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Independent component analysis of normal and abnormal rhythm in twin pregnancies

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Abstract

We investigated the utility of ICA for evaluation of fetal rhythm in five uncomplicated twin pregnancies and in five twin pregnancies complicated by fetal arrhythmia. Using objective and subjective criteria, we sought to determine how the signal-to-noise ratio, signal fidelity and interference rejection are affected when synthesizing the fetal signal using all the signal-containing ICA components (rank- p ICA) versus using the single dominant component (rank-1 ICA). The signal of each fetus was most commonly distributed over 1 or 2 ICA components, as previously observed in studies of singleton pregnancies; however, in 8 of 26 (31%) cases the signal of each fetus was distributed over 3, 4 or even 5 ICA components. Rank-1 ICA provided the highest SNR and interference rejection, but at the cost of reduced signal fidelity. Our results corroborate that in twin pregnancies, including twin pregnancies complicated by fetal arrhythmia, rank-1 ICA is very effective in isolating the QRS complexes of each fetus; however, it has some limitations when used for fetal rhythm evaluation due to signal distortion. Occasionally, rank-1 ICA completely separates the P-wave and the T-wave from the QRS complex, thus requiring the mixing of several ICA components to achieve acceptable signal fidelity.

Keywords

independent component analysis; multiple gestation; fetal magnetocardiography; QRS; P-wave; arrhythmia

1. Introduction

Many recent studies have documented the efficacy of fetal magnetocardiography (fMCG) for evaluation of fetal heart rate and rhythm. fMCG provides a precise signal source for computation of fetal heart rate tracings, allowing accurate quantification of beat-to-beat fetal heart rate variability (Van Leeuwen *et al* 1999, Wakai 2004). It also provides waveform information, allowing assessment of rhythm with efficacy approaching that of postnatal

ECG. A number of studies have demonstrated the diagnostic utility of fMCG for evaluation of fetal arrhythmia (Menendez *et al* 2001, Hosono *et al* 2002, Abe *et al* 2005) and other high-risk conditions (Kahler *et al* 2001).

Twin pregnancies are an important class of high-risk pregnancy. These pregnancies have higher risk of such potentially lethal complications as pre-eclampsia, preterm birth, low birth weight and twin-twin transfusion. Another serious complication is fetal arrhythmia. Management of twin pregnancies complicated by arrhythmia is especially difficult when drug therapy is involved. Several fMCG studies of twin pregnancies involving fetal supraventricular tachycardia (Wakai *et al* 2003, Schiermeier *et al* 2008) and AV block (Zhao *et al* 2008) have been reported. In such cases, fMCG is useful for monitoring the drug effect in the normal, as well as the affected, fetus.

The task of separating a weak fetal cardiac signal from large maternal cardiac interference is a classic problem in signal processing. This task becomes considerably more challenging in twin pregnancies, when there are two fetal signals of interest. Among the commonly used filtering techniques, independent component analysis (ICA) is particularly well suited for this task (Comani *et al* 2005). In principle, ICA is able to separate the MCGs of the two fetuses and the mother at the same time, with no additional effort compared to a singleton pregnancy. Most other filtering techniques must be applied sequentially to isolate each signal of interest from the two others. Furthermore, some temporal filtering techniques of removing cardiac interference, such as matched filtering, require efficient detection of the interfering heartbeats. This becomes considerably more difficult with the presence of an additional fetal cardiac signal due to the increased incidence of overlapping QRS complexes.

Previously, Burghoff and Van Leeuwen (2004) demonstrated the efficacy of ICA in twin pregnancies in terms of the efficiency of QRS detection. The goal of our study is to assess the utility of ICA for evaluation of fetal rhythm in normal twin pregnancies and in twin pregnancies complicated by fetal arrhythmia. Using objective and subjective criteria, we examined how the signal-to-noise ratio, signal fidelity and interference rejection were affected when more than one ICA component was used to synthesize the signal.

2. Methods

2.1. Subjects

The subjects were ten sets of fetal twins, studied between 20 and 37 weeks' gestation (table 1). Five of these pregnancies were uncomplicated, as determined by clinical history, echocardiography and fMCG. In the other five pregnancies, at least one of the fetuses had an abnormal rhythm. The University of Wisconsin Institutional Review Board approved the protocol to study the patients and informed consent was obtained from each mother prior to the procedure.

2.2. fMCG recordings

A brief ultrasound exam was performed to determine the approximate lie of each fetus. The fMCG recordings were made using a 37-channel superconducting quantum interference (SQUID) magnetometer (Magnes, 4D Neuroimaging, Inc., San Diego, CA) in a magnetically shielded room. The signal was digitized at 520 Hz, and the analog filter passband was 0.1–200 Hz. A digital filter was applied to further band-limit the signals to 1.0–80 Hz. Several 10 min recordings were taken from each subject. For the purposes of this study, we selected recordings in which signals from both fetuses could be resolved.

2.3. Signal separation methods

Signal separation was performed using three methods—matched filtering, rank-1 ICA and rank- p ICA, which are described below. Matched filtering is perhaps the most widely used technique of removing cardiac interference. It does not appreciably distort the signal unless there is temporal overlap of the signal and interference; thus it was used as a reference, against which the ICA outputs were compared. Furthermore, the effect of matched filter distortion on assessments of waveform morphology can be reduced to a negligible level by averaging a sufficient number of complexes and/or excluding complexes that strongly overlap the interference.

Ideally, ICA isolates the signal of interest to a single ICA component. This is possible if the signal is rank-1. In general, however, we expect the fMCG to be at least rank-2 due to rotation of the cardiac axis during the QRS complex. The rank increases further if the signal is nonstationary due to fetal movement or rhythm changes. Given the complexity of the signal and the interferences, it is common for the fetal signal energy to be spread over several ICA components; however, these components commonly exhibit widely varying SNR. We therefore sought to compare the result of using just the single dominant component versus using all the components containing significant signal energy.

2.3.1. Matched filtering—Matched filtering is a temporal filtering technique for removing cardiac interference, in which a template of the interference is subtracted from the recording whenever the interfering heartbeat is detected. The first and most difficult step is to detect all of the interfering heartbeats using a QRS detection algorithm. This is accomplished by selecting a template, usually consisting of a representative QRS complex, and computing the autocorrelation between the template and the signal. Peaks in the autocorrelation that exceed a user-specified threshold are assumed to indicate the precise time of occurrence of a QRS complex. Specification of the threshold entails a trade-off between maximizing detection sensitivity and minimizing false detections, and is adjusted from subject to subject. In twin pregnancies, QRS detection becomes much more difficult due to the additional fetal signal. To alleviate this problem, ICA is used to isolate the interference prior to QRS detection. After all the QRS complexes are detected, the template is scaled and subtracted from the recording at the time of each QRS complex. The template is scaled by the correlation between the template and the data so that the filter can adapt to beat-to-beat amplitude changes, such as those associated with breathing and body movements. The T-wave can be removed along with the QRS complex by widening the template to encompass the T-wave, but this was not done here because it compromises removal of the QRS complex.

To isolate the signal of fetus A, matched filtering was performed sequentially to remove interference first from the mother and then from fetus B. Similarly, to isolate the signal of fetus B, matched filtering was performed sequentially to remove interference first from the mother and then from fetus A.

2.3.2. Rank-1 ICA—In rank-1 ICA we retain the single ICA source component with the highest SNR for the fetal signal of interest, using the FastICA algorithm. FastICA is based on a fixed-point iterative scheme and uses non-Gaussianity as a measure of statistical independence (Hyvarinen 1999). Previous studies assessing the performance of several ICA algorithms on fMCG data have shown that FastICA gives the best result (Comani *et al* 2004, Mantini *et al* 2006, Hild *et al* 2007).

Prior to applying ICA, it is necessary to obtain the matrix of right singular vectors, $\mathbf{V}$, of the magnetic field data, $\mathbf{X}$, using singular value decomposition: $\mathbf{X} = \mathbf{U}\mathbf{D}\mathbf{V}^T$, where $\mathbf{U}$ is the matrix of left singular vectors, $\mathbf{D}$ is the diagonal eigenvalue matrix, and $\mathbf{V}^T$ is the transpose

of $\mathbf{V}$. By applying ICA to $\mathbf{V}^T$ we can construct the ICA source components, $\mathbf{Y}$, which are related to $\mathbf{V}$ and to mixing matrix, $\mathbf{A}$, as follows: $\mathbf{V}^T = \mathbf{A}\mathbf{Y}$. Rank reduction is commonly performed prior to application of ICA (Comani *et al* 2004).

2.3.3. Rank- p ICA—In the rank- p approach, we synthesize the fetal signal of interest from all ICA source components with $\text{SNR} > 1.5$, where SNR is defined in the next section. This corresponds approximately to retaining all ICA source components in which the fetal signal is visually apparent. The retained components are combined by projecting them back to the magnetic field measurement space according to

$$\tilde{\mathbf{X}} = \mathbf{U}\mathbf{D}\tilde{\mathbf{V}}^T = \mathbf{U}\mathbf{D}\mathbf{A}^T \tilde{\mathbf{Y}}, \quad (1)$$

where $\tilde{\mathbf{X}}$ is the rank- p reconstruction of the magnetic signal and $\tilde{\mathbf{Y}}$ is formed by zeroing the rows of $\mathbf{Y}$ corresponding to the unwanted sources. If the fetal signal is confined to a single component, then rank- p ICA is identical to rank-1 ICA. The rank- p ICA results shown below are for cases with $p > 1$.

2.4. Performance measures

The performances of rank-1 and rank- p ICA were evaluated on the basis of SNR, interference attenuation and signal fidelity, using matched filtering as a basis for comparison. The performance measures require measurement of the amplitudes of the P-wave and QRS complex of the fetal signal of interest and the amplitudes of the QRS complexes of the interfering maternal and fetal signals. The measurements were taken from the channel with the largest fetal signal following reprojection onto the sensor space, which is generally different for each twin fetus.

The SNR is defined as the signal amplitude divided by the root-mean-square (rms) noise, where the signal amplitude is the peak-to-peak QRS amplitude and the rms noise is estimated in the raw recording during the time periods from the end of the T-wave to the beginning of the next P-wave, when no signal is present. With the aid of a computer program, the estimates were made using all the fetal complexes within a 20 s period during which the fetal heart rate was stable. Typically, this corresponds to analyzing approximately 50 fetal beats, which we consider sufficient for statistical purposes.

Generally, the attenuation of the cardiac interference from the mother and the other twin fetus is incomplete. Attenuation of the maternal interference in the fetal signal of interest is computed as

$$A_m = \left(1 - \frac{X_{f1} X_m^T}{X_{f1}^T X_m} \right) * 100, \quad (2)$$

where X_{f1} and X_m are the amplitudes, respectively, of the fetal signal and the maternal interference in the raw recording, and X_{f1}^T and X_m^T are the corresponding amplitudes after signal processing, using ICA, X^{ICA} , or matched filtering, X^{MF} , techniques. Because ICA can alter the amplitude of the fetal signal, A_m depends on the ratio of the fetal signal before and after signal processing, as well as the ratio of the maternal interference before and after signal processing. This penalizes the methods if they attenuate the signal as well as the interference. If the fetal signal is unchanged by signal processing, then $X_{f1}/X_{f1}^T = 1$ and A_m

reduces to its standard form. When evaluating attenuation of the interference from the other twin, A_{f2} , we substitute X_{f2} in place of X_m in (2).

Signal fidelity of the ICA outputs, X^{ICA} , was assessed by computing their correlation with the matched filtering output, X^{MF} , according to

$$C = \frac{\langle X^{MF} X^{ICA} \rangle}{\| X^{MF} \| \| X^{ICA} \|} \quad (3)$$

where $\langle \dots \rangle$ is the inner product and $\| \cdot \|$ is the magnitude, or L2 norm. To mitigate the effect of noise, the measurements were made on averaged waveforms, using autocorrelation to align all of the complexes within a 20 s interval. C was computed separately for the fetal P-wave and fetal QRS.

2.5. Waveform intervals

QRS durations were measured from averaged waveforms computed from rank-1 ICA, rank- p ICA and raw data. Averaging was performed using autocorrelation to align approximately 50 consecutive fetal complexes. Bland–Altman plots were used to assess the concordance of the measurements (Bland and Altman 1986).

3. Results

The high-risk condition of the twin fetuses and the number of ICA components with $SNR > 1.5$ obtained in each recording session are summarized in table 1. The main results of the study are summarized in table 2, which shows the computed performance measures averaged over all the recordings. Figures 1–5 display the bar graphs of SNR, QRS correlation, P-wave correlation, fetal interference attenuation and maternal interference attenuation, showing results from each of the individual recordings. The numbers on the x -axis correspond to those in the first column of table 1. The results are described in greater detail below.

The number of ICA components with $SNR > 1.5$ was highly variable, ranging from 1 to 5 (table 1). In only 9 of 26 (35%) cases was the signal confined to a single component.

The SNR was slightly higher for rank-1 ICA than for rank- p ICA (table 2; figure 1). This is expected since rank-1 ICA uses the component with highest SNR, whereas rank- p ICA incorporates components with weaker signal, which allows a more accurate reconstruction of the waveform but degrades the overall SNR. The poorer performance of the matched filter is due to the fact that it uses data from a single channel, whereas ICA combines data from all channels to increase SNR.

The correlations of the QRS complex and the P-wave with the matched filtering output were lower for rank-1 than for rank- p ICA (table 2; figures 2 and 3). This is not surprising because the true rank of the signal is almost certainly greater than 1. The correlation was lower for the P-wave than for the QRS complex, most likely because the P-wave has much lower amplitude and is more easily corrupted by noise.

Occasionally, the interfering cardiac signals showed relative amplification, rather than attenuation, resulting in negative attenuation (table 2; figures 4 and 5). This problem did not occur for the matched filter. It should be noted, however, that these instances of negative attenuation occurred when the amplitude of the interference was already low in the raw recording. For example, in the one case in which rank-1 ICA produced negative attenuation

of maternal interference, the amplitude ratio of maternal interference to the fetal signal in the raw recording was only 13%. Attenuation of maternal interference was poorer for rank- p ICA than for rank-1 ICA (table 2), and rank- p ICA showed more instances of amplification of maternal interference. Attenuation of fetal cardiac interference was similar for rank-1 and rank- p ICA.

Subjective assessment of waveform morphology was performed by superimposing averaged waveforms derived from the rank-1 ICA, rank- p ICA, match-filtered, and the raw signals. Generally, concordance between the rank- p ICA waveforms and the matched-filtered waveforms was very high, whereas concordance between the rank-1 ICA waveforms and matched-filtered waveforms was poorer, consistent with the correlations in table 2. Specifically, concordance was very high when the signal was isolated to a single ICA component, but it deteriorated when the signal was distributed over several components. In most cases, the resulting distortion was modest, but in two cases ICA completely separated the P- and T-waves from the QRS complex. Figure 6 shows one such example.

Figure 7 shows Bland–Altman plots comparing QRS measurements for rank-1 ICA versus the raw signals and for rank- p ICA versus the raw signals. The 95% limits of agreement are -11 to 9 ms for rank-1 ICA, and -5 to 6 ms for rank- p ICA. The 95% confidence intervals for the bias are -3 to 1 ms for rank-1 ICA, and -1 to 2 ms for rank- p ICA, implying that the means do not differ significantly. The data of the fetuses with normal and abnormal rhythm show no obvious differences.

Figure 8 shows rhythm strips from the six patients with high-risk conditions. ICA was highly effective in isolating the fetal signal from the maternal and fetal interferences. Distortion of the fetal QRS was modest for both rank-1 and rank- p ICA. Note also that interference from the maternal T-wave is significantly lower in the ICA tracings than in the raw and matched-filtered tracings. In the subjects with intermittent tachycardia (figures 8(a) and (b)), the efficacy of ICA was similar during sinus rhythm and tachycardia.

4. Discussion

Our results corroborate that in twin pregnancies, including twin pregnancies complicated by fetal arrhythmia, ICA is very effective in isolating the QRS complexes of each fetus. Signal separation was successful in all ten cases. Previously, Burghoff and Van Leeuwen (2004) used ICA to separate signals successfully in seven of nine twin pregnancies. The high SNR and ease of use of rank-1 ICA, compared to such techniques as matched filtering, make it very convenient for analysis of fetal heart rate in twin pregnancies. On the other hand, rank-1 ICA has some limitations when used for fetal rhythm evaluation due to signal distortion. In most cases the distortion does not alter the time of onset or termination of the QRS, P- and T-waves, implying that waveform interval measurements are not adversely affected. Occasionally, however, rank-1 ICA completely separates the smaller components of the fMCG, i.e. the P-wave and T-wave, from the QRS complex, thus requiring the mixing of several ICA components to achieve acceptable signal fidelity. We also found that the signal of each fetus could be distributed over as many as five ICA components, whereas prior studies of singleton pregnancies found that the signal was usually confined to one or two ICA components (Mantini *et al* 2005). These differences may reflect the increased complexity of the signal in twin pregnancies, as well as the influence of the magnetometer array, as discussed below.

Rank-1 and rank- p ICA represent extremes of a continuum. As expected, we found that the signal-to-interference ratio, signal fidelity and interference rejection varied with rank in a predictable manner. Rank-1 ICA provided the highest SNR and interference rejection, but at

the cost of reduced signal fidelity. Rank- p ICA provided improved signal fidelity and narrower limits of agreement for measurement of QRS duration, but at the cost of reduced SNR and poorer interference rejection. For rhythm evaluation signal fidelity is paramount, and it is unrealistic to expect that rank-1 ICA or any rank-1 representation of the data can capture all the important information in the recording. On the other hand, rank- p ICA combines all of the ICA components in which the fetal signal of interest is visually detectable, but some of these components may contain relatively weak signal and strong interference. Alternative methods of synthesizing the signal from ICA components may provide a useful compromise between the extremes of rank-1 and rank- p ICA. For example, the rank can be adjusted to account for a specified percentage of signal power.

Although matched filtering shows low distortion and good interference attenuation in the averaged waveforms, it suffers from several limitations that are apparent in the rhythm strips. First, matched filtering is susceptible to distortion when QRS complexes overlap. This occurs because the template scaling is then based on the superimposed complexes, resulting in incomplete removal of the interfering complex and distortion of the complex of interest. Second, matched filtering is less effective than ICA in removing interference arising from the T-wave. The T-wave can be removed along with the QRS complex by substantially widening the template to encompass the T-wave, but this compromises removal of the QRS complex. In contrast, ICA automatically removes both the QRS complex and the T-wave. Third, matched filtering shows relatively low SNR, which limits its ability to resolve P- and T-waves in rhythm strips. Lastly, matched filtering is relatively time consuming to perform and requires considerable user input because QRS detection is very difficult in twin pregnancies. Even if the maternal signal is distinct—and this is not always the case—the two fetal signals are usually difficult to distinguish. If the QRS complexes are misidentified, then the signal of interest may be subtracted out or the interference may be left intact. The problem can be greatly alleviated by using ICA to isolate the signals prior to performing QRS detection, but this increases the number of processing steps.

Rhythm changes associated with ectopy and intermittent arrhythmias, such as supraventricular tachycardia, are potentially problematic for ICA and other spatial filtering techniques that assume signal stationarity. This has not been investigated previously for cases of clinically significant arrhythmia. If the spatial pattern of the signal is altered by the arrhythmia, then some degree of distortion will occur. In two subjects with intermittent arrhythmia studied here, distortion was not evident in the rhythm strips during the brief periods of tachycardia; however, precise assessment of distortion is difficult for transient and irregular rhythms because averaging cannot be employed.

Several limitations of the study are acknowledged. First, the evaluation of signal processing methods can be difficult and depends heavily on the intended application. For assessment of fetal heart rate, the quality of the fetal heart rate tracings depends entirely on QRS detection efficiency, which is strongly associated with SNR; thus, SNR provides a simple, useful indicator of signal quality. Distortion and residual cardiac interference usually are not highly problematic unless they are severe. Fetal rhythm assessment, however, is considerably more complex, requiring evaluation of the morphology and timing of the P-, QRS and T-wave components. Mathematical indices of filter performance and subjective evaluation of signal morphology were utilized in this study. Mathematical indices can quantify such performance characteristics as signal fidelity and interference rejection, but the observed differences are not always diagnostically significant. Subjective assessments of waveforms and rhythm strips often provide more meaningful results, but the results are more difficult to quantify.

Second, the findings of this study partly reflect the magnetometer used to make the recordings. Generally, the performance of ICA and other spatial filtering methods is dependent on the number, location and configuration of the magnetometer channels. A wide range of sensors have been used to record the fMCG, some with more and some with fewer channels than our 37-channel sensor. Signal separation generally improves as the number of channels increases, and is likely to be a more important factor for twin versus singleton pregnancies due to the higher number of sources and the greater spatial extent of the signal.

In summary, ICA is an effective technique for processing of fMCG signals in twin pregnancies. It is very useful for fetal heart rate computation. It is also useful for rhythm analysis; however, care should be taken to ensure that the smaller waveforms components are adequately preserved.

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Figure 1.
Bar graphs of the signal-to-noise ratio per recording: rank-1 ICA (solid), rank- p ICA (cross-hatched) and matched filtering (void).

Figure 2.
Bar graph of the QRS correlations per recording between rank-1 ICA and matched filtering (solid) and rank- p ICA and matched filtering (cross-hatched).

Figure 3.

Bar graph of the P-wave correlations per recording between rank-1 ICA and matched filtering (solid) and rank- p ICA and matched filtering (cross-hatched). In five recordings the P-wave could not be resolved.

Figure 4.

Bar graph of attenuation of fetal interference per recording: rank-1 ICA (solid), rank- p ICA (cross-hatched) and matched filtering (void). Negative values were found in five cases and were excluded for clarity.

Figure 5.

Bar graph of attenuation of maternal interference per recording: rank-1 ICA (solid), rank- p ICA (cross-hatched) and matched filtering (void). Negative values were found in four cases and were excluded for clarity.

Figure 6. Averaged waveforms from fMCG recording 6. Rank-*p* ICA is concordant with matched filtering; however, rank-1 ICA severely attenuates the P- and T-waves.

Figure 7.
Bland–Altman plots of QRS measurements for rank-1 ICA and the raw signal (above) and for rank- p ICA and the raw signal (below).

Figure 8.

Rhythm strips taken from subjects with high-risk conditions. Each panel shows (from top to bottom) rank-1 ICA, rank- p ICA, matched-filtered and raw tracings. Rank-1 ICA and rank- p ICA were identical for the recordings in (d) and (f); therefore we show only one trace. The fetal signals of interest are marked by arrows. Maternal interference is marked by 'm' and fetal interference is marked by 'f'. (a) Frequent reentrant premature atrial contractions were seen in recording 5 taken from a subject with intermittent supraventricular tachycardia (recording 5). (b) A brief episode of atrial flutter was seen in recording 24. (c), (d). Persistent bradycardia was seen in recordings 18 and 25, respectively. (e) Overt QRS-T discordance was present in a twin fetus with rhabdomyoma (recording 21). (f) The other twin with rhabdomyoma had a normal rhythm (recording 22).

Table 1

Listing of the 26 fMCG recordings taken from 10 twin pregnancies over 13 sessions. Fetus A of twin pair 2 showed very brief episodes of intermittent supraventricular tachycardia (SVT) and frequent ectopy due to reentrant premature atrial contractions. Fetus B of twin pair 6 had complete AV block (CAVB) with a nonreactive heart rate of 56 bpm in association with left atrial isomerism. Both fetuses of twin pair 8 had cardiac rhabdomyomas, i.e. benign cardiac tumors. Fetus A had a normal heart rate, but showed overt QRS-T discordance; fetus B had a normal heart rate and rhythm. Fetus B of twin pair 9 showed rare, brief episodes of atrial flutter at a rate of about 200 bpm. Fetus A of twin pair 10 had CAVB with a nonreactive heart rate of 61 bpm in association with left atrial isomerism. The other fetuses had structurally normal hearts and normal heart rate and rhythm. The last column shows for each recording the number of ICA components with SNR>1.5

	Gestational age of twin pair	High-risk condition/arrhythmia	ICA components with SNR >1.5
1	Pair 1, fetus A: 28 4/7 weeks GA	–	4
2	Pair 1, fetus B: 28 4/7 weeks GA	–	1
3	Pair 1, fetus A: 37 weeks GA	–	3
4	Pair 1, fetus B: 37 weeks GA	–	2
5	Pair 2, fetus A: 21 4/7 weeks GA	Intermittent SVT, ectopy	4
6	Pair 2, fetus B: 21 4/7 weeks GA	–	4
7	Pair 3, fetus A: 20 weeks GA	–	2
8	Pair 3, fetus B: 20 weeks GA	–	1
9	Pair 3, fetus A: 26 1/7 weeks GA	–	5
10	Pair 3, fetus B: 26 1/7 weeks GA	–	3
11	Pair 4, fetus A: 37 weeks GA	–	1
12	Pair 4, fetus B: 37 weeks GA	–	1
13	Pair 5, fetus A: 29 3/7 weeks GA	–	2
14	Pair 5, fetus B: 29 3/7 weeks GA	–	2
15	Pair 5, fetus A: 30 5/7 weeks GA	–	4
16	Pair 5, fetus B: 30 5/7 weeks GA	–	2
17	Pair 6, fetus A: 28 6/7 weeks GA	–	2
18	Pair 6, fetus B: 28 6/7 weeks GA	CAVB	1
19	Pair 7, fetus A: 30 2/7 weeks GA	–	2
20	Pair 7, fetus B: 30 2/7 weeks GA	–	1
21	Pair 8, fetus A: 33 4/7 weeks GA	Rhabdomyoma/QRS-T discordance	3
22	Pair 8, fetus B: 33 4/7 weeks GA	Rhabdomyoma/normal rhythm	1
23	Pair 9, fetus A: 30 3/7 weeks GA	–	1
24	Pair 9, fetus B: 30 3/7 weeks GA	Atrial flutter	2
25	Pair 10, fetus A: 25 1/7 weeks GA	CAVB	2
26	Pair 10, fetus B: 25 1/7 weeks GA	–	1

Table 2

Comparison of performance measures for rank-1 ICA, rank- p ICA and matched filtering. The rank- p ICA results were obtained from the 17 recordings with $p > 1$. Rank-1 ICA and matched filter results were derived for these 17 recordings, as well as for all 26 recordings. In a few cases, the interference was amplified, rather than attenuated, by rank-1 ICA and rank- p ICA. These cases were termed failures. The attenuation was computed excluding and including failures

	Rank-1 ICA <i>n</i> = 26; <i>n</i> = 17	Rank-<i>p</i> ICA <i>n</i> = 17	Matched filter <i>n</i> = 26; <i>n</i> = 17
Signal characteristics			
Signal-to-noise ratio	13.8; 14.3	13.0	9.8; 10.7
rms noise (pico-tesla)	0.09; 0.09	0.14	0.14; 0.18
Signal amplitude (pico-tesla)	1.3; 1.4	1.7	1.4; 1.6
Correlation: QRS complex	0.94; 0.93	0.98	–
Correlation: P-wave ^a	0.86; 0.85	0.89	–
Fetal interference attenuation			
Failures	3; 2	2	0
Attenuation (excluding failures)	58%; 57%	59%	68%; 68%
Attenuation (including failures)	47%; 47%	46%	68%; 68%
Maternal interference attenuation			
Failures	1; 1	3	0
Attenuation (excluding failures)	52%; 55%	29%	68%; 71%
Attenuation (including failures)	57%; 63%	59%	68%; 71%

^aThe P-wave could not be resolved in five recordings (two were due to AV dissociation in CAVB and three were due to a low signal-to-noise ratio); thus, the P-wave correlation and distortion were based on five fewer measurements, i.e. $n = 21$ and $n = 12$.