Hardware Approach of R-Peak Detection for the Measurement of Fetal and Maternal Heart Rates

M. A. Hasan[1], Md Mamun*[2]

[1] School of Electrical and Electronic Engineering
The University of Adelaide
South Australia 5005, Australia
[2] Department of Electrical, Electronic and Systems Engineering
Universiti Kebangsaan Malaysia
43600 UKM, Bangi, Selangor, Malaysia
*mdmamun.ukm@gmail.com

ABSTRACT

Fetal heart rate (FHR) monitoring is a routine for obtaining significant information about the fetal condition during pregnancy and labour. Fetal condition may change abruptly during the pregnancy period. Therefore, a continuous fetal electrocardiogram (FECG) monitoring will ease the fetal well-being. An algorithm has been developed to detect R-peak for the simultaneous measurement of the fetal and maternal hearts rates during pregnancy and labor for fetal monitoring. The algorithm is based on a cross-correlation, adaptive threshold and statistical properties in the time domain. The performance achieved for the R-peak detection for the heart rate measurements shows that the model can extract R-peak for both, mother and fetus utilizing a single-lead configuration. The algorithm has been implemented in the field of propagation gate array (FPGA). The design was synthesized and fitted into Altera's Stratix EP1S10 using the Quartus II platform because of its enhanced DSP capability. Test case results showed an error percentage of around ±0.3% and ±0.5% for the R-peak detection of maternal and fetal mortality respectively. The system is capable of running at a maximum clock frequency of 48.56MHz, and consumes 9633 logic elements, 101616 memory space and 4 units of DSP blocks.

Keywords: FPGA, Electrocardiogram, VHDL, DSP, Fetal heart rate, QRS.

RESUMEN

EL monitoreo de la frecuencia cardiaca fetal (FHR) es una rutina para obtener información significativa sobre el estado del feto durante el embarazo y el parto. La condición fetal puede cambiar abruptamente durante el período de embarazo. Por lo tanto, un continuo monitoreo fetal por medio de electrocardiograma (FECG) facilitará el bienestar fetal. Se ha desarrollado un algoritmo para detectar el pico R para la medición simultánea de las frecuencias cardiacas fetal y materna durante el embarazo y el trabajo de monitorización fetal. El algoritmo se basa en la correlación cruzada del umbral adaptativo y propiedades estadísticas en el dominio del tiempo. El desempeño obtenido para la detección del pico R para las mediciones del ritmo cardíaco muestra que el modelo puede extraer picos R para ambos madre y feto utilizando una configuración de una sola via. El algoritmo ha sido implementado en el arreglo de compuertas de propagación (FPGA). El diseño fuésintetizado y acomodado en Stratix de Altera EP1S10 utilizando la plataforma Quartus II debido a su capacidad DSP mejorada. Los resultados de las pruebas de caso mostraron un porcentaje de error de alrededor de ± 0,3% y ± 0,5% para la detección R-pico de la mortalidad materna y fetal, respectivamente. El sistema es capaz de funcionar a una frecuencia de reloj máxima de 48.56MHz, y consumes 9633 elementos lógicos, 101616 espacio de memoria y 4 unidades de bloques DSP.

1. Introduction

The electrocardiogram (ECG) is the electrical signal produced by the heart and contains the distinctive shape known as the QRS complex. The time between two successive R peaks of the QRS complex is known as the RR interval and the heart rate (HR) is the reciprocal of the RR interval expressed in Beat Per Minute (BPM). Electronic fetal heart rate (FHR) monitoring is used to determine if the fetus is free from any complications such as antenatal uteroplacental insufficiency and fetal hypoxia, and to determine the fetal health [1]. Continuous efforts are being made to produce more efficient and accurate methods to extract the fetal RR interval, and gain a better interpretation of the FHR patterns by researchers.

At present, Doppler ultrasound has become a popular technique of monitoring the FHR abdominally but attempts to produce a portable system have not been successful because of its sensitivity to movements [2]. A method utilizing the abdominal electrocardiogram (AECG) has a better prospect for long-term monitoring but requires much signal processing to be done [2, 3]. This method is non-invasive and has potential to convey the electro- physiological information, which helps to determine the conditions of the fetus such as stress and acidosis, and uterine activity [3, 4]. The disadvantages of such systems require intermittent repositioning of the transducer and they are only suitable for use with highly trained midwifes. The ultrasound transducer is problematic and uncomfortable while the procedure involves launching a 2 MHz signal towards the fetus. The use of Doppler ultrasound (invasive manner) is not suitable for long periods of FHR monitoring [5-7]. Doppler ultrasound technique suffers from the limitation of sensitivity to movement and most Doppler systems rely upon some form of averaging to produce their FHR data. In contrast, methods utilizing the AECG have a greater prospect for long-term monitoring of FHR and fetal well-being using signal processing techniques. The AECG signal can also be used for antepartum non-invasive FHR determination through the detection of small fetal cardiac potentials at the surface of the maternal abdomen [8]. The AECG can be used to produce true RR interval data, which is suitable for heart rate variability studies if required. Its advantages are that it is completely non-invasive and unobtrusive, has comparatively low power requirements and can be used over extended (e.g. 24 hours) periods. The method additionally allows the maternal heart rate (MHR) to be recorded since the MECG is also detected from the AECG. The advantage of using AECG to extract FECG is that additional information can be extracted compare to using Doppler ultrasound although the accuracy of this technique is much lower compare to the former one [9].

The Field-programmable gate arrays (FPGA) offers a potential alternative to speed up the hardware realization [10, 11]. From the perspective of computer-aided design, FPGA comes with the merits of lower cost, higher density, and shorter design cycle [12]. It comprises a wide variety of building blocks. Each block consists of programmable look-up table and storage registers, where interconnections among these blocks are programmed through the hardware description language [13]. This programmability and simplicity of FPGA made it favorable for prototyping digital system. FPGA allows the users to easily and inexpensively realize their own logic networks in hardware. FPGA also allows modifying the algorithm easily and the design time frame for the hardware becomes shorter by using FPGA [14].

In this work we propose the framework of FPGA-based hardware realization of fetal heart-rate detection algorithm. The VHDL is selected as the hardware description language, which could be used to realize the maternal and fetal QRS complex extraction to measure both the FHR and maternal heart rate (MHR). The use of VHDL for modeling is especially appealing since it provides a formal description of the system and allows the use of specific description styles to cover the different abstraction levels (architectural, register transfer and logic level) employed in the design [11]. In the method computation of, the problem is first divided into small pieces; each can be seen as a submodule in VHDL. Following the software verification of each submodule, the synthesis is then activated. It performs the translations of hardware description language code into an equivalent netlist of digital cells. The synthesis helps integrate the design work and provides a higher feasibility to explore a far wider range of architectural alternative [12]. In this study, to validate the effectiveness of the method, various maternal ECG have been used. The method provides a systematic approach for hardware realization, facilitating the rapid prototyping of Fetal heart-rate detection.

2. Clinical significance of FECG morphology

Biomedical signal implies a collective electrical signal acquired from any organ that represents a physical variable of interest where the signal is

considered in general a function of time and is describable in terms of its amplitude, frequency, and phase. FECG is a biomedical signal that provides electrical representation of FHR to get the vital information about the condition of fetus during gestation and labor from the recordings on the

mother's body surface. Sometimes the FECG is the only information source in early stage diagnostic of fetal health and status. The FECG signal is very much related to the adult ECG, containing the same basic waveforms including the P-wave, the QRS complex, and the T-wave. The PQRST complex as shown in figure 1 is an electric signal produced by the contraction of the heart's muscle called myocardium. It is composed of three parts; first, the P-wave reflects the contraction of the atriales. Second, the QRS-complex is related to the contraction of the ventricles, due to the magnitude of the R-wave, it is extremely reliable. Finally, the T-wave, which corresponds to the repolarization phase, which follows each heart contraction.
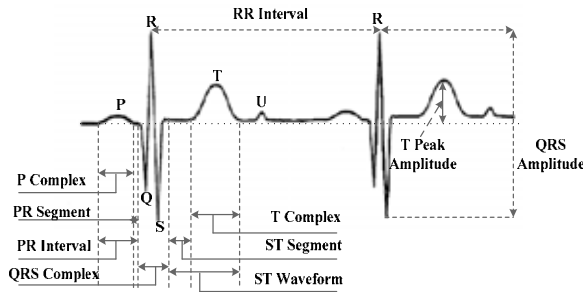

Figure1. FECG shows key features:
the PQRST complex

3. Methodology

3.1 R-peak detection of maternal QRS

The detection of maternal QRS complexes begins with cross-correlating the signal with an average maternal QRS template. The cross-correlation output of the signal x at each instant n with the template s(k) is given by

$$y(n) = \sum_{k=0}^{M} h(k)x(n-k) \qquad (1)$$

where, $h(k) = \begin{cases} s(M-k), & 0 \le k \le M \\ 0, & elsewhere \end{cases}$

The template s(k) with (M + 1) equally spaced points over 80 ms has been empirically found to be optimized for the detection of maternal QRS complexes when M = 8. The width of the template is based on the normal width of the maternal QRS

complex [15]. The template is continuously updated with the detection of R peaks to take into consideration the variation of shape of the maternal QRS complexes in AECG.

The local maxima search routine measures the slope of the cross-correlated output by

$$y'(n) = y(n) - y(n-1) \qquad (2)$$

It also assumes a maximum at sample (n - 1) when the slope changes from $y'(n-1) \ge 0$ to $y'(n) < 0$. If no maximum is found in the subsequent 20 ms (assumed to be the minimum fetal QRS duration), the sample value y(n-1) and corresponding instant are saved as the local maximum. This 20 ms search interval is necessary to avoid taking small spikes on the slopes of the QRS complexes as maxima.

Three values, $V_{M1} > V_{M2} > V_{M3}$, and their time instants corresponding to the largest three local maxima are stored within an R wave search interval. The length of the search interval is initially one second (in fact 1024 ms for computational simplicity) and it is then continuously updated after the first RR interval measurement. The one-second search interval and the saving of 3 local maxima assume that the maternal heart rate (MHR) does not exceed 120 BPM which means at most 2 maternal R peaks can be found in the initial search interval. If V_{M1} is validated as the R peak then the value V_{M2} is taken as the noise. V_{M3} is kept for cases when V_{M2} is validated as the R peak. The threshold used in the detection is set initially by assuming a minimum maternal R peak of 10 μV and it is continuously updated based on the levels of both R peak and noise [16]. A possible maternal R peak is assumed to be found when the value V_{M1} exceeds this threshold. V_{M2} is also considered as an R peak if the value is comparable to that of V_{M1} and the resulting heart rate is below 120 BPM, as earlier assumed. Hence the criteria:

$$2V_{M2} > V_{M1} \qquad (3)$$

and

$$|t_{M2} - t_{M1}| > 512 \ ms \qquad (4)$$

If V_{M2} also exceeds the threshold, the QRS template is compared with the complexes associated with both V_{M1} and V_{M2}. The one with the least mean square error is taken to be the R peak. The other peak is assumed to be a large spike in the signal and its position is saved for use in the fetal R peak validation routine. If V_{M2} has the larger error, its position is saved only if inequality in (3) applies, because smaller V_{M2} may be associated with an actual fetal R peak.

The running average used in this algorithm is performed to average the QRS templates, RR intervals, levels of R peak and noise. The b-th value of the running average A(b) is given by a weighting of the previous average A(b-1) plus that of the new value C(b) as shown in the following equation:

$$A(b) = \{1 - k(b)\}A(b-1) + k(b)C(b) \qquad (5)$$

where, $k(b) = \begin{cases} \dfrac{1}{b} & , \ b \leq B \\ \dfrac{1}{B} & , \ b > B \end{cases}$

The running averages of noise and R peaks (A_N and A_R) are estimated over B recent values where, B = 8 in (5) has been empirically found to be effective. Based on these averages, two thresholds, TM_1 and TM_2 are used in the R wave search. They are given by

$$TM_1 = A_N + \frac{A_R - A_N}{4} \qquad (6)$$

$$TM_2 = \frac{TM_1}{2} \qquad (7)$$

The adaptation of the threshold to varying R peak and noise levels, and the R wave search interval are based on the method proposed in [17].

If the maximum search limit is reached while the local maximum V_{M1} has a value less than TM_1, then V_{M1} is taken as a possible R peak if it exceeds the second threshold, TM_2. If no such V_{M1} is found, a signal loss is assumed. The local maxima values are then set to zero for the subsequent R wave search. Four latest maternal RR intervals are maintained in record for the purpose of checking

coincidences of the maternal with the fetal R waves.

3.2 R-peak detection of fetal QRS

The maternal electrocardiogram (MECG) complex is then subtracted upon detection of a maternal QRS to remove the maternal contribution from the abdominal signal. This complex is of fixed duration, 160 ms before and 320 ms after the maternal R peak instant. This duration assumes that the average MHR is less than 125 BPM and it should normally include the P and T waves, if any. The MECG template is matched with actual MECG in the abdominal signal by scaling it with the factor,

$$K = \sqrt{\frac{Value1}{Value2}} \qquad (8)$$

where, Value1 < Value2. These values are obtained from the cross-correlation of abdominal signal with maternal template and auto correlation of the maternal template. If the cross correlation value is greater than the auto correlation value, then the abdominal signal is multiplied by the factor K and MECG template is subtracted, if not, MECG template is multiplied by factor K and subtracted from the abdominal ECG signal.

The detection of the fetal QRS complex begins by differencing local maxima and minima on the output of the subtracted signal when the time marker counter, which was initiated at the second accepted maternal R peak, has reached 2048 ms [18]. This duration ensures that the 2 second delayed samples are already within the MECG subtracted region of the signal. Observing the waveforms, it is possible to differentiate between fetal events and noise events if the amplitudes are similar. This is partly because of the rapid and large deflections between a local maximum and the following local minimum when a fetal beat has occurred. From (2), a minimum is assumed at sample (n - 1) when the slope changes from y'(n-1) < 0 to y'(n) ≥ 0. The absolute value of the difference between successive peak and valley is computed for each max-to-min interval.

The local maxima search routine is performed on the output of the differencing of local maxima and minima routine, and three largest maxima, $V_{F1} >$

$V_{F2} > V_{F3}$ are kept as before. The initial search interval is 640 ms so that at most two fetal R peaks can be found by assuming the FHR does not exceed 187 BPM during the initial search interval. The first search is repeated for another subsequent 640 ms if the largest local maximum, V_{F1} is concurrent with a maternal QRS complex and V_{F2} is smaller than a threshold or is also concurrent. The threshold used in the FHR detection is set initially by assuming a minimum fetal R peak of 5 μV and it is continuously updated [17]. The routine is similar to that for the maternal case but uses the following criteria to accept V_{F2} as a possible fetal R peak:

$$1.5V_{F2} > V_{F1} \qquad (9)$$

and

$$\left| t_{F2} - t_{F1} \right| > 320 \ ms \qquad (10)$$

The second search is repeated if the accepted first fetal R peak is found to be concurrent with a maternal QRS complex or if

$$2V_{F3} > V_{F1} \qquad (11)$$

i.e. the signal is noisy with all its three local maxima having comparable values. The fetal and maternal QRS complexes are concurrent if

$$\left| t_F - t_M \right| < 64 \ ms \qquad (12)$$

where t_F and t_M are the fetal and maternal R peak instants, respectively. The range in (12) accounts for possible overlap of the two complexes, which are assumed to have widths of 50 and 80 ms respectively. The overlap is checked by relating the fetal R peak instant to the four latest maternal RR intervals.

The subsequent fetal R wave detection procedure is the same as that for the maternal R wave using two thresholds, TF_1 and TF_2 which are set as in (6) and (7), according to the running average of the R peaks and noise with B = 8 in (5). The determination of the fetal R wave search interval is also based on the method proposed in [18]. The second threshold, TF_2 is used when the maximum search limit is reached. A signal loss is assumed

when no maximum exceeding the threshold is found. When the second threshold is used to identify a fetal R peak, the peaks are averaged with B = 4 so that the first threshold will quickly adapt to the smaller signal.

After a possible fetal R wave is found, a continuation of the search for up to 220 ms is carried out unless the maximum search limit is reached. This forward searching reduces the possibility of false R wave detection with the assumption that the heart rate does not exceed 270 BPM. Then the program branches to the validate and update routines. The validate routine first checks if

$$V_{F3} > TF \qquad (13)$$

and

$$1.5V_{F3} > V_{F1} \qquad (14)$$

where TF is the threshold used to detect V_{F1}. These conditions mean that the fetal R peak was obtained in a very noisy signal. Otherwise, similar checks are made with V_{F2}, where

$$V_{F2} > TF \qquad (15)$$

and

$$1.5V_{F2} > V_{F1} \qquad (16)$$

also imply a noisy signal.

If V_{F1} is the only maximum above the threshold then it is taken as a fetal R wave. If V_{F2} also exceeds the threshold, then V_{F1} is checked for coincidence with possible spikes by relating its instant to the four maternal values which are kept in the record. The spike position, t_S and the position, t_{F1} in the signal associated with the local maximum, are compared for

$$t_S - t_{F1} |< 40 ms \qquad (17)$$

which allows for the difference in correlation delay when obtaining t_S and t_{F1} respectively. If V_{F1} is identified as a large spike in the signal, then V_{F2} and V_{F3} are assumed to be the fetal R peak and the noise, respectively.

Thresholds and search interval limits are updated according to the procedure described earlier and the local maxima values are then set to zero for the subsequent R wave search.

3.3 System realization in hardware

The QRS detection algorithm was initially implemented in Visual C++ because it is simpler and faster to verify the functionality and reliability. Then, the algorithm was implemented in VHDL; where Altera's Quartus II version 4.0 is used as the platform. As a result, for VHDL implementation the algorithm has to be thought of as a structural, behavioral and physical version of the algorithm. The advantage of using Quartus II is that the system can be synthesized into a physically available FPGA, or the built-in simulation device models. The built-in simulation device models emulate the real device with the actual timing and power values. Thus, its performance in terms of timing, speed, power consumption, total logic element counts and functionality can be ascertained. Modifications can be easily performed and its impact to the physical implementation, especially in terms of timing and functionality can be immediately known.

Figure 2. Top level block diagram.

Figure 2 shows a simplified block diagram of the implementation of the system. Basically, the system is categorized into three main sections, the common, maternal and fetal sections. The common block, shared by both maternal and fetal sections are the data input section, memory register section, memory initialization section and main control section. Maternal blocks consist of the maternal initialization sections (XCM1 block, inipar1 block, maternal inipar2 block and iniSub block), maternal RR interval block, maternal validation block, maternal subtraction block and maternal correlation & local maxima section. Fetal blocks consist of fetal initialization section, fetal extraction section, fetal correlation section, fetal local maxima search section, fetal template update section and fetal coincidence section. The pins for the system PIN_NEWDATA, PIN_DATA and PIN_DATAREQ are used to interface with an external module to retrieve new data. When the system is done, PIN_RB_RE, PIN_RB_RADD and PIN_RB_RDATA are used to access the DPRAM to retrieve the stored maternal and fetal RR interval results from their corresponding memory segment.

4. Results and discussion

4.1 Data structure

In this research, the signals used were downloaded from MIT database website. The signals consist of both normal AECG and AECG with paroxysmal atrial fibrillation. The test signals consist of both normal and atrial fibrillation ECG.

The data set consists of 50 record sets. Each record set contains two 30-minute with consecutive record names (e.g., n01 and n02), and two 5-minute "continuation" records with names ending in c (e.g., n01c and n02c). All four records in each record set are excerpts of longer continuous AECG recordings of a single subject. The 50 record sets come from 48 different subjects. The records with names beginning with p come from subjects who have paroxysmal atrial fibrillation (PAF). The second (even-numbered) record in each pair of 30-minute records contains the ECG immediately preceding an episode of PAF. Thus, for example, record p16 immediately precedes the episode of the PAF in record p16c.
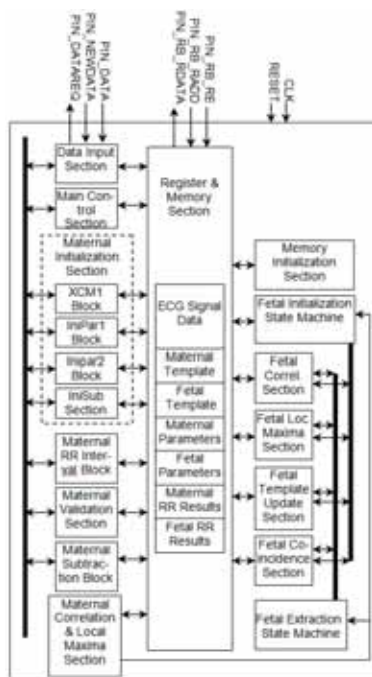
The first (odd-numbered) record of the set (for example, record p15) contains 30 minutes of the AECG during a period that is distant from any episode of PAF. Distant means there is no PAF during the 45-minute period before or after the 30-minute record in this case. The corresponding 5-minute continuation record (e.g., record p15c) shows the minutes immediately following the PAF-distant record.

The records with names beginning with *n* come from subjects who do not have documented atrial fibrillation, either during the period from which the records were excerpted or at any other time. The subjects include healthy controls, patients referred for long-term ambulatory ECG monitoring, and patients in intensive care units.

All signals are converted into text format and graphical format in excel files.

The *.dat files downloaded are in binary format. They contain the digitized ECGs with 16 bits per sample, least significant byte first in each pair, 128 samples per signal per second, samples from each channel alternating, nominally 200 A/D units per millivolt.

They are manually converted to text file format *.txt by using a C++ program, confil.cpp. Since the total number of samples is large (128 samples per second = 7680 samples per minute, thus total samples = 7680*40 = 307200 samples per subject), only two thousand samples are converted in each text file (2000*4 = 8000 samples per subject).

4.2 Visual C++ and VHDL simulation

The result in table 1 using Visual C++ shows encouraging results with the test case, where the fetal R peak could be detected up to 98%. Upon completion of the test case simulation using VHDL, the system performs a read request to retrieve all the maternal and fetal results. A sample read operation for maternal and fetal R peaks detection is shown in figure 3 with the initial 4900 sample data. The Quartus simulation result shows that the

VHDL models are functioning almost similar to the Visual C++ function. The results for both versions are shown in table 2 and 3. Comparing the maternal and fetal RR interval values (in terms of number of samples between the intervals), the maternal error is consistently less than 0.3%, and the fetal error percentage is within 0.5%.

All the differences are caused by the rounding effect during computation. However, when a fetal peak loss happens, an error rate up to 4% might have occurred, owing to slightly different search limit implemented in the VHDL. Despite this, the VHDL interpretation of the system displays great similarities to the Visual C++ version.

Description		Value
Maternal	Total R peak	164
	Detected	164 (100%)
Fetal	Total R peak	235
	Detected using first threshold	182 (77%)
	Detected using second threshold	5 (02%)
	Coincidence	46 (19%)

Table 1. Test simulation using Visual C++.

Sample No.	RR intervals		% Diff
	VC++	VHDL	
1	297	297	0%
2	299	299	0%
3	301	301	0%
4	295	295	0%
5	296	297	0.3%
6	294	293	-0.3%
7	297	297	0%
8	292	292	0%
9	299	298	-0.3%
10	296	295	-0.3%
11	296	295	-0.3%
12	290	291	0.3%
13	289	288	-0.3%
14	290	291	0.3%

Table 2. Comparison between VHDL and Visual C++ results detecting number of maternal RR intervals.
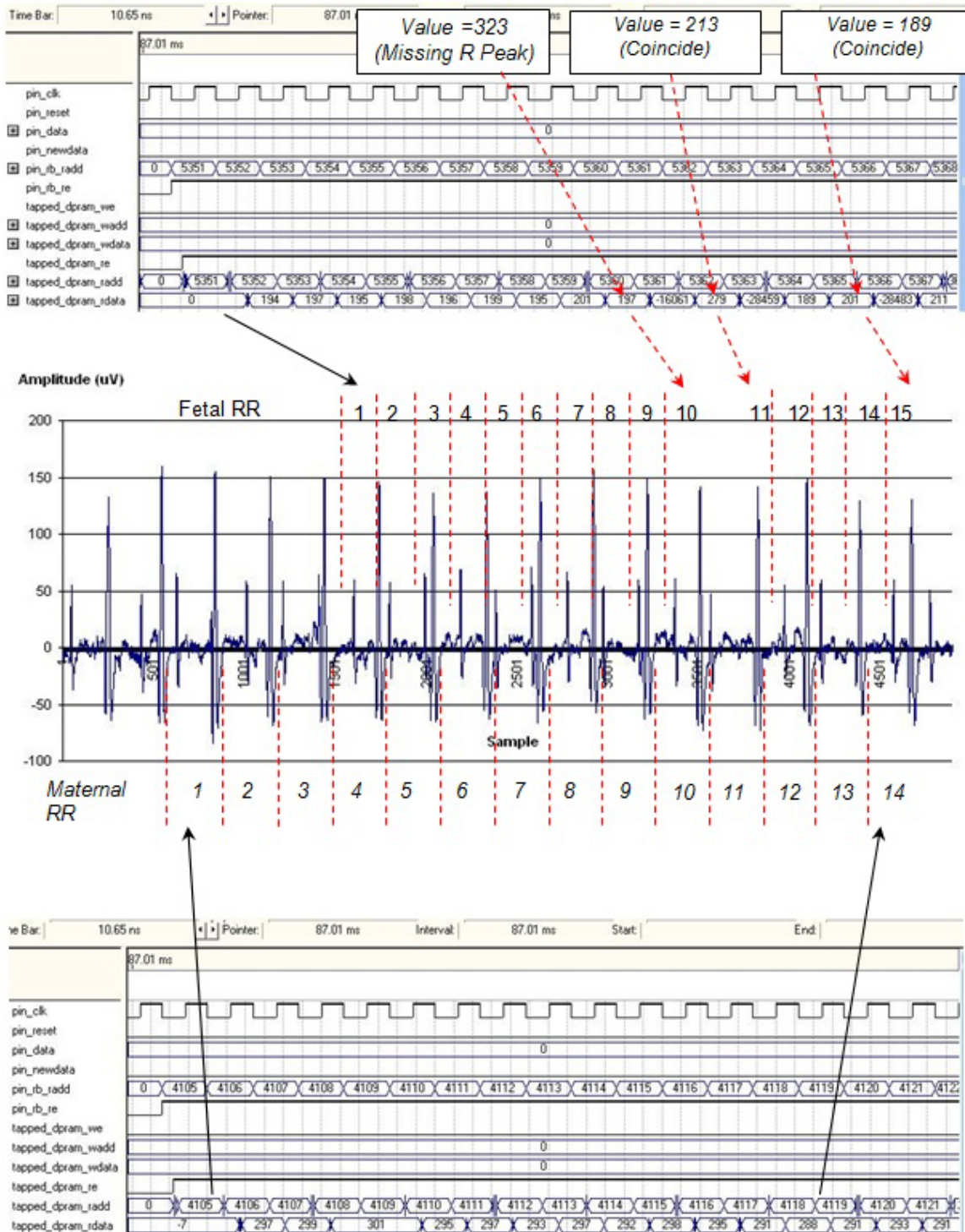
Figure 3. R peak detection of maternal and fetal with 4900 data.

| Sample No. | RR Intervals | | % Diff. |
	VC++	VHDL	
1	194	194	0%
2	197	197	0%
3	195	195	0%
4	197	198	0.5%
5	197	196	-0.5%
6	198	199	0.5%
7	196	195	-0.5%
8	201	201	0%
9	197	197	0%
10	312	323	3.5%
11	290	279	-3.8%
12	212	213	0.5%
13	190	189	-0.5%
14	201	201	0%

Table 3. Comparison between VHDL and Visual C++ Results detecting number of fetal RR intervals.

4.3 Synthesis

Table 4 and 5 show the resources consumed during compilation to fit the system into an Altera's Stratix device. The total resources required are calculated, allocated and then fitted into Altera Stratix EP1S10 device. The tables below show the number of logic elements, registers, memory and DSP units used during fitting and compilation. The DSP units are used for the implementation of the accumulator and multiplication between the signal and template points for both the fetal and maternal correlation block.

Description	Total
Device	EP1S10F780C5
Netlist size	10376 Nodes
Usage	9,633/10,570 (91%)
Total memory bits	101,616/920,448 (11%)
DSP blocks	4/48 (08%)
Total pins	346/427 (81%)

Table 4. Summary of Resource Fitting.

Block		Logic cells	Register	Memory bits	DSP
Top		9,633	1586	101,616	4
Common	Data input block	33	30	0	0
	Initialization block	143	55	0	0
	Registers and memory block	1,489	742	101,616	0
Maternal	Initialization and extraction block	1,053	130	0	0
	a. Main state machine	198	36	0	0
	b. Inipar1 sub-block	174	48	0	0
	c. Inipar2 sub-block	254	0	0	0
	d. Initxcm1 state machine	191	10	0	0
	e. Inisubtract state machine	236	36	0	0
	Correlation block	516	107	0	2
	RR Interval block	315	6	0	0
	Validation block	1,224	151	0	0
	a. Main state machine	936	91	0	0
	b. Error check state machine	288	60	0	0
	UpMatPar block	730	0	0	0
	Subtraction lock	502	114	0	0
	a. Main state machine	156	48	0	0
	b. MPK state machine	258	56	0	0
	c. XCM2 state machine	88	10	0	0
Fetal	Initialization block	1,003	15	0	0
	a. Main state machine	414	15	0	0
	b. Coincidence sub-block	589	0	0	0
	Extraction block	1630	35	0	0
	Correlation block	290	100	0	2
	Local Maximum block	233	42	0	0
	Template block	472	59	0	0

Table 5. Fitter resource allocation.

5. Conclusion

The performance achieved for the heart rate measurements from the AECG shows that the model can extract both R-peak of maternal and fetal utilizing a single-lead configuration. The result using Visual C++ shows that the fetal R peak could be detected up to 98%. Test case results also showed an error percentage of around ±0.3% and ±0.5% for the R-peak detection of maternal and fetal respectively. The system is capable of running at a maximum clock frequency of 48.56MHz, and consumed 9633 logic elements, 101616 memory space and 4 units of DSP blocks. Therefore, we can concluded that the developed algorithm and hardware approach will be a useful tool in the assessment of the fetal condition and its relationship to that of the mother's.

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