Virtues and Vices of Source Separation Using Linear Independent Component Analysis for Blind Source Separation of Non-linearly Coupled and Synchronised Fetal and Mother ECGs

M Sabry-Rizk, W. Zgallai, A. McLean[1], E. R. Carson*, and K. T. V. Grattan

Electrical, Electronic and Information Engineering Department, and *Centre for Measurement and Information in Medicine, City University London, Northampton Square, London EC1V OHB, UK. Tel: +44 20 7477 8937, Fax: +44 20 7477 8568, Email: m.sabry-rizk@city.ac.uk. [1] Department of Obstetrics and Gynaecology, Royal Free and University College Medical School, London, UK.

Abstract: In this paper, we address the imminent problem which arises when researchers unjudiciously use a linear and instantaneous (memoryless) model for the source mixing structures of independent component analysis (ICA), also known as blind source separation (BSS), in persuit of separating noisy and frequently nonstationary combined mother and fetal electrocardiogram (ECG) signals from cutaneous measurements under the following false assumptions. (1) Sensors (electrodes) are instantaneous linear mixtures of mother and fetal source signals. (2) Noise is an additive Gaussian perturbation. (3) Mother and fetal ECG signals are assumed to be stationary and linear, mutually statistically independent and statistically independent from noise. (4) Most of the second-order (SO) and fourth-order (FO) blind source separation (BSS) methods developed this last decade assume that third-order cumulants vanish hence the need to use FO. All these assumptions are not valid and will be challenged. We will expose these vices without providing any significant contributions for overcoming them. Rather, we provide a framework for investigations which are based on conformal mapping of nonlinear mixtures and novel dynamic nonlinear structures with time-variant memory to cater for quadratic coupling between mother and fetal which is quasi-periodical and the concomitant (quasi) cyclostationarity. Results given here show linear ICA shortfalls in nonstationary environment which is precipitated by quadratic coupling between mother and fetal ECGs during events of synchronised QRS complexes and P-waves and account for more than 20% of the 100,000 maternal cardiac cycles obtained from several clinical trials.

Keywords: Noninvasive fetal electrocardiogram, Blind source separation, linear/nonlinear independent component analysis, quadratically coupled sources, nonlinear and nonstationary mixtures.

I. DISCUSSIONS

I.1 Issues for discussions

- The unsuitability of using linear independent component analysis (ICA) or blind source separation (BSS) to the problem of separating fetal heartbeat from transabdominally measured signals.
- Wrong assumptions and conditions for solutions to the above problem.
- Evidence of nonlinear coupling and (quasi) cyclostationarity in the transabdominally measured signals.
- Present techniques for nonlinear ICA only cater for nonlinear mixtures and may not be adequate for nonlinear mixtures of individually nonlinear mother/fetal ECGs.

I.2 Linear Independent Component Analysis (ICA)

Blind source separation is to recover unobservable independent sources (or signals) from multiple observed data masked by linear mixing. Most existing algorithms for linear mixing models stem from the theory of the independent component analysis (ICA) [1]-[3]. Most of the second-order (SO) and fourth-order (FO) blind source separation methods developed this decade are aimed at blindly separating statistically independent sources that are assumed zero-mean, stationary and ergodic. Nevertheless, in many situations of practical interest, such as in noninvasive fetal heartbeat identification, the combined sources measured transabdominally are (quasi) cyclostationary due to nonlinear coupling. In these conditions it becomes important to wander whether the performance of these current SO and FO blind source separation methods which have been developed for stationary source may be affected by the potential nonstationarity of the latter limiting the analysis to the SO and FO cumulant-based blind source separation methods, the purpose of this paper is to bring some answers to this important question by looking at the nonlinearity, quadratic coupling and nonstationarity during events of synchronised QRS complexes and P-waves.

I.3 Wrong Assumptions in Mother and Fetal Source Separation

Recently, Lathauwer et al. [4-9], Zarzoso et al. [10] have attempted to separate mother and fetal electrocardiograms from cutaneous 8-32 channel recordings, by exploiting the second- and fourth-order statistics because notably the solution to the ICA problem lies in the fact that the assumption of statistical independence is a key factor. Statistical independence is relatively strong assumption but it is plausible in many contexts because it arises from a lack of physical relationship between the various sources. However, they focus at the second-order and fourth-order level based on the wrong assumption that the third-order cumulants for mother and fetal vanish (which is not true). Third-order cumulants do exist for mother and fetal ECGs and have been successfully exploited in many analyses [24].

Researchers in this field justify using linear mixtures based on inaccuracies in the assumption that the transfer from bioelectric current sources to body surface

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Abstract

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electrodes can be considered linear and resistive [21]. Even if this is justified as first approximation, the nonlinearities which characterise individual mother and fetal cardioelectrical activities [22], [23] will interact during their propagation through various body layers and mix with motion artefact, before they are finally picked up as the ECG signals by electrodes on the skin surface. It is important to realise that the cardiac signals have to penetrate through a complex system experiencing various effects and there is evidence of spectral tuning between the fetal heartbeat and uterus contractions [26], [27]. However, only evidence of quadratic coupling between the mother and fetal ECGs will be given in this paper due to lack of space. It is worth mentioning that in previous publications [22], [23] we provided evidence of non-Gaussian and multiplicative noise in individual ECGs.

The main drawback of these techniques, therefore, are their underlying simplistic assumptions, namely, linear sources, linear mixtures, and additive model for noise. Also, we strongly oppose the claim that third-order cumulants vanish for either mother or fetal ECG [24]. In fact, the utilisation of the third-order cumulants to extract fetal heart signals from the maternal ECG has proven to be a very robust technique provided that the observed signals are nonlinearly filtered and if necessary the linearised signals are deconvovled from any multiplicative noise before the third-order cumulant matching process is carried out [24], [25]. Furthermore, only 1-d diagonal slice is needed for the identification and reconstruction process [25], [30]. These publications prove beyond doubt that the pdfs for both mother and fetal ECGs are not even and third-order cumulants do exist.

I.4 Nonlinear Mixing Update

For nonlinear mixing models, many difficulties occur and both the linear ICA theory and existing linear demixing algorithms are no longer applicable because of the complexity of nonlinear characteristics. In addition, there is no guarantee for the uniqueness of the solution of nonlinear blind source separation unless additional constraints are imposed on the mixing transformation [11].

So far several authors studied the difficult problem of the nonlinear blind source separation and proposed a few efficient demixing algorithms [11]-[14], [15-19]. In addition, the extension of related linear ICA theories to the context of nonlinear mixtures has resulted in the development of nonlinear ICA. The so-called nonlinear ICA is to employ a nonlinear function to transform the nonlinear mixtures such that the outputs become statistically independent after the transformation. However, this transformation is not unique without some specific constraints on the function of nonlinear mixing. If s_1 and s_2 are two independent random variables, then $f(s_1)$ and $g(s_2)$ are also statistically independent regardless of the nonlinear functions f and g (see Fig. 1). At this junction we stress that if s_1 and s_2 are themselves nonlinear then we suggest a total review to the present nonlinear ICA theory.

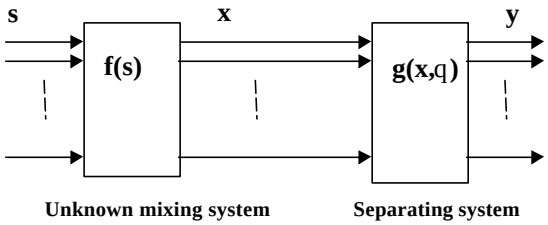

Fig. 1: Nonlinear mixing and separating systems for blind signal separation.

I.5 Framework for Our Nonlinear Model

We have succeeded in nonlinearly modelling fetal and mother ECGs, and in conformal mapping their mixing structures using an embedded Volterra-like structures with extended memory [28]. Modifications to the memory of these structures have been introduced to cater for nonstationarity [29]. In the next section we provide evidence of nonlinear quadratic coupling between mother and fetal respective ECGs and nonstationarity. This is followed by attempting to exploit linear ICA in mother/fetal source separation using eight electrodes and resulting in several misses during events of synchronised mother/fetal QRS complexes and P-waves. In general, in the context of linear ICA, it is assumed that each sensor receives a mixture of all the source signals: if there are fewer sources than sensors the received mixture of signals is linearly invertible: ideally the separating matrix should approximate the inverse of the mixing matrix.

II. RESULTS

Data Acquisition (I) for the purpose of identification of quadratic coupling and the concomitant nonstationarity

The data collection process included obtaining data from pregnant women at various stages of gestation. Abdominal electromyographic signals were obtained with consent of women using a pair of electrodes, Sonicaid 8000, a Pentium II PC and an interface card. Figs. 2 and 3 are self explanatory and show clear manifestations of quadratic coupling and nonstationarity through the exploitation of the bicoherence squared of transabdominally measured ECGs when the QRS complexes and P-waves of mother/fetal overlap. The scalp electrode was deemed necessary and was used as a marker for fetal heartbeats. Fig. 5 shows blind source separation results after carrying out a novel nonlinear identification procedure on the data of Fig. 4(a), using an embedded Volterra-like structure with an extended memory and modified to cater for time-variant nonlinearity. Three key channels are shown after the identification of the previously missing first, fourth, and seventh fetal heartbeats [28], [29].

Data Acquisition (II) for the purpose of repeating linear Independent Component Analysis

As in Data acquisition (I) but the number of surface electrodes is eight (minimum).

Linear ICA Results were obtained following the same procedures and algorithms in [4] and are shown in Fig. 4. Note that the first, fourth and seventh fetal signals have not been identified and marked X in Fig. 4(b). The missing fetal complexes are almost invariably coincident

with maternal QRS complexes or P-waves. These missing fetal complexes were recovered using an embedded Volterra-like structure with an extended memory and modifed to cater for time-variant nonlinearity [28], [29].

III. CONCLUSIONS

We have extolled one virtue and several vices of exploiting linear independent component analysis in separating mother and fetal electrocardiogram sources from cotaneous measurements. Linear ICA works well in separating mother and fetal sources under two conditions, namely, high signal-to-noise ratios and nonoverlapping mother/fetal QRS complexes and P-waves. We provided evidence of quadratic coupling between the mother and fetal electro-cardiograms which increases with the proximity of the occurrences of their respective QRS complexes and P-waves. This results in nonstationarity which is manifested in the OT triangle of the bicoherence squared. We have shown that, by giving one typical result due to lack of space, in as many cases as more than 20% in the 100,000 maternal cardiac cycles obtained from clinical trials, synchronised mother/fetal QRS complexes can not be detected using linear ICA. The need for higher-order statistics in linear/nonlinear independent component analysis does not preclude using the third-order cumulants in the concerned problem. For moderate noise (antepartum) and when the uterus is not contracting fiercefully as in labour, the separation is feasible resorting only to second-order statistics provided that nonlinearity is removed from the transabdominally measured ECGs.

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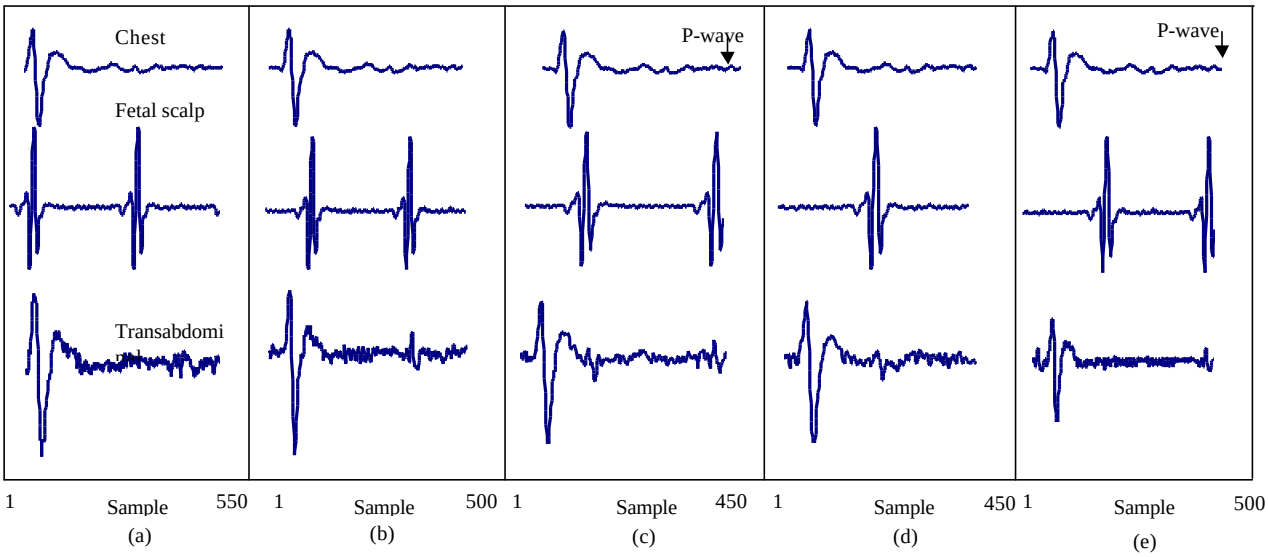

Figure 2: Simultaneous recordings of maternal chest ECG (top), fetal scalp ECG (middle) and transabdominal ECG (bottom). (a) The fetal and maternal QRS complexes severely overlapping (synchronised). (c) Fetal QRS-on-ST segment. The second fetal QRS complex within the maternal cycle coincides with her P-wave. (e) Fetal QRS-on-ST segment. The second fetal QRS complex within the maternal cycle coincides with her P-wave.

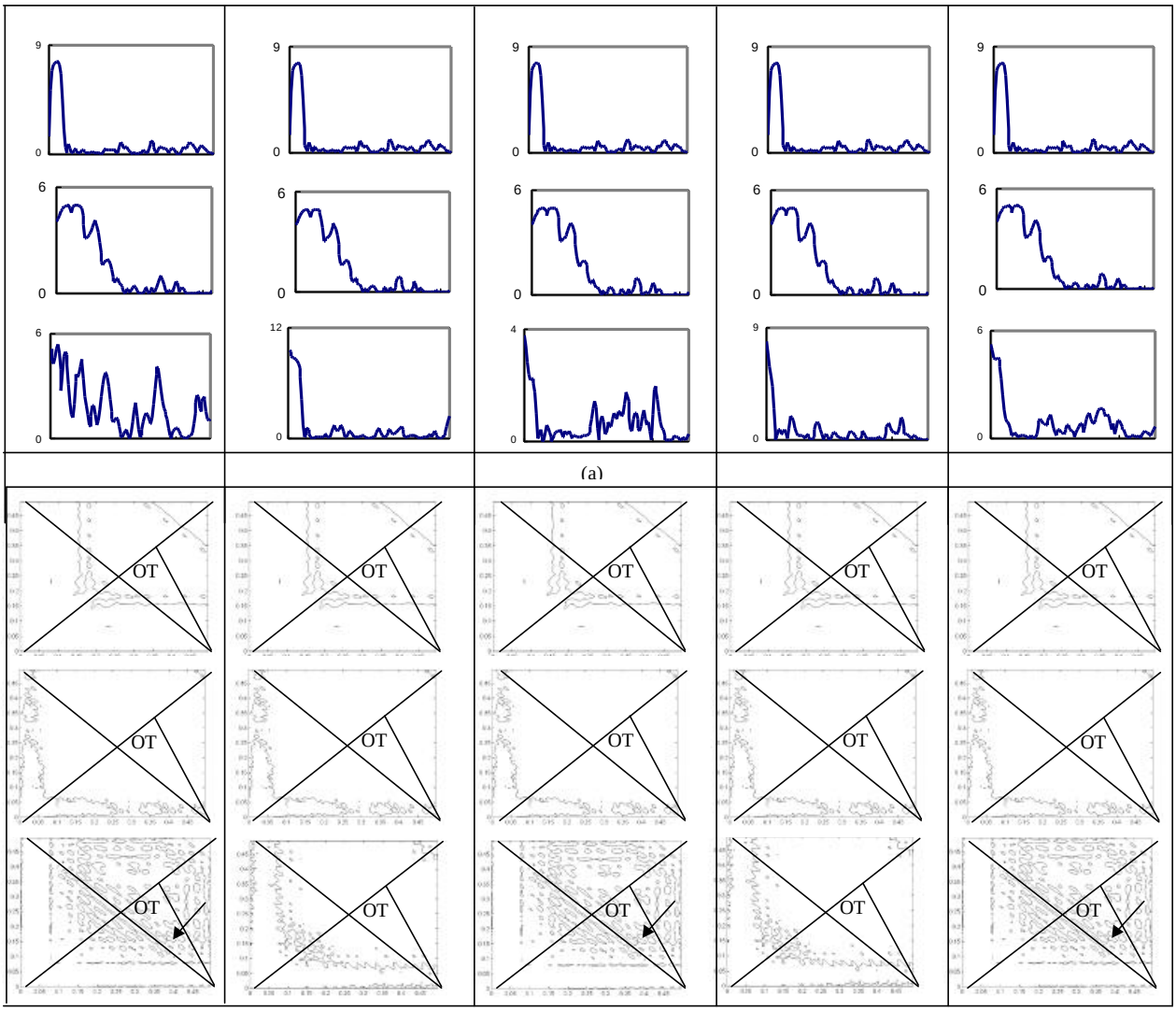

Figure 3: Exploitation of the bicoherence squared of simultaneous recordings (see Figure 2) of maternal chest ECG (top rows in (a)-(b)), transabdominal ECG (bottom rows in (a)-(b)), and fetal scalp ECG (middle rows in (a)-(b)), to detect quadratic coupling and nonstationarity particularly during events of synchronised maternal and fetal QRS complexes and P-waves. (a) Diagonal slices and (b) the corresponding contours with arrowheads pointing at activities in the OT region indicative of non-stationarity [16].

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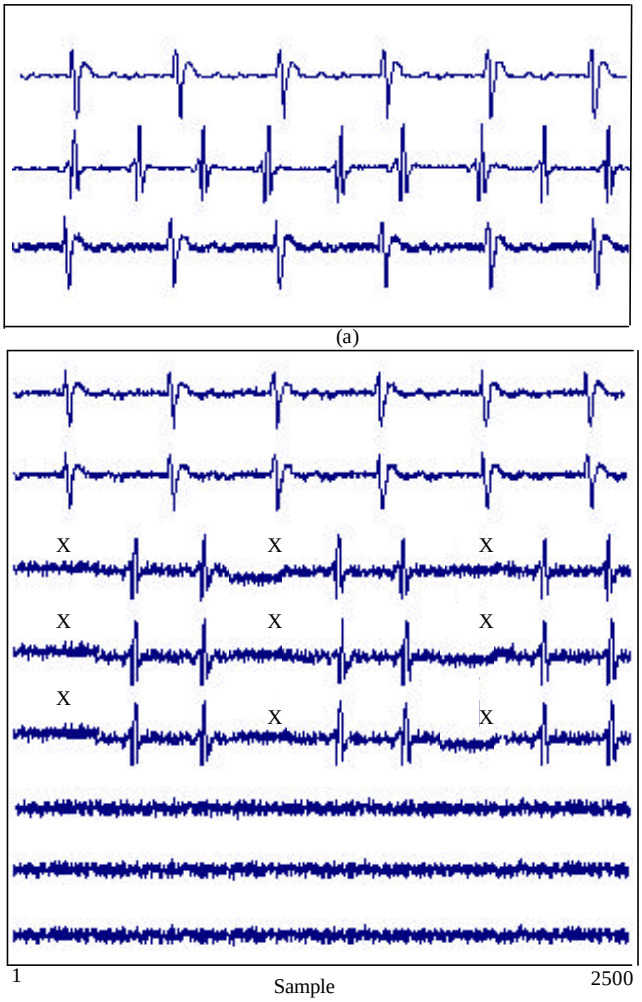

Fig 4: Simultaneous recordings of maternal and fetal ECGs.
(a) Maternal chest (top), fetal scalp (middle) and transabdominal ECG signals of length 2500 samples including five maternal cycles and 9 fetal cycles. The fetal scalp recording was deemed necessary and was used as a marker for fetal heartbeats.
(b) Outputs of 8 channel after applying blind source separation using second-order (SO) and fourth-order (FO) cumulants of the data. Channels 1 and 2 show the maternal signal. Channels 3, 4 and 5 are amplified to show the fetal signals. Note the first, fourth and seventh fetal signals have not been identified and are marked X. The missing fetal complexes are almost invariably coincident with either maternal QRS complexes or P-waves. The remaining channels, namely, 6, 7 and

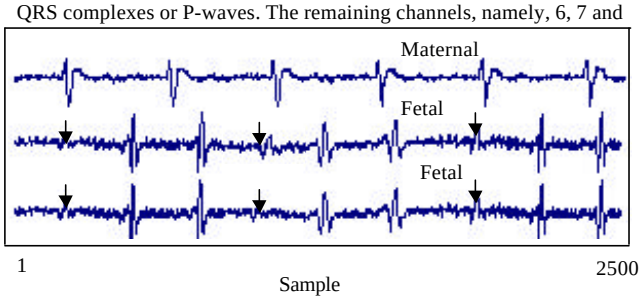

Figure 5: Blind source separation results after carying out a novel nonlinear identification procedure on the data of Fig. 4 (a), using an embedded Volterra-like structure with an extended memory and modified to cater for time-variant nonlinearity. Three key channels are shown after the identification of the previously missing first, fourth and seventh fetal heartbeats (arrowheads).