Performance of a Method to Generate Fetal Cardiotachograms Using Fetal Phonocardiography

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Abstract

In this work the capability of a fetal Phonocardiogram (PCGf) processing method to generate reliable time series has been evaluated. Twenty-nine simultaneous PCG and ECG signals were recorded from 18 adults and 11 fetus. Each PCG signal was processed to extract the starting (S), maximum (M), and ending points (E) from the envelope of S1 and S2. The time series (SS, MM, EE) were compared with the pattern signal by ECG using time and frequency heart rate variability indexes derived from each time serie. Data were analysed using ANOVA and post hoc test for repeated measures. Results on adults have shown that with the proposed method, SS1, MS1, SS2 and MS2 are reliable time references to generate time series ($p>0.05$). On fetal signals, because of the recording setup, the method performance has been limited to detect MS2 as the only reliable time reference. Thus, the PCGf is a reliable source to produce at least one time serie equivalent to the pattern signal.

1. Introduction

During the last two decades, the fetal Phonocardiogram (PCGf) has been proposed as an alternative way to produce the fetal Cardiotachogram (SCTGf) in order to get information about fetal well-being [1,2,3]. To achieve this goal, it is necessary to extract reliable time references from the cardiac sounds (S1 and/or S2). This is not an easy task because of the poor signal to noise ratio (SNR) of the PCGf, and the cardiac sounds morphology. To contend with these problems, different filtering and envelope generation techniques have been used to extract the maximum point from the cardiac sounds envelope [1,3]. Specifically, we have proposed and evaluated a filtering scheme based on multiresolution analysis and de-noising techniques to filter the PCGf prior to extract time references from the Hilbert Transform envelope [4]. Our results, obtained on short simulated PCGfs (150 cardiac cycles), have shown that the best performance of the method is carried out when three levels of decomposition, wavelet Daubechies of sixth order, and adaptive thresholds, are used [5]. This methodology improves the SNR, reduces the deterioration of the cardiac sounds morphology, and therefore increases the precision to extract time references from the starting (S), maximum (M), and ending (E) points on the envelope associated to S1 and S2. Nevertheless, the knowledge about the precision of the time references extracted from short simulated signals is not enough to assure the method capability to produce reliable SCTGfs according to clinical standards [6] that use the ECG to generate the Cardiotachogram from the R wave (RCTG). The goal of this paper is to extend our observations on longer real PCGs, through the evaluation of the performance of our time references extraction method (EM) [4,5], by comparison of the heart rate variability indexes [6] derived from RR and the fetal cardiac sounds periods.

2. Material

The group of signals was composed of twenty-nine recordings from 18 adults (age: 18-42 years old) and 11 fetus (age: 28-41 weeks old) using 16-bit accuracy resolution and 1000 Hz sampling frequency. The setup was conformed by Nihon Kohden PCG and ECG amplifiers, a Biopac Systems analog-digital converter, and a piezoelectric microphone.

3. Methods

The main problem to evaluate the time series generated by PCGf, is the difficulty to get a reliable pattern to test them on short-term and long-term [7]. A possible pattern might be gotten from the abdominal ECG; however, it is possible to have some mistakes when the fetal R wave is extracted from complexes maternal-fetal overlapped. To avoid this possible error, and ensure our evaluation on the time series by PCG was reliable; this EM was first applied on signals recorded from adults. This stage gave us the opportunity to test the time references obtained by our EM on longer PCG signals with high SNR and well-known R wave position. In the next stage, the time series

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obtained by this EM on fetal PCC signals were also tested. All the evaluation process was based on heart rate variability indexes and was developed off-line using Matlab.

3.1. Protocol

It was developed in three stages:

STAGE 1: Consisted of a preliminary study, which let us know if our EM was able to produce reliable CTGs from high SNR and longer PCGs. Nine simultaneously PCG and ECG signals were recorded during 3 minutes from 9 adults (age: 19-42 years old). To get the highest possible SNR in the PCG recording, the microphone location on the chest, the subject position and the bandwidth filter were changed in each subject. The ECG signal was recorded mainly using DII lead.

STAGE 2: This study was developed to simulate a PCGf recording situation where, no matter the setup, the mother position, or microphone location changes, it is not possible to improve the SNR. This study gave us opportunity to evaluate the time series produced by our EM in this inconvenient but common situation avoiding the pattern signal deterioration. Nine simultaneously PCG and ECG signals were recorded during 5 minutes (according to variability study criteria [6]) from 9 adults in supine-dorsal position (age: 19-38 years old). The microphone was located on the chest and the analog filter was turned off. The ECG signal was recorded mainly using DII lead.

STAGE 3: In order to get the final evaluation of the time series generated using our EM, 11 simultaneously long PCGf and abdominal ECG signals recorded during 3-5 minutes were processed [2]. The microphone and the cardiac leads were located on the abdominal maternal wall while the mother was on supine-dorsal position with 28-41 weeks of pregnancy.

3.2. Time series generation

As has been described in previous works [4,5], in our method three time references from each cardiac sound are extracted from the PCG processed using adaptive filtering schemes by multiresolution analysis and the Hilbert Transform (HT). The PCG data from the stage 1 were processed, and S, M and E points were extracted on the HT envelope associated to each cardiac sound (S1 and S2). Next, the time series for each time reference, SCTGs (SS1-SS1, MS1-MS1, ES1-ES1, SS2-SS2, MS2-MS2, and ES2-ES2) were generated and compared against the pattern signal (RCTG). This reference signal was generated using the distance between consecutive R waves, and each R wave was detected manually. The process was also applied to the data from stages 2 and 3, but in the third data group the pattern signal was obtained using the fetal R wave extracted from the abdominal ECG by the method proposed by Echeverría et al [7].

3.3. Time series analysis

The SCTGs from each subject and each time reference were compared to the RCTG using time and frequency indexes [6]. The time indexes were the square root of the mean squared differences of successive intervals (RMSSD), the short-term variability (STV), and the long-term variability (LTV). STV was computed as the mean of the difference between consecutive intervals, and LTV as the mean of the differences between the maximum and the minimum intervals contained in segments of one-minute [8].

The frequency indexes were the total power (TP (0-1 Hz)), the power in low frequency range (LF (0.05-0.0722 Hz)), and the power in high frequency range (HF (0.1512-1 Hz)) [2]. To calculate the frequency indexes, the time series were interpolated using a cubic spline and a sampling frequency of 1 Hz in adults signals [6], and 2 Hz in fetal signals [2] before calculating the frequency response using a 12^{th} order autoregressive model.

Data were analyzed using ANOVA for repeated measures and Bonferroni's post hoc test for multiple comparisons where a value of $p<0.05$ was considered statistically significant.

4. Results

Figure 1 shows an example of the time series generated with the time references extracted by our EM from a subject in stage 1. The signal on the top corresponds to the pattern time serie generated by ECG and the next six correspond to those generated by PCG. Figure 2 shows the time series generated after processing a fetal signal following the same scheme described previously.

Tables I, II and III show the mean ($\bar{x}$) and standard deviation (sd) values calculated over the time and frequency indexes from the time series generated by using our EM on stage 1 (SNR between 14 and 25 dB), stage 2 (SNR between 11 and 20 dB), and stage 3 (SNR less than 13 dB) respectively. Results show that some time references (SS1, MS1, SS2 and MS2 in adults and MS2 in fetus) are able to produce time series with no significant differences ($p>0.05$) compared with RCTG.

5. Discussion and conclusions

The aim of the present work was to test the PCGf capability to generate fetal time series equivalent to that derived from the indirect fetal ECG. As one can see in figure 1, the time series extracted from adult signals by

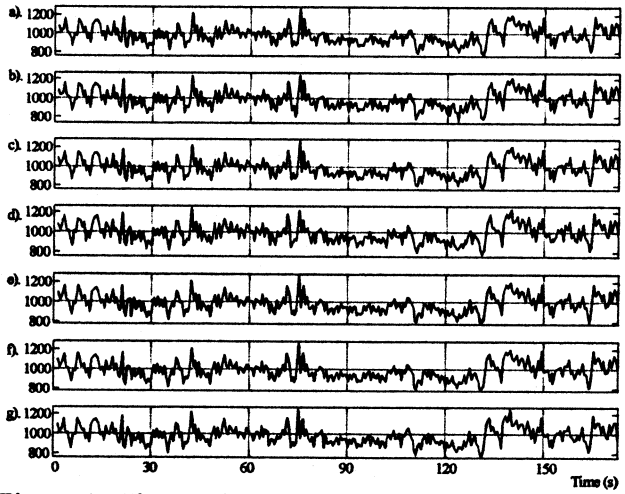

Figure 1. Time series generated from time references extracted on an adult PCG HT envelope. (a). By adult ECG. (b). By SS1. (c). By MS1. (d). By ES1. (e). By SS2. (f). By MS2. (g). By ES2. Units in vertical axis are ms.

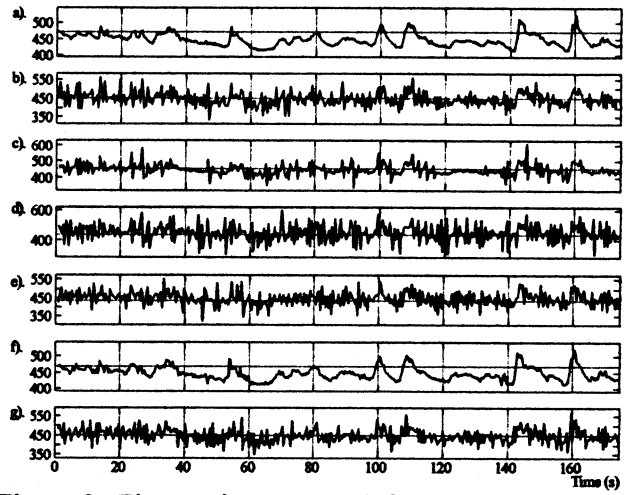

Figure 2. Time series generated from time references extracted on a fetal PCG HT envelope. (a). By abdominal ECG. (b). By SS1. (c). By MS1. (d). By ES1. (e). By SS2. (f). By MS2. (g). By ES2. Units in vertical axis are ms.

Table I. Mean and standard deviation values calculated for the time series generated from the stage 1, N= 9.

Time series	RMSSD $\bar{x} \pm sd$ (ms)	STV $\bar{x} \pm sd$ (ms)	LTV $\bar{x} \pm sd$ (ms)	TP $\bar{x} \pm sd$ (ms^2/Hz)	LF $\bar{x} \pm sd$ (ms^2/Hz)	HF $\bar{x} \pm sd$ (ms^2/Hz)
R-R	*47.1 ± 24.9*	*39.0 ± 20.7*	*194.9 ± 84.1*	*4669 ± 3571*	*216.3 ± 172.5*	*657.7 ± 474.6*
SS1-SS1	53.9 ± 21.6	44.3 ± 18.5	212.0 ± 79.4	5092 ± 3434	228.1 ± 167.4	786.6 ± 453.1
MS1-MS1	51.7 ± 25.4	42.2 ± 21.0	209.4 ± 85.0	5112 ± 3923	228.2 ± 178.7	775.9 ± 587.1
ES1-ES1	60.8 ± 22.4	48.8 ± 18.2	230.4 ± 74.8 *	5628 ± 3915	242.4 ± 181.2	883.5 ± 510.3
SS2-SS2	50.5 ± 21.8	40.9 ± 18.5	206.7 ± 78.6	5036 ± 3476	229.9 ± 170.5	690.5 ± 433.0
MS2-MS2	49.9 ± 21.5	40.2 ± 17.8	202.8 ± 78.4	5009 ± 3552	229.1 ± 172.2	666.8 ± 425.4
ES2-ES2	64.2 ± 14.7	50.7 ± 12.7	239.0 ± 68.7 *	3699 ± 3580	245.0 ± 173.2	876.9 ± 373.2

Table II. Mean and standard deviation values calculated for the time series generated from the stage 2, N= 9.

Time series	RMSSD $\bar{x} \pm sd$ (ms)	STV $\bar{x} \pm sd$ (ms)	LTV $\bar{x} \pm sd$ (ms)	TP $\bar{x} \pm sd$ (ms^2/Hz)	LF $\bar{x} \pm sd$ (ms^2/Hz)	HF $\bar{x} \pm sd$ (ms^2/Hz)
R-R	*42.7 ± 25.0*	*33.6 ± 20.0*	*181.4 ± 82.3*	*4242 ± 2935*	*182.2 ± 123.4*	*708.9 ± 744.4*
SS1-SS1	48.6 ± 22.5	37.5 ± 18.5	199.4 ± 76.0	4543 ± 2883	191.5 ± 122.7	780.0 ± 733.0
MS1-MS1	48.1 ± 24.0	38.0 ± 19.8	190.8 ± 81.4	4590 ± 2837	192.2 ± 121.2	801.7 ± 745.9
ES1-ES1	62.3 ± 26.3 *	48.5 ± 21.1 *	225.3 ± 81.8 *	5329 ± 3281 *	198.6 ± 120.8	1100.0 ± 890.3
SS2-SS2	46.6 ± 21.7	36.1 ± 17.7	195.4 ± 73.6	4389 ± 2841	186.9 ± 122.3	730.6 ± 699.0
MS2-MS2	47.0 ± 22.4	36.7 ± 17.9	191.6 ± 75.1	4345 ± 2821	185.5 ± 121.5	743.3 ± 691.2
ES2-ES2	55.7 ± 24.2	46.4 ± 19.3	215.5 ± 78.4	4829 ± 2936	196.0 ± 121.2	924.9 ± 831.2

Table III. Mean and standard deviation values calculated for the time series generated from the stage 3, N= 11.

Time series	RMSSD $\bar{x} \pm sd$ (ms)	STV $\bar{x} \pm sd$ (ms)	LTV $\bar{x} \pm sd$ (ms)	TP $\bar{x} \pm sd$ (ms^2/Hz)	LF $\bar{x} \pm sd$ (ms^2/Hz)	HF $\bar{x} \pm sd$ (ms^2/Hz)
R-R	*6.7 ± 2.6*	*4.7 ± 1.6*	*58.2 ± 20.4*	*2052 ± 1347*	*81.3 ± 59.0*	*29.6 ± 25.1*
SS1-SS1	51.0 ± 8.0 *	40.2 ± 6.1 *	179.8 ± 37.1 *	3296 ± 1771 *	101.8 ± 67.1	731.4 ± 256.8 *
MS1-MS1	28.5 ± 18.3 *	20.1 ± 12.5 *	120.0 ± 62.9	2640 ± 2038	92.7 ± 76.7	322.1 ± 314.8
ES1-ES1	67.9 ± 11.7 *	53.0 ± 9.7 *	231.1 ± 42.2 *	4436 ± 2419 *	121.3 ± 80.7	1260.8 ± 430.7 *
SS2-SS2	58.4 ± 8.3 *	45.2 ± 5.8 *	200.5 ± 40.2 *	3861 ± 1980 *	112.2 ± 77.1	985.5 ± 294.8 *
MS2-MS2	14.1 ± 7.3	10.3 ± 4.8	76.9 ± 22.5	2220 ± 1475	85.6 ± 64.6	79.4 ± 72.9
ES2-ES2	56.7 ± 6.9 *	44.2 ± 5.7 *	192.9 ± 30.1 *	3480 ± 1687	102.0 ± 66.7	844.9 ± 209.0 *

* Significant differences among index by SCTG and index by RCTG ($p < 0.05$)

the proposed method match well with the reference signal by ECG. The quantitative results in tables I and II confirm that it is possible to generate reliable time series by using time references extracted from the PCG. Specifically, SS1, MS1, SS2 and MS2 time references are able to produce time series with no significant differences ($p>0.05$) compared with the most reliable time serie by ECG. Tables I and II also show significant differences ($p<0.05$) among some indexes by time series generated using ES1 and ES2, and the pattern signal. These results show that the methodology has still problems to extract reliable time references from the ending of the cardiac sounds as was mentioned on previous works [4,5]. Our experience after processing data from stages 1 and 2, have shown that the main problem to extract these kind of references is the morphology at the ending of the cardiac sounds, which is usually modulated by valvular splitting phenomena and a decreasing exponential wave [9]. These facts make necessary to develop a method able to contend with these characteristics and improve the detection of ES1 and ES2 in order to generate reliable time series using these points.

Respect to fetal signals from stage 3, figure 2 shows that the only time reference that produces a time serie equivalent to the pattern signal is MS2. This observation is confirmed by results on table III, where the time serie produced by this point is the only one that has no significant differences ($p>0.05$) with the pattern signal, neither in short-term indexes nor in long-term indexes. The study of PCGf signals from this stage showed that S2 was the sound with the highest SNR in the majority of the recordings. This observation shows how the SNR is a factor that may guarantee that at least the maximum point from the cardiac sound will be able to generate reliable time series. Therefore, if the SNR for S1 were increased, it would be possible that MS1 became a time reference capable to generate reliable time series, like MS2. This implies that the recording process must assure that at least one cardiac sound will be noticeable compared to the background noise. The main problem to do that, is the presence of noise and interference factors that surrounds the PCGf and avoid the possibility to get an useful PCGf from which a reliable time reference could be extracted (MS1 and/or MS2). To contend with this fact, it is necessary to improve the setup acquisition data by looking for a microphone, with better acoustic impedance and frequency response, in order to improve the SNR [1]. Thus, our EM could be able to produce reliable time series by using time references extracted from the PCGf, at least SS1, MS1, SS2 and ES2 as in the adult case.

Finally, from the results of the present study, we conclude that reliable time series can be generated by using time references extracted from the PCG with our EM, specifically SS1, MS1, SS2 and MS2. In the particular case of the PCGf, MS2 and probably MS1 are time references capable to produce time series equivalent to those produced by the RR interval.

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References

[1] Zuckerwar AJ, Pretlow RA, Stoughton JW, Baker DA. Development of a piezopolymeter pressure sensor for a portable fetal heart rate monitor. IEEE Transactions on Biomedical Engineering 1993; 40(9): 963-9.

[2] Ortiz R, González R, Peña MA, Carrasco S, Gaitán MJ, Vargas C. Differences in foetal heart rate variability from phonocardiography and abdominal electrocardiography. Journal of Medical Engineering and Technology. To publicate.

[3] Kovács F, Tõrõk M, Habermajer I. A rule-based phonocardiographic method for long-term fetal heart rate monitoring. IEEE Transactions on Biomedical Engineering 2000; 47(1): 124-30.

[4] Jiménez A, Ortiz MR, Peña MA, Charleston S, Aljama AT, González R. The use of wavelet packets to improve the detection of the cardiac sounds from the fetal phonocardiogram. Computers in Cardiology 1999; 26: 463-6.

[5] Jiménez A, Ortiz MR, Peña MA, Charleston S, Aljama AT, González R. Performance of two adaptive subband filtering schemes for processing fetal phonocardiograms: Influence of the wavelet and the level of decomposition. Computers in Cardiology 2000; 27: 427-30.

[6] Task force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Heart rate variability: Standards of measurement, physiological interpretation and clinical use. Circulation 1996; 93: 1043-65.

[7] Echeverría JC, Ortiz R, Ramírez N, Medina V, González R. A reliable method for abdominal ECG signal processing. Computers in Cardiology 1998; 25:529-32.

[8] Farmakides G, Weiner Z. Computerized analysis of the fetal heart rate. Clinical Obstetrics and Gynecology 1995; 38: 112-20.

[9] Cloutier G, Grenier MC, Guardo R, Durand LG. Spectral analysis of closing sounds produced by Ionescu-Shiley bioprosthetic aortic heart valves, part 2: Computer simulation of aortic closing sounds and estimation of their truncation level and signal-to-noise ratio. Medical and Biological Engineering & Computing, 1987; 25(9): 492-6.

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