Wavelets and the Unborn Child

Research project: Data Mining and Knowledge Discovery
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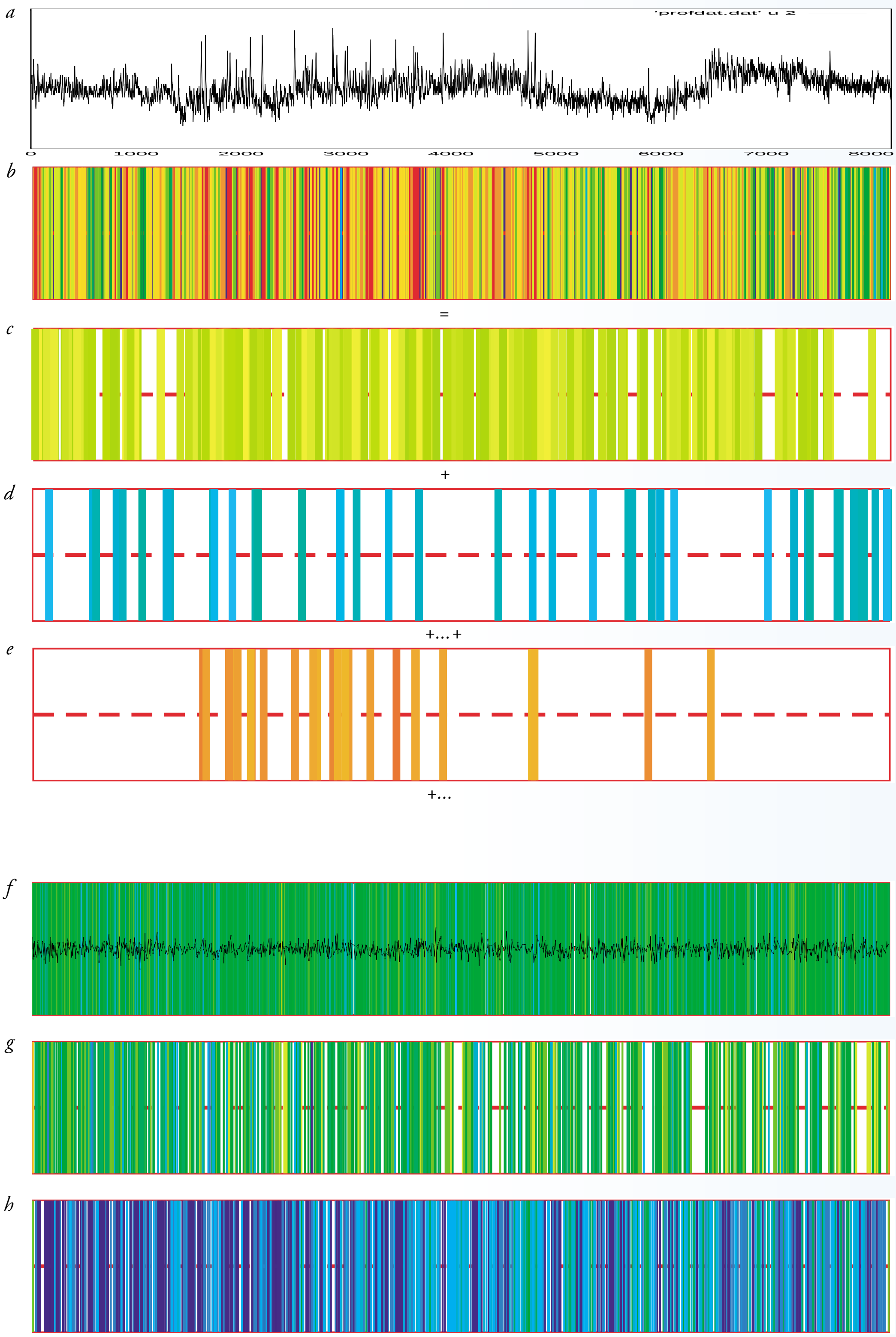
Introduction

During labour, the attending medical staff use fetal heart rate recordings for evaluation of fetal well being and may base immediate intervention, such as a Caesarean section or taking a fetal scalp blood sample, on this. Using characteristics derived in real-time from the heart rate, obstetricians can predict a good outcome very well. However, in cases of fetal heart rate patterns considered 'bad' by the obstetrician, at least half of these turn out to have been false alarms and the (operative) intervention unnecessary. Decision making can be improved by providing relevant information contained in the heart rate on a more solid, objective basis, making it independent of the personal experience of the specialist. This is enabled by recent progress in the modelling and analysis of heartbeat inter-beat dynamics, using the most advanced methods of signal processing (wavelet transform). CWI is tackling the mathematical side of this problem in cooperation with the Academic Medical Centre in Amsterdam (W.J. van Wijngaarden) and the Institute of Information and Computing Sciences of Utrecht University (R. Castelo). After mimicing the obstetrician's expert knowledge, the ultimate goal is to provide better than human performance by automated learning of predictive models.

Heart rate monitoring

Fetal heart rate monitoring started in the 1970s, and is now performed worldwide. Its aim is to warn in time for hypoxia (decreased oxygen content in tissue) during the hours preceding delivery, in which case intervention is necessary. The interpretation of observed cardiotocograms (CTGs) is a skill which is acquired through years of experience. Nevertheless, these visual interpretations by experts still differ widely. Whereas normal CTGs generally lead to a normal delivery, an abnormal CTG turns out to have indicated a real problem in only half of the cases at best. Not knowing this in advance, the clinicians do not take chances and intervene. Thus the number of interventions has dramatically increased since the introduction of CTG monitoring; many of these having been unnecessary. Computerized CTG analysis can lead to uniform and objective interpretation by providing a reproducible determination of fetal heart rate characteristics. The resulting automated system will be based on better external information, such as a complete pregnancy history. It will draw more useful information from the fetal heart rate recordings by using new analysis approaches which have shown their potential in heartbeat studies of adults. Finally, data mining algorithms are used to extract from this integrated information a generic model for effective heart rate monitoring leading to better fetal outcome prediction.



The Hölder exponents of a signal (a), indicating its local 'roughness', can be represented as a coloured 'barcode' (b). (Blue = smooth, red = rough.) Time points with the same colour have the same roughness. The complete barcode consists of interwoven monochromatic sets (c-e), often with a fractal structure. Simple processes like Brownian noise (f) are monochromatic, or 'monofractal'. Whereas the beats of a healthy heart (a) form a complex, multifractal pattern, diseases like congestive heart failure are characterized by more regular (g) or smoother (h) beat patterns, their barcodes being almost monochromatic or bluish, respectively.

Three obstacles

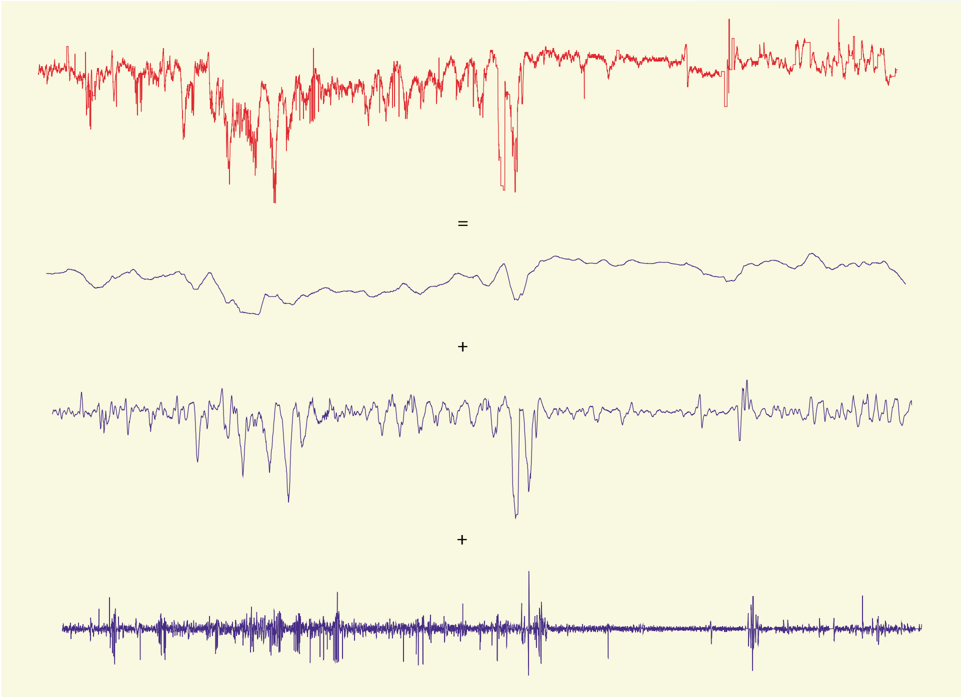
Fluctuations of human heartbeat intervals have been studied recently with modern (statistical) methods such as wavelet-based multifractal analysis and detrended fluctuation analysis. The captured scaling and correlation characteristics provide new insights into the non-linear dynamics of the heart, pointing for example to malfunctioning.
Three obstacles prevent direct application of these methods to fetal heartbeat. First, the statistical techniques require large data sets (about 2^{15} ~ 30,000) to provide reliable estimates. Because the typical heart rate of a fetus is 130 beats per minute, the generation of such a data set takes more than four hours. However, decisions about an intervention have to be taken at considerably shorter notice (10 – 60 minutes). Another serious problem is the presence of sudden drops in the heart rate of the fetus (deceleration). These 20 – 200 beats long drops, which do not necessarily imply hypoxia, spoil standard analysis methods because their inter-beat intervals can be an order of magnitude larger than the other heartbeat fluctuations. The third, and perhaps most serious obstacle is that fetal heartbeat during labour is very complex and dynamic, and its characteristics non-stationary.

Multifractals and wavelets

In time series, such as heart rate recordings, the signal is a non-differentiable ('singular') function at almost all in points time. The strength of a singularity, indicating the local 'roughness' of the signal, is measured by the so-called Hölder exponent. A signal may contain singularities of different strengths. The set of all singularities with the same Hölder exponent can be fractal, i.e., the pattern of their time points exhibits self-similar features on various scales. If a signal contains fractal sets with different Hölder exponents, it is called multifractal. A relatively simple process like fractional Brownian noise is monofractal: all singularities in the signal have the same strength. In several complex phenomena, such as fully developed turbulence, this is not the case. The signals produced by these processes are characterized by many interwoven fractal sets of singularities forming an intricate, unique 'barcode' of the process. Such signals are quite normal: heart rate fluctuations of healthy individuals are multifractal. Several methods have been developed over the years to analyze a signal by decomposing it into a number of elementary building blocks. In the classical Fourier method these building blocks are sine and cosine functions, which keep undulating to infinity. A relatively new method uses highly localized, wave-like functions, called wavelets. The wavelet method is well-suited to detecting singularities in a signal, and determining their strength (local roughness), characterized by the Hölder exponent.

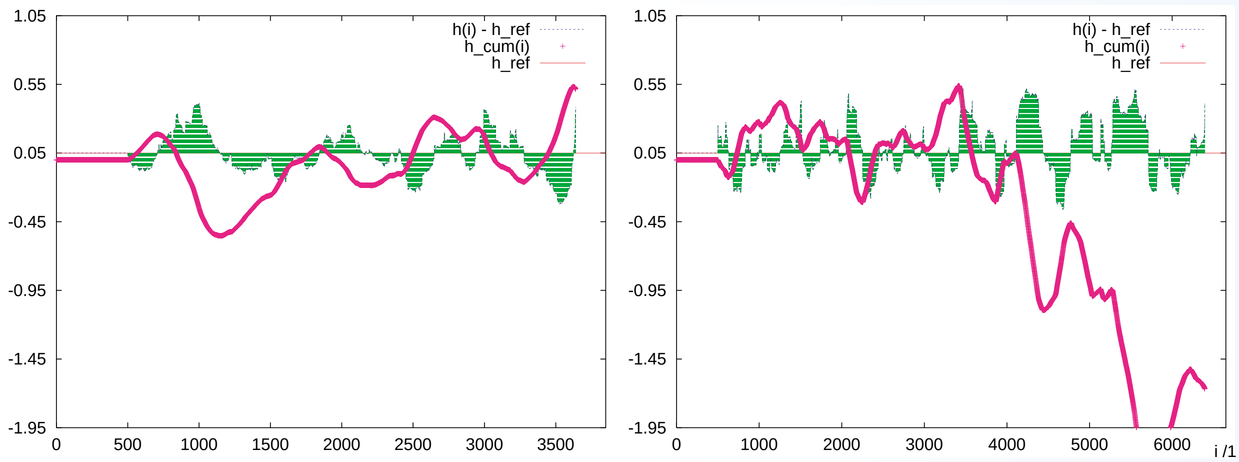
Three remedies

By applying wavelet techniques to multifractal signals, CWI has been able to provide reliable roughness estimates based on local information, thus avoiding the need of large data sets. This has been shown to be helpful in obtaining short-time characteristics of fetal heartbeat variability. Ultimately these characteristics are expected to be obtained in an automated scheme fit for real-time implementation.
Furthermore a signal decomposition scheme has been designed, different from the standard wavelet decomposition method, in order to capture the unique features of the fetal heartbeat analyzed by obstetricians in standard clinical practice. This decomposition separates the high frequency variability component from the deceleration component, thus minimizing the influence of decelerations on the estimation of the signal's roughness spectrum.

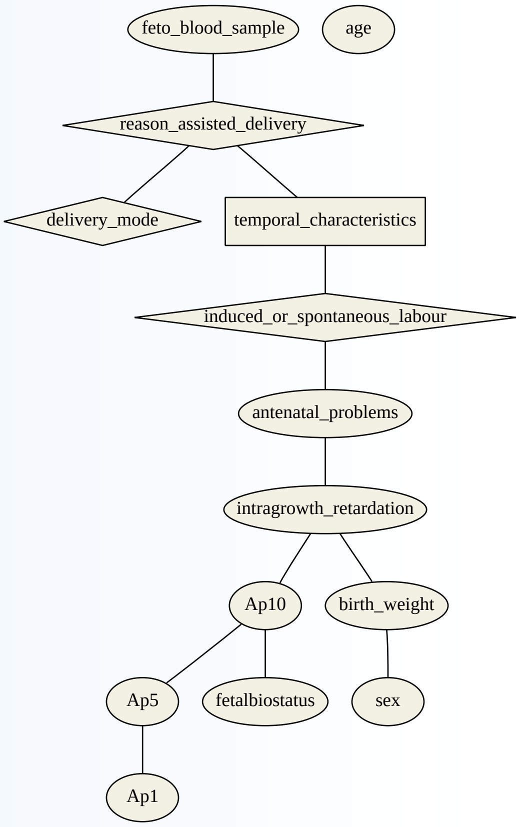


Mimicing the obstetrician – decomposition of fetal heartbeat (a) into meaningful components: (b) baseline, (c) accelerations/decelerations, and (d) 'normal' variability.

Most standard characteristics derived from the fetal heartbeat signal are non-stationary, reflecting dynamic changes in the condition of the fetus and the degree of stress to which it is subjected. The departure of the spectral model from stationarity has been used as an advantage. A cumulative indicator, measuring the departure from a prefixed stationary reference, has proved a novel promising characteristic with diagnostic potential. If the indicator oscillates near zero or steadily increases, the outcome is good.
In the case of hypoxia the indicator plunges down to negative values, even after an initially stable condition, reminding us that during labour problems may occur any moment.



The cumulative Hölder exponent (red line), i.e., the linear time integral of local exponents, appears to be a characteristic with diagnostic potential. A non-decreasing line (a) is a good sign, whereas a drop of this line (b), corresponding to decreasing roughness of the signal, indicates a bad outcome.



Simplified version of the best dependence network obtained with data mining techniques.

Discovering the unknown model

Devising methods to extract new information from the fetal heartbeat signal, for example possibly useful new characteristics, is only part of our research. By integrating this information with external data concerning the status of the fetus, we aim to discover a computerized model which not only mimics the obstetrician's working praxis, but goes beyond it by revealing new knowledge. To this end we carried out a study with a thousand fetal heartbeat records, each covering three half-hour intervals just before birth. From these records we derived the following time series characteristics:
(1) the 'baseline', i.e., the short-time average heart rate level
(2) the short-time average integral of accelerations and decelerations
(3) the 'cumulative' Hölder exponent, i.e., the integral of local exponents relative to an estimated average exponent.
Together with data such as fetal blood composition, these characteristics form a bulk of data to which we have applied data mining techniques to find an underlying 'delivery model'. In particular, by taking a Bayesian approach we derived graphical Markov models from the data and employed them to capture and represent the conditional independencies among the random variables that we identified in our data.
By applying the Markov Chain Monte Carlo method, we obtained a posterior distribution over the set of models. This distribution weighs the different competing models and provides a measure of the uncertainty of each of them, as well as a notion of the support that they receive from the data. This measure of uncertainty, combined with the opinion of the expert, provided a sound way of selecting the most economical models. We have found to our satisfaction primary agreement of the best models with

the expert's knowledge. For example, in the computer model fetal heartbeat characteristics are connected to fetal outcome variables, like Apgar scores and biochemical composition of the blood, only via the decisions of the obstetrician. (An Apgar score is a kind of report mark for the baby, reflecting its status in minutes after birth, giving an indication of the need of resuscitation.) Indeed, in practice there is no evidence that these characteristics are directly related to the fetal outcome. Also the cumulative Hölder exponent appears to play a substantial role in the network of dependencies, on a par with established monitoring quantities like baseline heart rate and acceleration/deceleration integral. Whether we can find a better characteristic than the present cumulative Hölder exponent (a simple linear integral) deserves further study.

The computer will probably never completely replace the specialist, but it can be turned into a useful tool in guiding the obstetrician at work and provide for consistency of fetal heart rate interpretation and labour management. The satisfactory results so far give hope that by continuing our research along these lines we may obtain predictive models for fetal surveillance, and discover unknown relationships that are relevant to the domain expert.