+1} we apply the algorithm described in previous section. This leads to 16 estimations of the fetal heart rate if we consider only the "positives amplitudes" or 32 estimates if we analyse the "positive" and "negatives amplitudes" in the same time. We selected the second posibility. A vector with all estimations is formed. It is clear that through the 32 cases we might be decided that for some Doppler signals S_iD_j no cardiac rhythm exists, and thus the first step in our algorithm is to search the Doppler signals where we have found a cardiac FHR estimation. For sensors and depths where an estimation is available, we sorted in descending order of the values of $I_1(t_{n+1}, S_i, D_j)$. If an equal value of $I_1(t_{n+1}, S_i, D_j)$ is detected on several signals, then the final FHR is chosen as the heart rate estimated on the signal with the highest detection probability in the analysing window, $FHR(t_{n+1}) = argmax(I_1(t_{n+1}, S_i, D_j), \Omega(t_n, S_i, D_j))$. The detection probability is computed at each instant time, for every Doppler signal, as the ratio between the number of the valid estimation heart rates and the total number of intervals analysed inside the time window. For example, suppose that for signal S_1D_2 we found 5 valid estimation in our time window t_0,...,t_n. The total number of estimations is n+1. The detection probability for the Doppler signal S_1D_2 is 5/n+1, with n obviously bigger than 4. After we chosen fetal heart rate at time t_{n+1}, $FHR(t_{n+1})$, the last step in our algorithm consists in updating the detection probabilities. The updating procedure of detection probability is performed in the time window t_1,...,t_{n+1}. We will compute the detection probability after validation of heart rates detected on each signal at time t_{n+1}. The validation step consists in eliminating those heart rates that are outside of the interval |FHR(t_{n+1}) - FHR(t_{n+1},S_i,D_j)| $< \epsilon$. The procedure is expressed by:

$$\begin{cases} if \ \ |FHR(t_{n+1}) - FHR(t_{n+1}, S_i, D_j)| \ > \ \epsilon \\ \quad FHR(t_{n+1}, S_i, D_j) = NaN \\ else \\ \quad FHR(t_{n+1}, S_i, D_j) = FHR(t_{n+1}, S_i, D_j) \end{cases}$$

B.2 ALGORITHM 2

As we have mentioned, the second algorithm is based on the statistics properties of the FHR on each Doppler signal and on the statistics of fusioned final FHR. In figure 5 we present the principle of this algorithm. Suppose that our analyse is made in the same temporal interval t_0,...,t_n. We made the same notation S_iD_j regarding the Doppler signals and FHR for the final fusioned FHR. With the values of FHR computed at moments t_0,...,t_n, we make a statistic for every Doppler signal. This statistic is available at time instant t_{n+1}. Thus, for every Doppler signal S_iD_j we have at t_{n+1} a mean $\mu(t_n, S_i, D_j)$ and a variance $\sigma^2(t_n, S_i, D_j)$, that depend on the values at t_0,...,t_n. Also, at t_{n+1} we have a mean $\mu_{FHR}(t_n, S_i, D_j)$ and a variance $\sigma^2_{FHR}(t_n, S_i, D_j)$ corresponding to final fusioned FHR. The first step in our algorithm is to find the number $P(t_{n+1})$ of the Doppler signals where the FHR estimation verifies their statistic in the same time with the statistic of final cardiac rhythm. For example the value of FHR at time instant t_{n+1} on S_1D_2, which is $FHR(t_{n+1}, S_1, D_2)$, should be inside of the two intervals [$\mu(t_n, S_1, D_2)$ - $3\sigma^2(t_n, S_1, D_2)$, $\mu(t_n, S_1, D_2)$ + $3\sigma^2(t_n, S_1, D_2)$], and [$\mu_{FHR}(t_n)$ - $3\sigma^2_{FHR}(t_n)$, $\mu_{FHR}(t_n)$ + $3\sigma^2_{FHR}(t_n)$]. If this is true then we increase $P(t_{n+1})$, if not, we simply ignore this Doppler signal and its estimate. After we identified the signals, the step two of the algorithm consists in finding the weigths used in the linear combination [3], that gives the fusion FHR at time t_{n+1}. The weights $k_p(t_{n+1}, S_i, D_j)$ satisfy the folowing relation:

$$\begin{cases} \sum_{p=1}^{P(t_{n+1})} k_p(t_{n+1}, S_i, D_j) = 1 \\ k_p(t_{n+1}, S_i, D_j) = \frac{1}{\sigma^2_p(t_n, S_i, D_j) \sum_{p=1}^{P(t_{n+1})} \frac{1}{\sigma^2_p(t_n, S_i, D_j)}} \end{cases}$$
$$FHR(t_{n+1}) = \sum_{p=1}^{P(t_{n+1})} k_p(t_{n+1}, S_i, D_j) FHR(t_{n+1}, S_i, D_j) \quad (5)$$

The third step is to find the fusioned FHR at time t_{n+1}. This is done by the equation just above. Having the value of the fusioned FHR at t_{n+1}, we must only update the time interval analyse and the statistics. For doing this, we drop out the value of FHR at t_0 and we count the value of FHR at t_{n+1}. Thus, we compute a new mean and variance with the values for time interval t_1,...,t_{n+1}. This is true both for Doppler signals and for final fusioned FHR.

IV. EXPERIMENTAL RESULTS

In a first time we point out the influence of size W, and the overlapping step, in detection of FHR. Figure 6 presents the results obtained using I_1 for W=4s with no overlapping

and W=2s with an overlapping step of 250ms for the same Doppler signal. The overlapping value was chosen to detect the heart rates of 60 beats/min [1]. We found that an optimum value for W, is around of 2 seconds. In [1] an adaptive method of selecting W is proposed as being 3-4 times the value of last beat to beat interval. Knowing that for normal foetus the heart rate is between 110 beats/min. - 160 beats/min, which corresponds in time domain to the interval 545ms - 375ms, our choise is closely to what we have found in the literature. Because the adaptive method of setting W value seems to be unclear when the rhythm is lost, we decided to keep W constant.

Another interesting point was to test which method (1)-(4) estime better the FHR on a given signal. This discusion was made in section A.1, where the results for all methods were shown in figure 3. We remarked the superiority of autocorrelation technique, both from a detection and real time computation point of view. Autocorrelation, is the best trade-off in terms of probability detection, false detection and speed computation.

Further investigation was to determine precisely how the algorithms work. We found that in case of high W values (like 4 seconds), generaly we have a poor detection probability, specifically in accelerations and decelerations moments. This is true even when we are using or not an overlapping step. In this case our monitoring is not a sure one, and for some examens, the time for which we lost the rhythm is important. We reduced the time of non detections to a smaller period than the period of a reference system, using a smaller value for W in the same time with an overlapping step. We can observe this in figure 7.c, d comparing with figure 7.b, where we used the first algorithm based on amplitude of autocorrelation function. By comparing the two algorithms between them, we found that for the same parameters W and overlapping step, see figures 7.c and 7.d, the second algorithm estime better the fetal heart rate. The comparation was made in a subjective way, because it is impossible to access to numerical values of our reference.

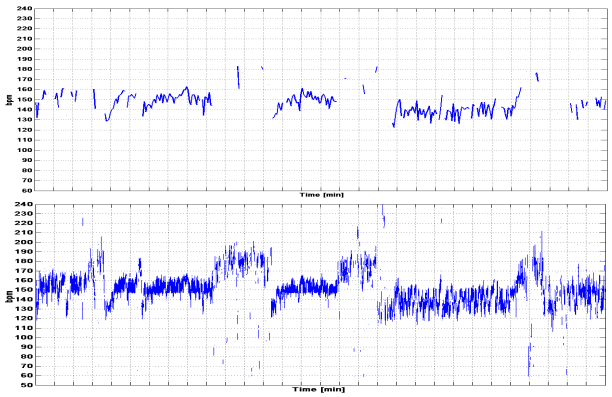

Fig. 6. *Autocorrelation I_1: 19-SAB-CA: Sensor 2, Depth 3: a) W=4s, no overlapping; b) W=2s, overlapping of 250ms*

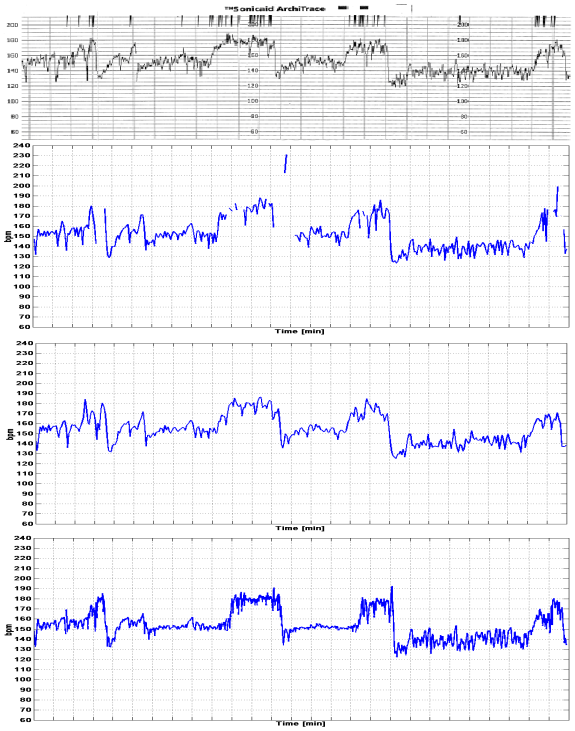

Fig. 7. *Patient 19-SAB-CA: a) Reference SONICAID; b) Algorithm 1, W=4s with no overlapping; c) Algorithm 1, W=2s with overlapping step of 250ms; d) Algorithm 2, W=2s with overlapping step of 250ms*

V. PERSPECTIVES

Future investigations will be made in estimating the FHR using the algorithms that implies a prediction for the next time t_{n+1} of FHR. Algorithms which use Kalman filtering [4]-[7], are reported. The problem of interest in these algorithms is to see until which point we are able to make such a prediction of FHR in terms of overlapping. Another point of interest is to develop fusion algorithms that find the final heart rate starting from groups of signals. The reason for doing this, is to eliminate the corrupted signals or the false estimates of the FHR. A final task, will be to use the information given by the others sensors focalized on lower and upper members, helping in this way to decide if the lost of FHR is caused by a foetus moving.

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