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Foetal heart rate power spectrum response to uterine contraction

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Abstract Cardiotocography is the most diffused prenatal diagnostic technique in clinical routine. The simultaneous recording of foetal heart rate (FHR) and uterine contractions (UC) provides useful information about foetal well-being during pregnancy and labour. However, foetal electronic monitoring interpretation still lacks reproducibility and objectivity. New methods of interpretation and new parameters can further support physicians' decisions. Besides common time-domain analysis, study of the variability of FHR can potentially reveal autonomic nervous system activity of the foetus. In particular, it is clinically relevant to investigate foetal reactions to UC to diagnose foetal distress early. Uterine contraction being a strong stimulus for the foetus and its autonomic nervous system, it is worth exploring the FHR variability response. This study aims to analyse modifications of the power spectrum of FHR variability corresponding to UC. Cardiotocographic signal tracts corresponding to 127 UC relative to 30 healthy foetuses were analysed. Results mainly show a general, statistically significant (t test, $p < 0.01$) power increase of the FHR variability in the LF 0.03–0.2 Hz and HF 0.2–1 in correspondence of the contraction with respect to a reference tract set before contraction onset. Time evolution of the power within these bands was computed by means of time-varying spectral estimation to concisely show the FHR response along a uterine contraction. A synchronised grand average of these responses was also computed to verify repeatability, using the contraction apex as time reference. Such modifications of the foetal HRV that follow a contraction can be a sign of ANS reaction and, therefore, additional, objective information about foetal reactivity during labour.

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1 Introduction

Cardiotocography (CTG) is the most diffused prenatal diagnostic technique in clinical practice for foetal assessment [16, 38, 47] and, currently, in Italy, it is a medical report having legal value. It is based on the simultaneous recording of foetal heart rate (FHR) and Uterine Contractions (UC). CTG provides information about foetal well-being during pregnancy and labour to gynaecologists and obstetricians; it is generally used from the 32nd–35th week of gestation to delivery.

FHR and UC signals can be recorded (as in our case) using probes appropriately placed onto maternal abdomen: a US-Doppler probe to detect FHR and a strain gauge transducer belt to appraise UC [16, 19, 51]. Autocorrelation techniques, employed in US technology, provide FHR detection not very different to that obtained using direct ECG [10, 23, 50, 51].

Since its introduction in the clinical routine, CTG monitoring has led to a drastic reduction of intrapartum and precocious child mortality [38, 14] and morbidity. Recently, the International Federation of Gynaecology and Obstetrics issued specific guidelines [12] about CTG analysis. However, CTG reading and interpretation is still lacking in objectivity [2, 11, 13] and it has demonstrated to be scarcely predictive for foetal risk and to provide limited indications about foetal illness or distress [15, 47]. In particular, recent studies [3] confirm that the results are still subjective for visual interpretation of CTG traces, which is widely used, especially in CTG signals corresponding to non-reactive foetuses.

To assess foetal health, clinicians evaluate different parameters of the signals. Shape, intensity and frequency of UC, foetal movements, the average, variability, accelerations and decelerations of FHR are mainly evaluated [8, 29, 30]. In particular, during labour, FHR

alterations in correspondence to UC are estimated to assess foetal reactivity.

Some automatic software provides signal-processing facilities to offer support to clinicians to determine and quantify some of these parameters. However, diagnoses largely depend upon observer's expertise and training; furthermore, objective clinical criteria to recognise foetal distress by CTG data are still poorly defined, especially in labour. Therefore, it is important to try to obtain more reliable and objective methods for CTG interpretation. More detailed information about the foetal status can be particularly useful during the last period of gestation: just before or even during labour.

The study of FHR variability (FHRV) can provide additional information mainly related to the foetal autonomous nervous system (ANS) control of the heart [45]. In particular, spectral analysis provides a tool for quantifying rather small changes in FHRV that may remain undetected if only visual interpretation of FHR tracings is used [46].

Changes in FHR control, elicited by the ANS in response to foetal hypoxia, were reported [48]. Another study [44] found that an increase of pulsatility in cerebral veins was inversely correlated with FHRV preceding foetal distress. A recent study [46] tested whether term foetuses born with marked cord artery acidaemia would reveal differences in FHR spectral analysis during the last hour of the recording compared with a non-acidotic control group: they preliminarily reported that marked foetal acidosis was associated with frequency-specific changes (mainly an increase in the 0.04–0.15 Hz band, which in turn modify the foetal sympathovagal balance) in FHR variability. FHRV spectral analysis provides further information about the compensation ability of foetal ANS responding to the stress of labour.

Analogously as for adults, specific stimuli can alter heart autonomic regulation and in turn generate specific modifications in the HR. Foetal HRV response to stimuli can reveal precious information about ANS reaction and compensation, which in turn depends on foetal well-being status. Indeed, a uterine contraction is a strong compressive stimulus; it provokes an acute hypoxic stress to the foetus and generally elicits reactions in the FHR. It is well known that a FHR deceleration usually follows a UC and this sign is of great interests for physicians.

Interest in studying UC reactions is also outlined by recent studies [18, 24] in which UC were elicited by an oxitocin challenge test (OCT) to explore the consequent blood flow changes. One of them [18], for example, demonstrated in foetal cerebral veins that blood flow changes are significant for IUGR foetuses. Another [24] detected a pathophysiological mechanism disclosed only during UC.

Therefore, it is worth investigating eventual FHRV spectral modifications, which reflect foetal ANS activities in response to an UC. This can provide additional and objective information to support clinical diagnosis, especially during labour.

The aim of this study was to investigate spectral alterations in the FHRV signal in response to UC for healthy foetuses. A study of the reaction of foetal ANS to UC may help in the understanding of specific foetal reactivity, capability and modality of foetal compensation to hypoxic stress by using only the natural disturbance caused by UC during usual monitoring.

2 Methodology

2.1 Signal acquisition

CTG signals were acquired using a HP-M1351A cardiotocograph. A multi-transducer US PW Doppler probe (carrier frequency at 998.4 kHz, pulse repetition rate of 3.2 kHz [15]), placed upon the maternal abdomen, is used to detect foetal heartbeats. An autocorrelation technique is used to accurately extract beat-to-beat intervals, which provides an effective resolution better than 2 ms [15]; then values are expressed in beats per minutes. A three-level signal indicating the 'quality' of the received Doppler signal (which can result optimal, acceptable or insufficient, the latter corresponding to signal loss) and its capability to accurately detect foetal heartbeats is also recorded.

A second probe, basically consisting of a strain gauge, also placed upon the maternal abdomen, is used to indirectly measure uterine pressure (output is expressed in mmHg) and then contractions.

Those signals (FHR, UC and signal quality) are internally sampled at 4 Hz (corresponding to a sampling interval of 250 ms), and then transferred to the output serial port of the device. With reference to FHR, if no new foetal beat is detected within a sampling interval, the previous value is held (zero-order interpolation).

CTG signals were recorded using a laptop PC directly connected (via RS-232 cable) to the HP-M1351A monitor.

2.2 Signal pre-processing

To select reliable FHR segments, to eliminate possible artefacts related to the Doppler technique and to get rid of the zero-order interpolation, a pre-processing algorithm was developed and employed [22].

Recorded FHR signals may contain artefacts or can be interrupted because of degradation, or even loss, of the Doppler signal mainly due to relative motion between US probe and foetal heart, maternal movements and other causes (as a matter of fact, CTG devices usually clearly show the signal strength-quality signal, see above Sect. 2.1). The pre-processing algorithm segments each recorded signal into a number of reliable continuous tracts.

Intrinsically, FHR are uneven sampled series: FHR values are available only when new heartbeats occur. In

general, to obtain evenly sampled series, cardiotocographs (e.g. HP-1351x), use a zero-order interpolation and provide FHR data at fixed sampling time instants (i.e., in the same time instants when UC values are recorded); this results in delaying some samples and adding some duplicates. This is an efficient solution for FHR time-domain or other rough analyses, e.g. to compute classical parameters, such as baseline, accelerations and decelerations, but it is not suitable for frequency analyses because interpolation introduces alterations in the FHR power spectrum [22].

In order to eliminate the spectrum alterations due to zero-order interpolation, the pre-processing algorithm recovers the true FHR series from raw CTG data. An important constraint was that the duplicated samples cannot be simply deleted to recover the true FHR series, since they can arise by equal subsequent beat-to-beat intervals. The developed algorithm recovers original samples substantially on the base of a simple time rule: the sum of the recovered R–R intervals must match the elapsed time.

Afterwards, an opportune procedure (substantially a median filter) recognises and then removes possible arrhythmic beats by substituting with linearly interpolated values [43]. Finally, FHR pre-processed data are uniformly re-sampled [7] at 4 Hz and aligned with UC (within 0.25 s).

2.3 Patient enrolment and signal selection

Cardiotocographic recordings relative to 30 healthy pregnant women (singleton pregnancies), who did not take drugs, close to delivery (33–42 gestation weeks; mean = 39 weeks, SD = 2 weeks) were considered for the analysis (12 CTG were recorded few hours before the delivery). Apgar scores, birth weights and other information were collected in order to involve only CTG regarding healthy foetuses in the analysis; in particular, enrolled infants had Apgar scores ≥7 at 1st minute and ≥9 at the 5th minute, birth weights (ranging from 2.7 to 4.25 Kg; mean = 3.33 Kg, SD = 0.39 Kg) appropriate for the gestational age and no one needed neonatal intensive care unit treatment.

CTG recordings have an average duration of about 30 min.

CTG recordings with evident UC were chosen for the analysis; UC were selected respecting specific criteria in order to achieve a sort of uniformity for the UC stimuli. Only UC of pronounced amplitude (at least 40 mmHg with respect to the resting tone), isolated (at least 130 s must elapse between the end and the start of two subsequent contractions), corresponding to good FHR and UC signal quality (without any probes misalignment) and without marked foetal movements and/or superimposed maternal breathing, were considered for the analysis. Figure 1a offers an example of the CTG signals utilised.

After being visually inspected and further approved by expert gynaecologists, 127 UCs compliant with the above-mentioned specifications were enrolled in the analysis. In order to carry out a quantitative comparison between the FHRV power spectrum modifications related to UC with respect to a reference condition, two kinds of time segments of the same length (231 samples, about 57 s) were selected; in the following we shall call them: 'reference-segments' chosen before the UC onset and 'UC-segments' chosen in correspondence of the UC (slightly retarded with respect to the UC apex). In particular, the UC-segment starts 30 samples before the UC apex and ends 200 samples after it (spectrum modification was supposed subsequent to UC stimulus) while the reference-segment ends 35 s (140 samples) before the beginning of the UC-segment. Such time intervals are reported in figures (from 2 to 4), as double-line segments superimposed to graphics (above time-axis).

2.4 DC and VLF suppression

FHR power spectrum is mainly composed of a DC component (average of the FHR); a very low frequency (VLF) band (0–0.03 Hz), which shows a $1/f$ characteristic shape; an explicit lobe centred at about 0.1 Hz within low frequency (LF) band (0.03–0.2 Hz); relatively much littler lobes within high frequency (HF) band (0.2–1 Hz), linked to sporadic, transient activities (e.g. foetal pre-breathing movements) (values adapted from [5, 31, 36, 45, 53]).

DC and VLF represent slow fluctuations of the FHR and, for a short-term analysis, are better represented in time domain (i.e. baseline and floating line—running mean and median line-of the FHR signal). To filter out these components from the raw FHR signals, the baseline and the floating line [29, 30] were computed (by a smoothing cubic spline) and then subtracted from the FHR signal [41]. Actually, this operation corresponds to a high-pass filtering (about 0.03 Hz) of the signal. By removing such components, the FHRV signals were obtained.

2.5 FHRV time-frequency analysis

Parametric and non-parametric time-varying methods were used to estimate power spectrum of the FHRV signal, which shows a non-stationary behaviour. FHRV spectrogram was obtained by using the short time fourier transform (STFT), considering sliding Hamming windows of 128 samples (which corresponds to 32 s) and using 99% overlap.

Usually, HRV spectrum can be also investigated using auto regressive (AR) estimation [5, 6, 20, 32, 36]. Previous studies [40, 45] suggested considering an AR model of eight poles to correctly describe the FHRV signal. To obtain a time-varying AR estimation, an or-

dinary RLS algorithm was employed, setting the forgetting factor to 0.99.

A main lobe around 0.1 Hz appears evident in all the recordings. Most of the FHRV power is concentrated in the LF components [47]. At higher frequencies there was no specific spectral component, merely little, sporadic, transient activities. These findings are in accordance with other studies [27, 45] regarding the spectral analysis of the FHR signal.

2.6 Time-varying LF and HF power estimation

Our analysis concentrated on the LF and HF bands spectral content. As for study on adults, LF and HF bands power represent ANS activities for heart rate control. To concisely describe spectral modifications against time, the power associated with these bands was computed, for each time instant, $P_{\mathrm{LF}}(t)$ and $P_{\mathrm{HF}}(t)$, as expressed by:

$$P_{\mathrm{LF}}(t) = \frac{1}{T}\int_{0.03}^{0.2} |S_{\mathrm{FHRV}}(f,t)|^2 \mathrm{d}f,$$

$$P_{\mathrm{HF}}(t) = \frac{1}{T}\int_{0.2}^{1} |S_{\mathrm{FHRV}}(f,t)|^2 \mathrm{d}f,$$

where, $S_{\mathrm{FHRV}}(f,t)$ represents the time-varying spectral estimation of the FHRV signal computed using STFT and AR-RLS methods and T is the time interval considered.

It is then possible to draw LF and HF power time-courses along with UC evolution (see Sect. 3).

In the case of AR-RLS method, a simple post-processing of the estimated power time-course was employed in order to identify (median filter, length = 10 samples) and then eliminate not significant isolated spikes (due to presence of disturbing noise of the recursive algorithm).

We did not consider the VLF band very slow rhythms, since it is generally necessary to use long recordings (even up to 24 h recordings) to provide sufficient resolution [5]. However, time evolution of the floating line was reported in figures.

2.7 Synchronised signal averaging

A synchronised grand average of the responses was also attempted to verify repeatability. In other words, an average of all the LF and HF power signals was performed by aligning these signals with respect to the start of the segments, both for UC segments and reference segments. The aim of this operation was to try to highlight a common foetal ANS response to UC in a physiological situation.

A synchronised grand-average was also performed for the UC signals.

2.8 Statistic analysis

A Student's t test was used to check the statistic separation between the UC-segments and the reference-segments spectral power populations. The test, using a level of statistical significance set to p value < 0.01, was carried out separately for both LF and HF bands and for both analysis methods (non-parametric and parametric spectral estimation).

3 Results

An example of FHRV time-frequency distribution obtained by STFT method is reported in Fig. 1b and c. To appreciate the time relation between an UC and the corresponding changes in the FHRV LF and HF powers, Figs. 2 and 3 present, as examples, two signals' time courses (Fig. 2 refers to CTG number 6—our internal numbering—while Fig. 3 refers to CTG number 113). From the top, the FHR signal (bold line) with the floating line superimposed (thin line), the UC signal (Figs. 2a, 3a), the LF power estimated using STFT (Figs. 2b, 3b) and AR-RLS (Figs. 2c, 3c) algorithms, the HF power estimated using STFT (Figs. 2d, 3d) and AR-RLS (Figs. 2e, 3e) algorithms are represented along with the same time axis. In these figures, the zero on the time axis represents the UC apex and the two horizontal double-lined segments represent the reference-segment ([−100, - 42.5] s) and the UC-segment ([−7.5, +50] s). Please note that the y-axis used to represent the HF power time course is one third of that used for LF.

As illustrated by Figs. 2b, c and 3b, c, the intensity of the LF lobe increases just after the corresponding UC. In particular, LF power starts to increase slowly during the first part of the contraction; it shows an evident peak after the contraction apex with delays that range from 20 to 40 s, and after the acme, it slowly tends to return to the resting value. As a whole, the power modification lasts 50–60 s. This pattern is still recognisable for the time-varying HF power (Figs. 2d,e, 3d,e). It is worth noting that the power, relative to the second example signal (see Fig. 3), shows a clear modification, even if there is not a corresponding modification of the floating line.

Figure 4 shows the results obtained computing the synchronised grand average (for LF and HF bands, respectively), utilising all the 127 UC-related signals analysed. The averages are plotted as solid lines, while dashed lines represent the SD.

In the lower part of the figure are reported the synchronised grand average of the FHRV powers computed using STFT and AR-RLS (LF_ STFT: Fig. 4c, LF_ AR-RLS: Fig. 4d, HF_ STFT: Fig. 4e, HF_ AR-RLS:

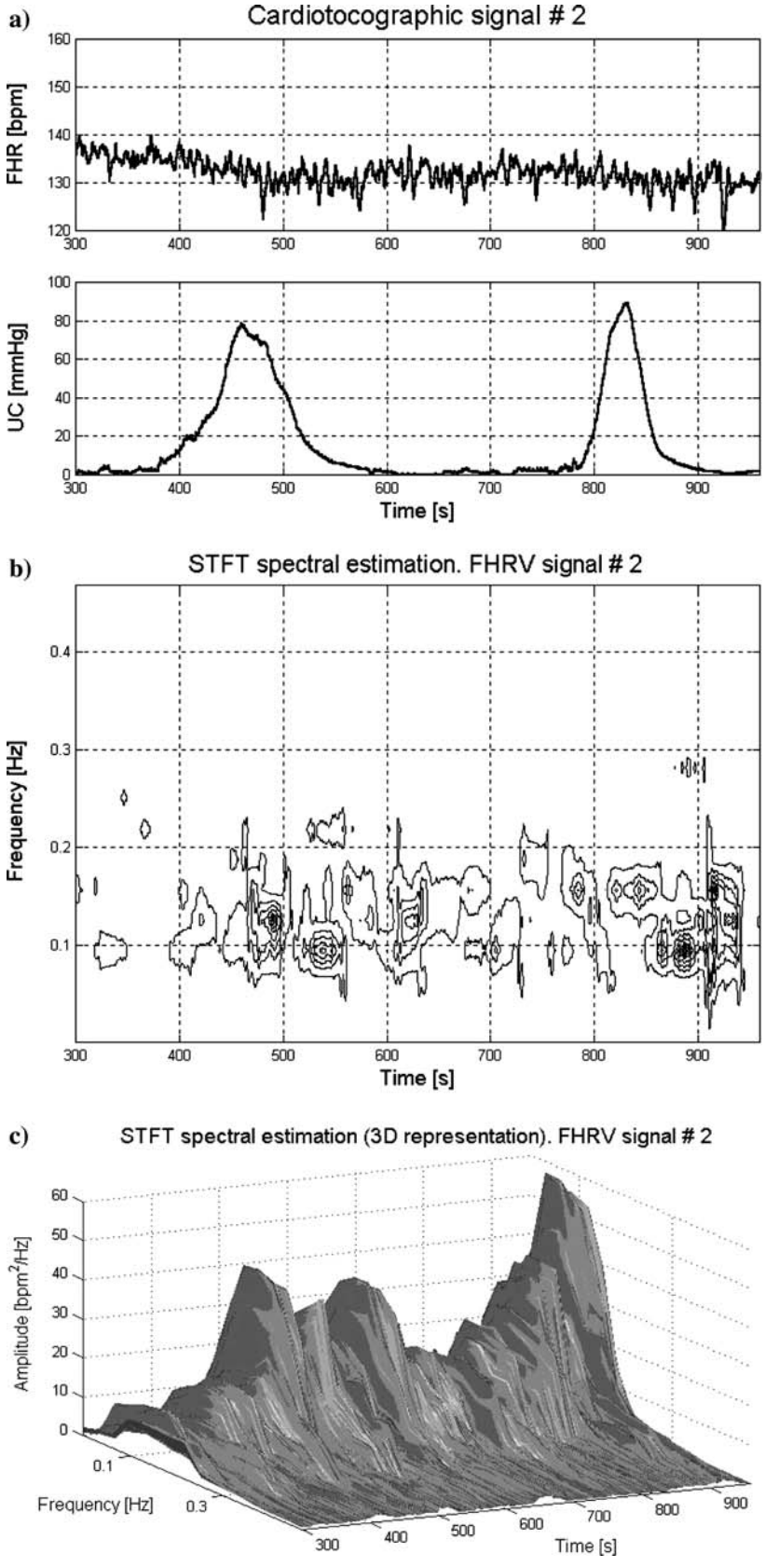


Fig. 1 Example of CTG recording (FHR and UC signals) during delivery, patient #2, week 40th (**a**). It is possible to recognise two UC, which were selected according to the required criteria. FHRV spectrogram, of FHR signal (**a**) shown on the top, computed using STFT, plotted using iso-levels contours (**b**) and as three-dimensional surface (**c**), is reported

Fig. 4f, respectively). The UC signal average (on the top) helps in the visualisation of the relative timing of the events and also shows the high repeatability of uterine contraction shape. The synchronised grand average of the floating lines (Fig. 4b) shows their mean trend and SD. All time axes are synchronised with the

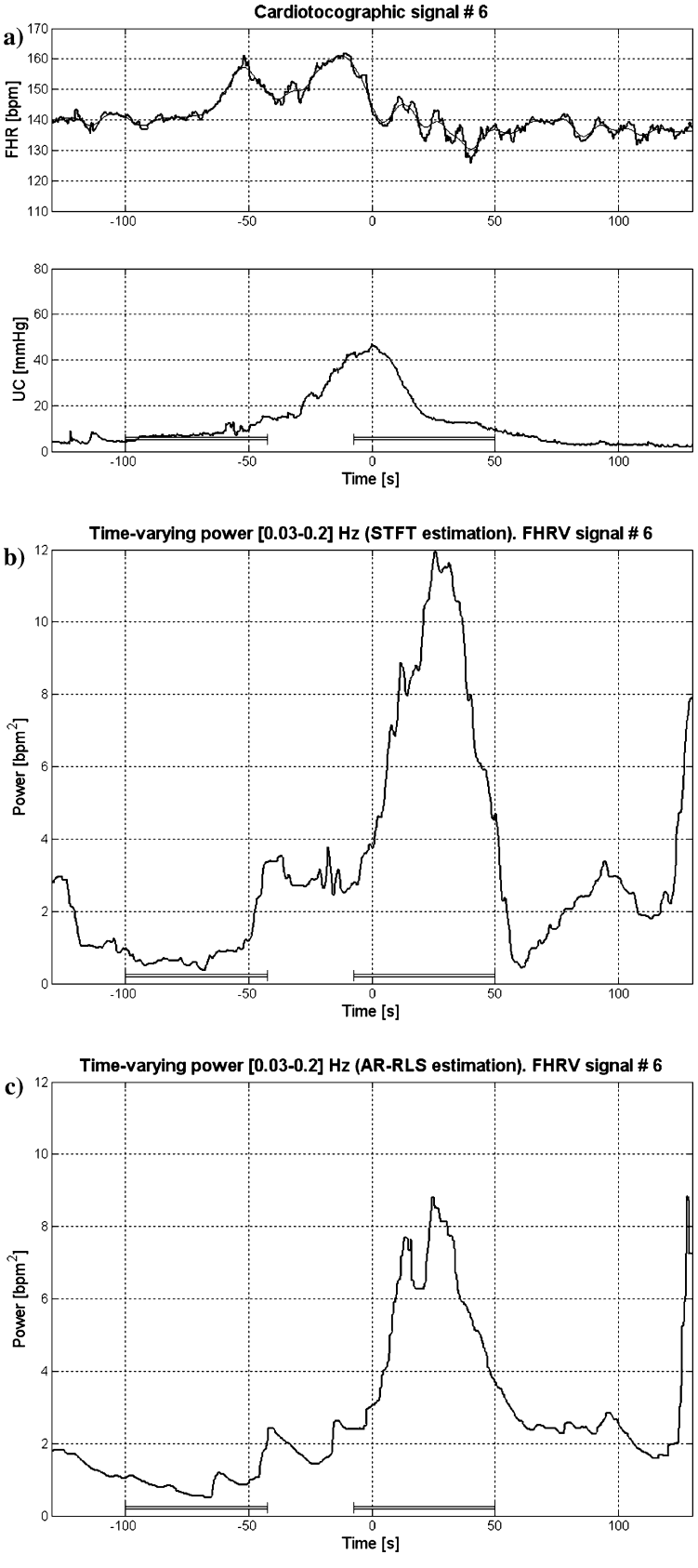
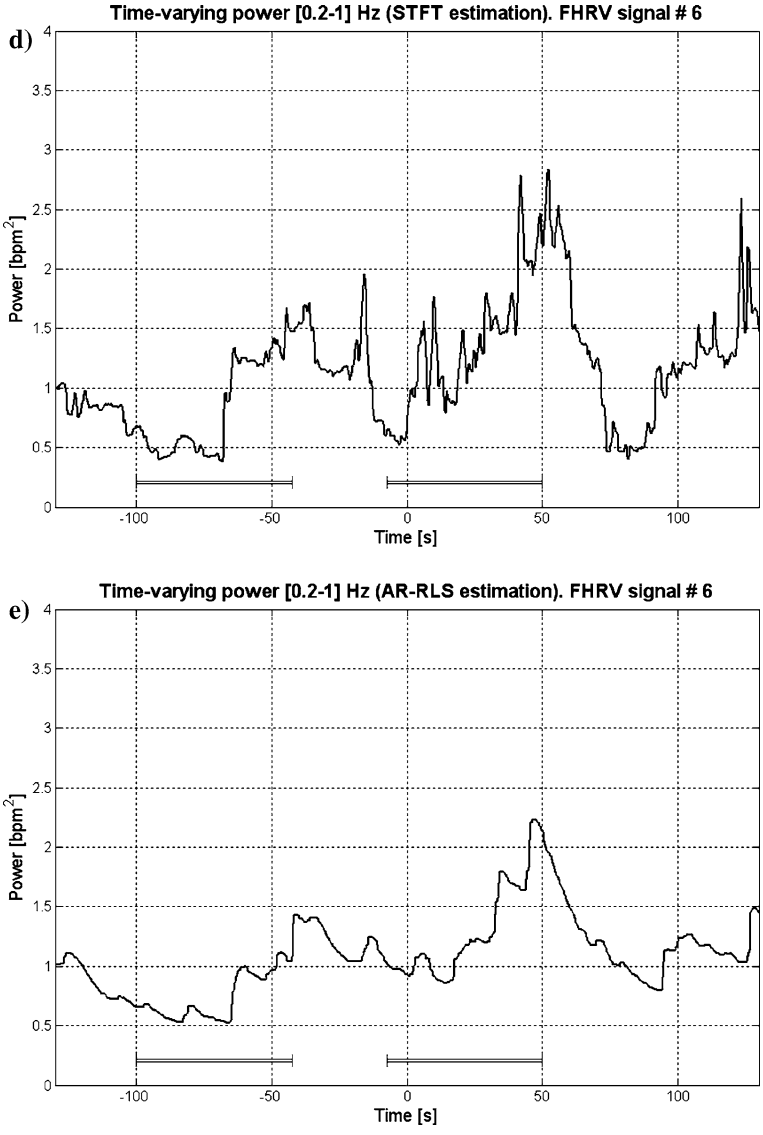


Fig. 2 First example of FHRV LF power variations in correspondence of UC #6, week 35th. From the top, the FHR signal (*bold line*) with the floating line superimposed (*thin line*) and the corresponding UC signal (**a**), the LF power time-course estimated using STFT (**b**) and AR-RLS algorithms (**c**), the HF power time-course estimated using STFT (**d**) and AR-RLS algorithms (**e**), are represented along with time, synchronised with the UC apex (time = 0)

Fig. 2 (Contd.)



contraction apex (time = 0). Average powers were computed for both FHRV power spectrum bands (LF and HF) and for both analysis methods (STFT and AR-RLS). Obtained results are reported in Table 1.

It is possible to note that average powers corresponding to UC-segments are about twice the value as average powers corresponding to reference-segments. Moreover, UC-segments population showed significantly different results compared with reference-segments population for both FHRV power spectrum bands and for both analysis methods (*t* test). Obtained significance levels (s) and confidence intervals (c) are reported in Table 2.

4 Discussion and conclusions

Clinicians regularly monitor FHR and UC for signs of at-risk (or compromised) foetal conditions. In particular, during labour, FHR alterations in correspondence to UC are evaluated, to assess foetal reactivity. It is well known that there is still controversy over the interpretation of different FHR patterns; objective clinical criteria to recognise foetal distress by CTG data are still poorly defined, especially during labour [4]. Positive predictive value of abnormal intrapartum FHR patterns for foetal acidemia is only around 30% [46], whereas detection of foetal distress, early in labour, may significantly improve the newborn's health. Therefore, it is important to try to obtain more reliable and objective methods for CTG interpretation and for neonatal outcome prediction. For this purpose, several methodologies have been employed (foetal oximetry, computerised systems, umbilical cord blood gas analysis, nonlinear analysis techniques and others [28, 34, 37, 42, 54]).

The importance in studying foetal reactions to UC was also underlined by recent studies [18, 24] in which UC were elicited by an OCT to explore consequent blood flow changes. But no clear conclusion is still

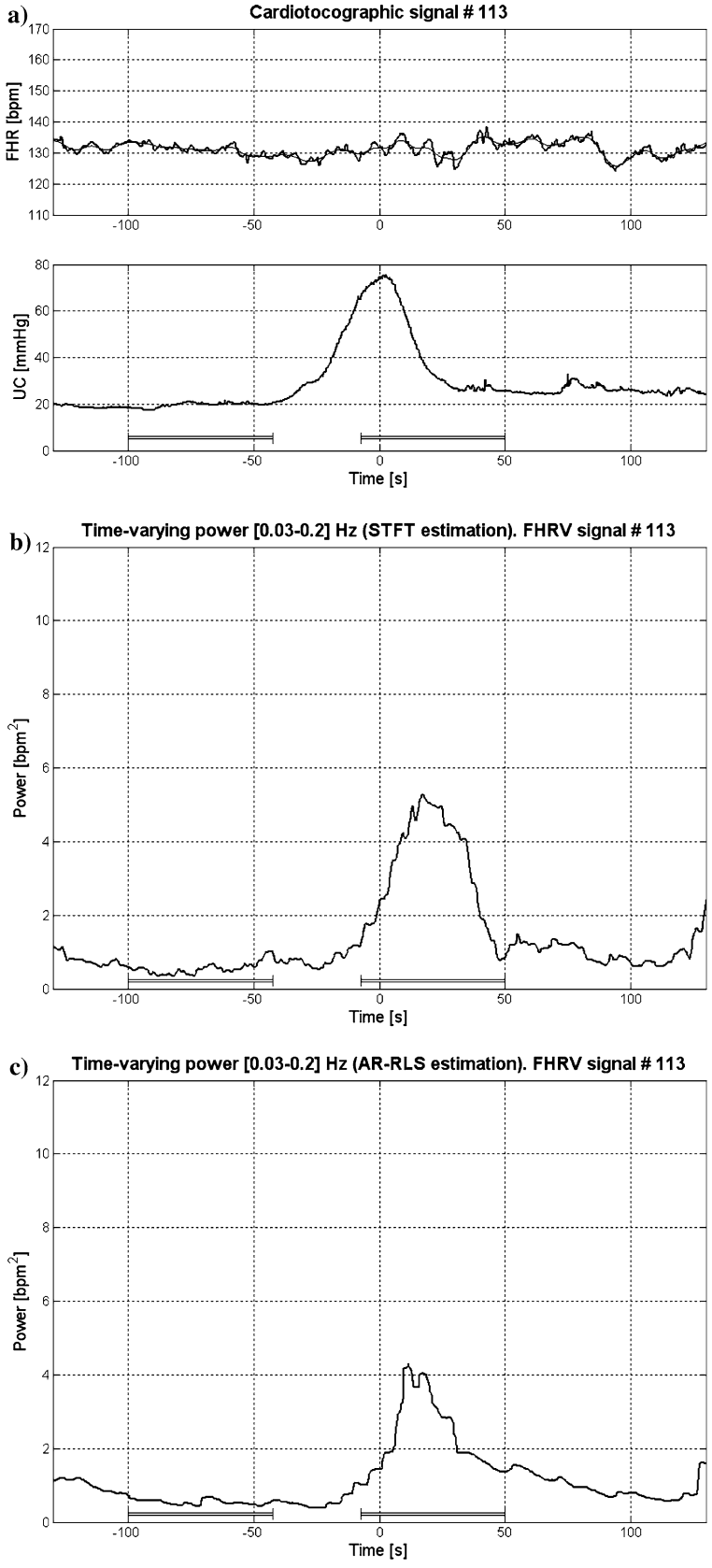
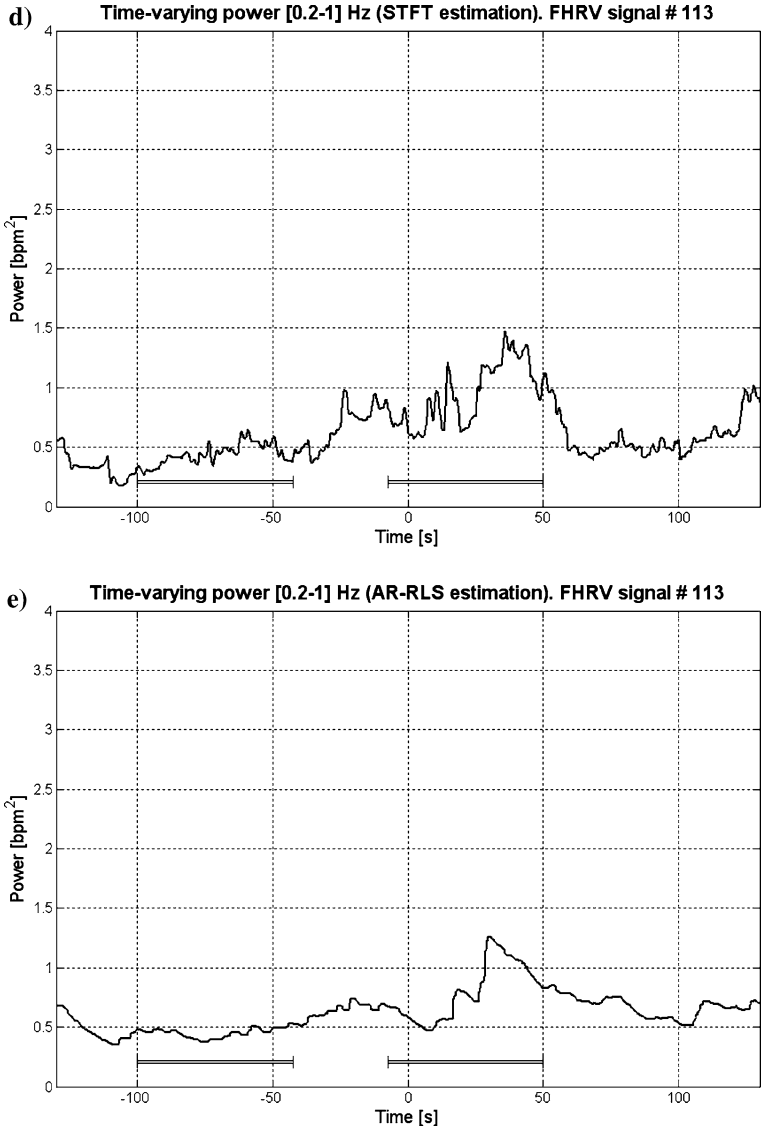


Fig. 3 Second example of FHRV LF power variations in correspondence of UC #113, week 40th. From the top, the FHR signal (*bold line*) with the floating line superimposed (*thin line*) and the corresponding UC signal (**a**), the LF power time-course estimated using STFT (**b**) and AR-RLS algorithms (**c**), the HF power time-course estimated using STFT (**d**) and AR-RLS algorithms (**e**), are represented along with time, synchronised with the UC apex (time = 0)

available. Besides, the literature regarding intrapartum CTG is not that rich as antepartum CTG mainly due to registration difficulties.

In this scenario, analysis of FHRV can provide additional, useful information related to the foetal ANS control of the heart and its compensation capability.

Fig. 3 (Contd.)



Analogously as for adults, specific stimuli can alter heart autonomic regulation and in turn generate specific modifications in the HR, particularly evident in frequency domain. Also for the foetus, there are different studies that analyse changes in FHRV in response to specific stimuli such as vibroacoustic stimulation [1, 25–27] or the effect of a cold Pressor test [52] to reveal foetal reaction capability.

FHRV power spectral analysis may provide valuable information to recognise foetuses at risk of acidosis [39], given that foetal distress modifies ANS functioning and then FHR. Indeed, a uterine contraction is a strong compressive stimulus [16] (intra-uterine pressure can become four times stronger than basal pressure) that severely solicits the immature foetal ANS. This stress causes reactions in the FHR; one of the most evident is an FHR deceleration that usually follows an UC, which is an important sign for physicians. Therefore, a more detailed study of the reaction of foetal ANS to UC such as FHRV spectral analysis may help in the understanding of specific foetal reactivity, capability and modality of foetal compensation to hypoxic stress.

Some authors investigated whether spectral components of FHRV during labour are associated with foetal cord arterial base deficit values at birth [39]. They found that foetuses with normal base deficit values had higher total FHRV and 0.07–0.13 Hz band in comparison with the others. They pointed out the possibility of UC influence in the results but their analysis was based on very short segments for detecting changes in FHR caused by UC. Other research groups examined changes in FHRV during UC but the reported results are not in agreement. Some studies, in fact, found that increase in uterine activity is associated with a decrease in FHRV [54]; whereas other studies reported an increase in short-term FHRV during UC [9].

Moreover there are conflicting data regarding correlation between FHRV and neonatal outcome. In some cases, decreased FHRV was associated with lower cord blood pH and Apgar scores; in others, any significant

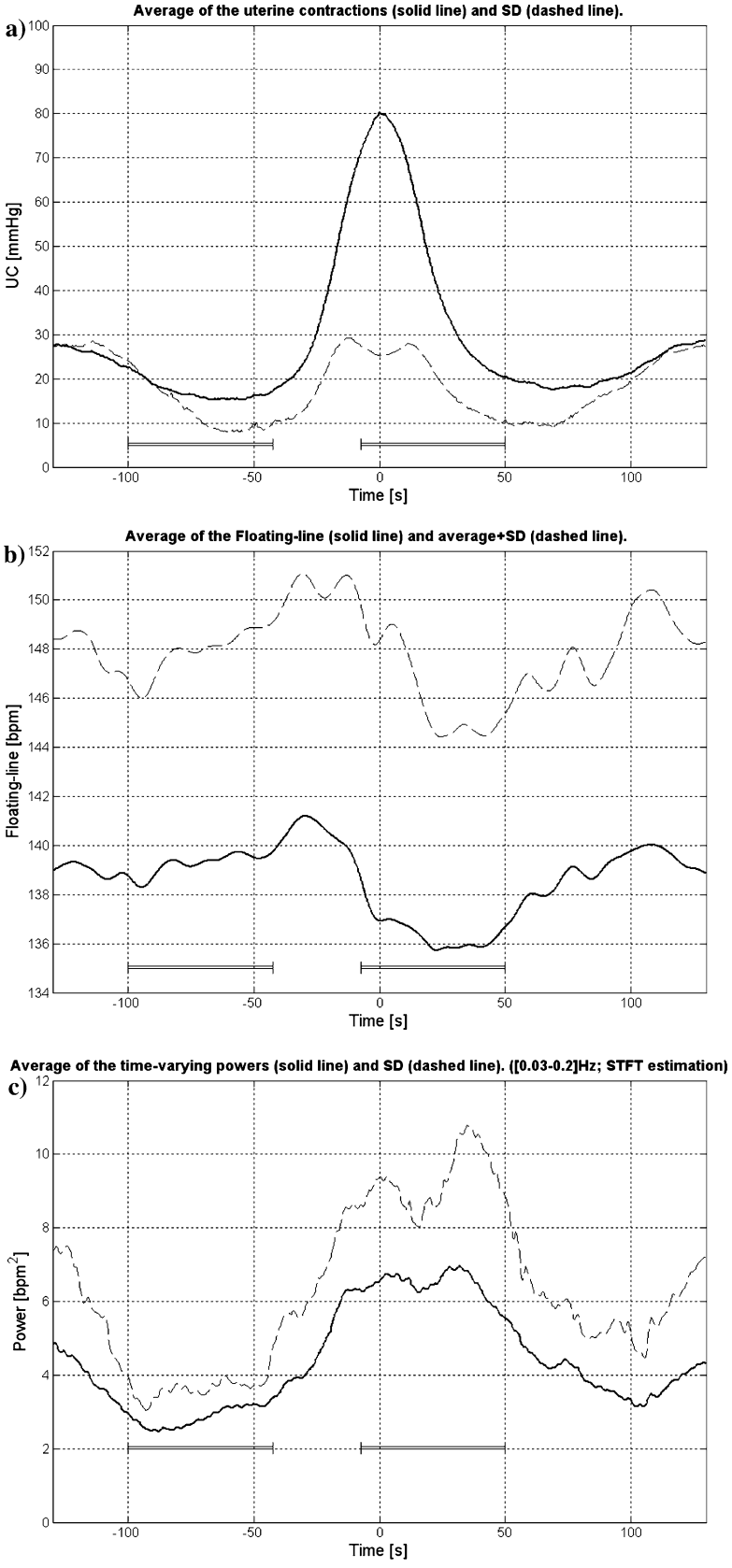
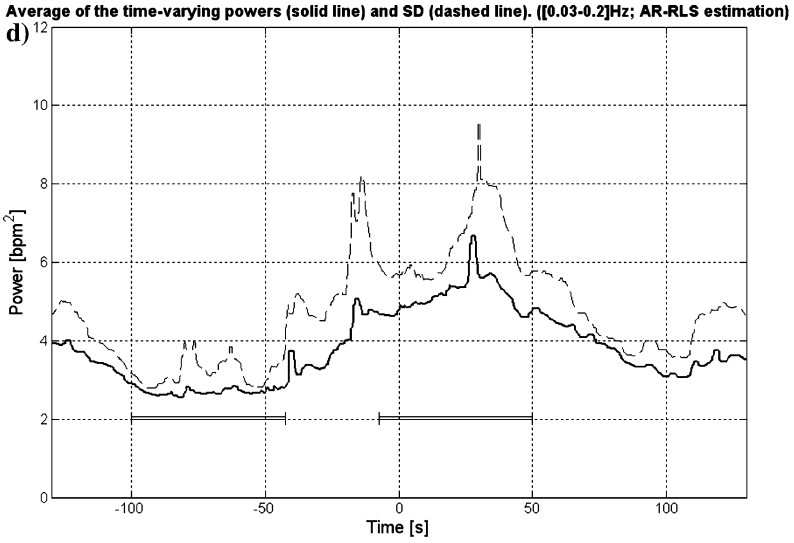
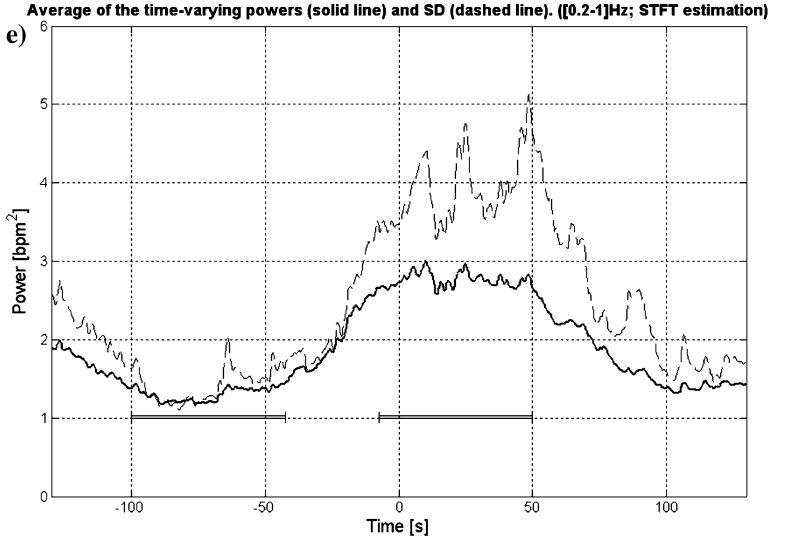


Fig. 4 Results of the synchronised grand average computed using all the 127 signals' chunks corresponding to the selected UCs. The average of all the contractions signals (**a**) and the average of all the corresponding floating lines (**b**) are shown in the upper part of the figure. FHRV power average (*bold line*) in LF band and its SD (*dashed line*) computed using STFT (**c**) and using AR-RLS (**d**), while power average (*bold line*) in HF band and its SD (*dashed line*) computed using STFT (**e**) and using AR-RLS (**f**) are reported along with the same time axis. All graphics are synchronised with the UC apexes (time = 0)

Fig. 4 (Contd.)


Average of the time-varying powers (solid line) and SD (dashed line). ([0.03-0.2]Hz; AR-RLS estimation)
d)
Power [bpm^2]
Time [s]
0
2
4
6
8
10
12
-100
-50
0
50
100


Average of the time-varying powers (solid line) and SD (dashed line). ([0.2-1]Hz; STFT estimation)
e)
Power [bpm^2]
Time [s]
0
1
2
3
4
5
6
-100
-50
0
50
100

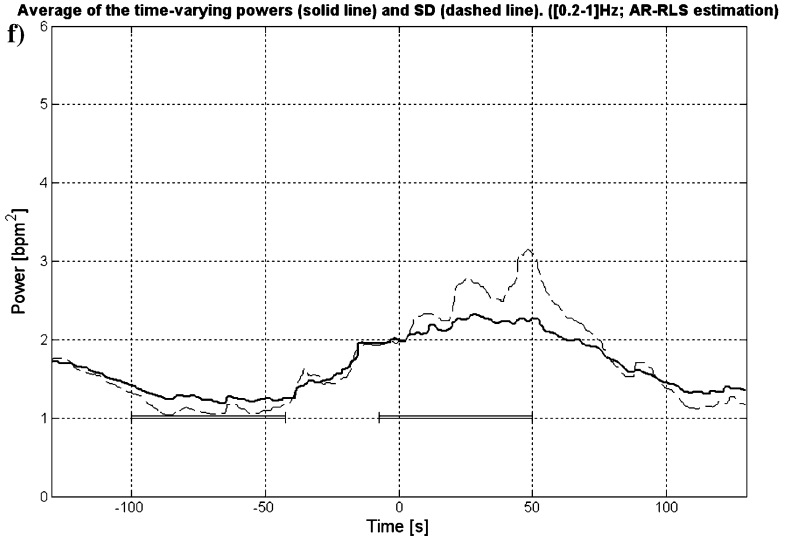

Average of the time-varying powers (solid line) and SD (dashed line). ([0.2-1]Hz; AR-RLS estimation)
f)
Power [bpm^2]
Time [s]
0
1
2
3
4
5
6
-100
-50
0
50
100

Table 1 The average of the powers in LF and HF bands, computed with both analysis methods (STFT and AR-RLS), are reported for the UC and reference segments in bpm^2

	Average LF power (bpm^2)	Average HF power (bpm^2)
STFT		
Ref. segments	164.86	75.13
UC segments	373.75	159.5
AR-RLS		
Ref. segments	160.11	72.98
UC segments	318.67	126.77

Table 2 The increase of the power for the UC segment population is confirmed by a *t* test for both analysis methods (STFT and AR-RLS)

	S	*c*	*h*
STFT			
LF	5.4E−7	1.03E + 2–3.14E + 2	*
HF	2.2E−6	3.92E + 1–1.29E + 2	*
AR-RLS			
LF	1.9E−5	6.42E + 1–2.53E + 2	*
HF	1.9E−5	2.17E + 1–8.58E + 1	*

Estimated significance levels (s) and confidence intervals (c) are reported here. An asterisk (*) in the last column means that the null hypothesis can be rejected at the significance level of 0.01

correlation between FHRV averaged over the last hour of labour and the umbilical cord pH or Apgar scores was found [54].

This work presents a study to investigate spectral modifications of the FHRV in response to the external stimulus represented by UC, for healthy foetuses, in order to improve understanding of foetal ANS reactions to this natural stress and to find possible predictive information about risky foetal conditions.

It is well known that gestational age (related to ANS maturation) considerably affects the foetal haemodynamic responses to stimuli and distress; nevertheless, weeks of gestation were similar in all our recordings so that it is possible to disregard this factor as an additional cause of FHR changes [35, 39].

It is also known that foetal behavioural states affect FHRV and that it is possible to recognise them also during labour [17, 49]. Their definition relies on the combination of three components: presence or absence of eye movements, body movements and specific heart rate patterns [49]; so that it is very difficult to establish with certainty the actual foetal behavioural state by the only CTG (during labour the identification of the states can be complicated by decelerations and their classification) [54]. However, a more simple classification can consist of differentiation between 'active' and 'quiet' status, considering the amount of variability of the FHR and the number and amplitude of accelerations ('quiet' traces show lower variability range and different bandwidth oscillations, while accelerations can be considered an indirect index of foetal body movements and then of an 'active' trace) [17, 33, 45, 49]. According to this rough differentiation, we classified 75 CTG as corresponding to foetuses in 'active' status and 52 CTG as corresponding to foetuses in 'quiet' status. In accordance with literature [21], for CTG corresponding to foetuses in 'active' status we obtained an overall power higher with respect to that of 'quiet'. However, for both CTG groups, we obtained a significant increase of the average power in LF and HF bands (*t* test, $p < 0.05$) during UC-segments with respect to the reference-segments. On this base, we can preliminarily substantiate that the described FHRV power spectrum response to UC is observed in both groups. However, this issue deserves a more detailed and exhaustive analysis.

To summarise, the results indicate a foetal reactivity (in terms of FHRV power spectrum increase with respect to the rest condition) to the mechanical compressive stimulus represented by an UC for healthy foetuses (the increase was confirmed by a *t* test, $p < 0.01$). From analysis of the results it emerges that the synchronised grand averages of FHRV LF and HF power signals result blunted with respect to single traces; also the SD results large. This phenomenon is due to the limited repeatability of the FHRV power response in terms of relative timing (due to different delays from the contraction apexes), amplitudes and shapes. Nevertheless, averaged FHRV power starts to increase more or less in correspondence to the UC onset and reaches its maximum value with a certain delay after the contraction apex.

In the future, more comprehensive studies, involving also cases of foetal distress and aiming to recognise characteristic patterns to distinguish foetal well-being and foetal distress, have to be further performed in order to propose such methodology in daily clinical practice. As also reported in a recent study [46], the value of spectral analysis in detecting changes in cardiac control is still poorly known in acidotic human foetuses, even if it is known that during the development of foetal hypoxia the ANS becomes activated and this causes changes in FHR control.

In addition, comparative studies with other concise indexes (e.g. STV) should improve the results and their clinical relevance. Also an in-depth analysis of the physiological mechanisms playing a role in the FHR control (both in normal states and in hypoxic and other pathological conditions) and a detailed study of the correspondence of FHRV spectral parameters to different HR control are of fundamental importance to clarify the prognostic value that can be reached and the scope of possible application of this analysis in daily clinical practice (particularly during labour).

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