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COMPUTER MATCHED FILTER LOCATION OF FETAL *R*-WAVES*

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Abstract—Statistical decision theory indicates that the best way to locate a signal of known waveshape is to use a matched filter. The degree of improvement actually achieved is investigated using actual signals of varying signal-to-noise ratio in which the maternal complex has been automatically eliminated by computer processing. It is shown that a simplified 3-point version of the matched filter provides almost as much improvement with the added advantage that prior knowledge of the fetal waveshape is not required. It is possible to improve the performance further by using a two-stage process that exploits the almost-periodic characteristic of the fetal ECG.

1. INTRODUCTION

THE FETAL electrocardiogram is an interesting and useful signal, yet the extent of the scientific literature on techniques for recording and processing the fetal ECG amply testifies to the inherent difficulties encountered by every investigator. The basic problem results from the fact that the fetal signal is very weak relative to the maternal signal and to the competing noise arising, perhaps from numerous biological action potentials. This is particularly true in the case of abdominal wall recordings which are the type most widely used.

Several techniques have been used to eliminate or minimize the maternal signal. By summing the abdominal signal in a differential amplifier along with a maternal ECG from another part of the body (HON and HESS, 1957) it is possible to minimize the contribution of the maternal signal. A similar technique has been used by SUREAU and TROCELLIER (1963). Others have used a grounded metal-braid belt around the mother's waist to reduce the maternal signal (SMYTH, 1953). Another variation (GODDARD *et al.*, 1966) uses a combination of spatial and temporal summing from "*n*" pairs of electrodes to minimize the maternal signal and to improve the signal-to-noise ratio. Since we have worked with digitized signals in a digital computer, we have used the computer to first locate the maternal peaks, then develop an average maternal waveshape, and then subtract this waveshape from each complex. (FAVRET and MARCHETTI, 1966). This results in an improved signal as shown in Fig. 1, but if the signal-to-noise ratio is poor, it becomes very difficult to locate each fetal *R*-wave or to ensure that false peaks are not selected. This is particularly true when the processing is to be done automatically, such as when the fetal *R*-wave is used as a trigger for a temporal averaging procedure (HON and LEE, 1963) or when precise beat-to-beat fetal heart rate is being studied (HON and HUANG, 1962). When averaging techniques are used a missed peak is not critical, but false peaks can cause serious distortion in the averaged waveform.

There are a variety of approaches that can be used to locate fetal *R*-waves automatically. The most straightforward is the use of an amplitude threshold. This is very simple to implement using electronic circuits or using a digital computer. It is usually satisfactory for normal electrocardiograms where signal-to-noise ratio is no problem. A better procedure that has been used

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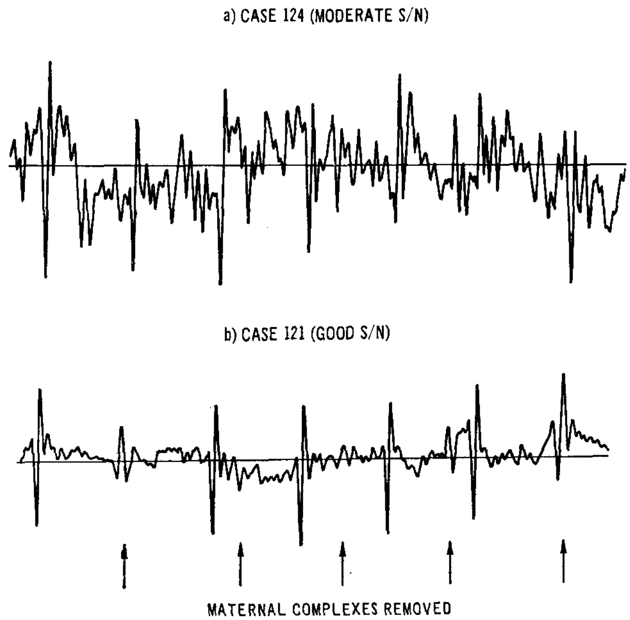

FIG. 1. Typical fetal signals after maternal elimination (unfiltered). Note that an amplitude threshold would miss some fetal peaks and/or locate false peaks.

in computer analysis of clinical electrocardiograms (STEINBERG *et al.*, 1962) computes the derivative of the signal and locates a negative peak corresponding to the RS portion of the original signal. This establishes a reference point in the cycle after which the *R*-wave peak is located in the original signal.

To improve the relative amplitude of the fetal *R*-wave, filters have been used with a pass band from 15 to 40 Hz. (VAN BEMMEL and VAN DER WEIDE, 1966). This is essentially a high-pass filter for such signals and it produces a signal approximating the derivative of the original signal. More recently (VAN BEMMEL, 1967) in order to provide detection only of the very weak fetal signals, matched filtering has been employed followed by rectification, envelope detection and autocorrelation.

Statistical decision theory indicates that the best way to locate a signal of known waveshape is to use a "matched filter" (TURIN, 1960). A matched filter is simply a filter whose impulse response is the time inverse of the waveform to be detected. Such filters can be implemented in several ways. A tapped delay line (transversal filter) is often used in radar, sonar and communication systems. In digital filtering (when the processing is done by digital computer) it is easy to implement the matched filter by crosscorrelating with the expected waveshape. In the case of the fetal electrocardiogram, the exact waveshape is not known *a priori.* However, rough approximations to the waveshape can be used and/or adaptative procedures can be employed to develop a more precise representation of the waveshape.

2. COMPUTER IMPLEMENTATION OF MATCHED FILTER

Digital or numerical filtering means that an input time series $\{X_k\}$ is operated upon in some specified manner to produce an output time series $\{Y_k\}$. In our case the input time series is a sampled (digitized) version of the fetal electrocardiogram with the maternal complex substantially removed. If plotted it is similar to

Fig. 1. The input time series may not exceed 10,000 points in our version, and we normally use a sampling rate of 224 samples per second. The signals were amplified and recorded using conventional band pass filtering (0·2–1000 Hz). Spectral analysis showed no significant energy, either signal or noise, above 50 Hz.

Since the desired operation is crosscorrelation, we wish to generate the output time series using the following equation:

$$Y_k = \frac{1}{2N+1} \sum_{j=-N}^{+N} h_j \, X_{k+j} \text{ with } \quad N < K < M - N + 1 \qquad (1)$$

in which M is the length of the input time series and $2N + 1$ is the length of the crosscorrelating waveshape. The "h's" are a set of weights which represent the expected fetal waveshape.

This equation is quite simple and straightforward to implement on a digital computer, but it may be relatively time-consuming if both M and N are large. Since most of the significant fetal waveshape (as far as the filtering is concerned) is contained in the QRS complex we use $N = 6$.

This gives us a "window" of 54 msec at our sampling rate, which is approximately the width of the QRS complex. To further save on computing time we do not compute each point in the output time series. We are only interested in the peaks and these will occur when the peak value of the h's is centered on a peak in the input time series. A "peak" here means a point whose amplitude is greater than both the preceding point and the following point. This reduces the computations by a factor of about 8.

The next consideration is the choice of the h's. Figure 2 shows two common fetal waveshapes with appropriate h sequences. All fetal waveshapes we have seen roughly approximate those shown in Fig. 2 or inverted versions of these waveforms. (Most are unsymmetric as in Fig. 2a). Notice that 4 points away from the major peak (in either direction): there is either a large value of opposite polarity or at least a value close to zero. Also note that several of the thirteen weights are close to zero, hence contribute only slightly to the summation. This suggests that a good approach to the matched filter might be achieved by using a much smaller number of weights, thus further reducing the computation time. A combination that is particularly attractive is one that uses only major peak and points 4 points away from it. Equation (1) becomes:

$$Y_k = \tfrac{1}{3}\,(-X_{k-4} + 2X_k - X_{k+4}) \text{ with } \quad 4 < K < M - 3. \qquad (2)$$

We call this the 3-point version. Not only does it save considerable computing time, but it is not necessary to know the exact shape of the fetal

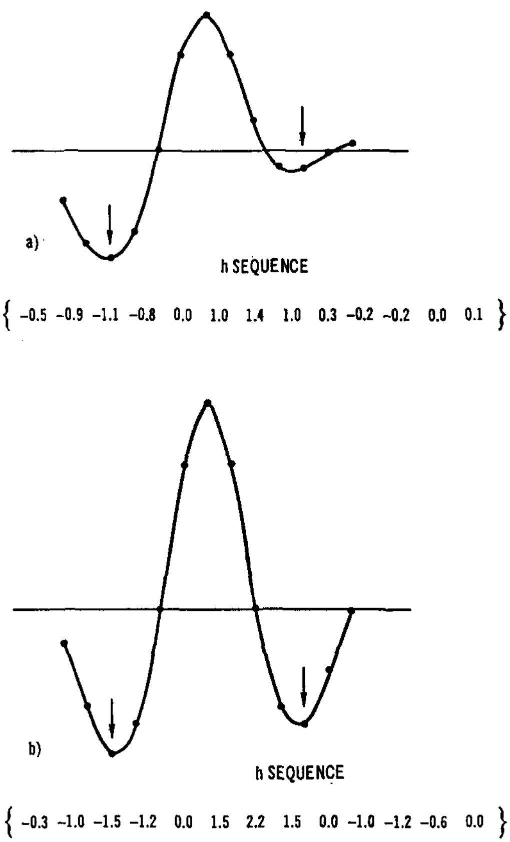

FIG. 2. The QRS portion of two typical fetal waveshapes along with the appropriate "h" sequence for a matched filter.

complex. Only the polarity of the major peak is necessary. Even this is not necessary if there are two significant peaks of opposite polarity, which is often the case.

This suggests an adaptative procedure if the full effectiveness of a matched filter is desired. Equation (2) is used initially with a high threshold to locate a few fetal peaks with high certainty. These are then averaged by the computer to obtain the optimum weights. The original input data is then reprocessed using equation (1). This can all be done by one computer program.

It is important to know what improvement in detection performance can be achieved by using the matched filter approach and what penalties are incurred if simplified procedures such as the 3-point version are used.

3. PERFORMANCE EVALUATION

In order to evaluate different filters and different decision procedures experimentally it is necessary to compute the "hit probability" and the "false alarm probability" for each filter decision procedure combination. The hit probability here represents the percentage of fetal peaks that are located correctly using a given procedure (or threshold). If all fetal peaks are located the hit probability is 1. The false-alarm probability measures the percentage of false peaks that were classified as fetal peaks.

We used the computer to assist in this task by requiring it to list the amplitude (or score) associated with each output peak, whether or not it was a *true* fetal peak. It further quantized these amplitudes into twenty different levels. Since it was possible to visually examine the records and verify which peaks were truly fetal peaks, a plot could be prepared showing the relative frequency of occurrence of output levels for both true and false peaks. Such a plot is shown in Fig. 3. These plots illustrate the sharp improvement provided by a matched filter approach over detecting the peaks on an amplitude basis without filtering. The clustering of the true peaks and the minimization of overlap between the two distributions in Fig. 3a assures a high hit probability and a low false-alarm rate.

This improvement occurs even when the signal-to-noise ratio is relatively good, as it is in the case shown. The improvement is more striking in the case of the poor signal-to-noise ratio.

This signal-to-noise ratio refers to the original recorded data (0·2–50 Hz). It should be noted that the noise energy is strongest between 1 and 5 Hz and drops off sharply with increasing frequency while the fetal signal energy is usually strongest between 8 and 30 Hz. The matched filter, although its spectral behavior is not simply described, does take advantage of the differences in signal and noise spectra in achieving its improved detection performance. However, the original data is stored in the computer unfiltered and undistorted so that it can be used in subsequent processing.

In order to compute hit and false-alarm probabilities it is necessary to choose a threshold. The decision procedure is that every output peak above the threshold will be called a fetal peak and every one below the threshold will be ignored. If a threshold of 10 were chosen in Figs. 3a and b the following probabilities would result:

	Amplitude only (unfiltered)	Matched filter
P (hit)	0·71	0·916
P (false alarm) ..	0·023	0·0022

Since the performance will vary with the threshold, it is preferable to vary the threshold and plot P (hit) vs. P (false alarm). This type of curve is usually called a Receiver Operating Characteristic (ROC). Such a curve for case 121 is shown in Fig. 4. One measure of "goodness" is how close the knee of the curve approaches the ideal operating point in the upper left corner. Three curves are shown: matched filter, 3-point version, and unfiltered. This type of plot provides a good measure of relative performance. Case 121 has a relatively good signal-to-noise ratio, but significant improvement is obtained by the matched filter or even by the 3-point version.

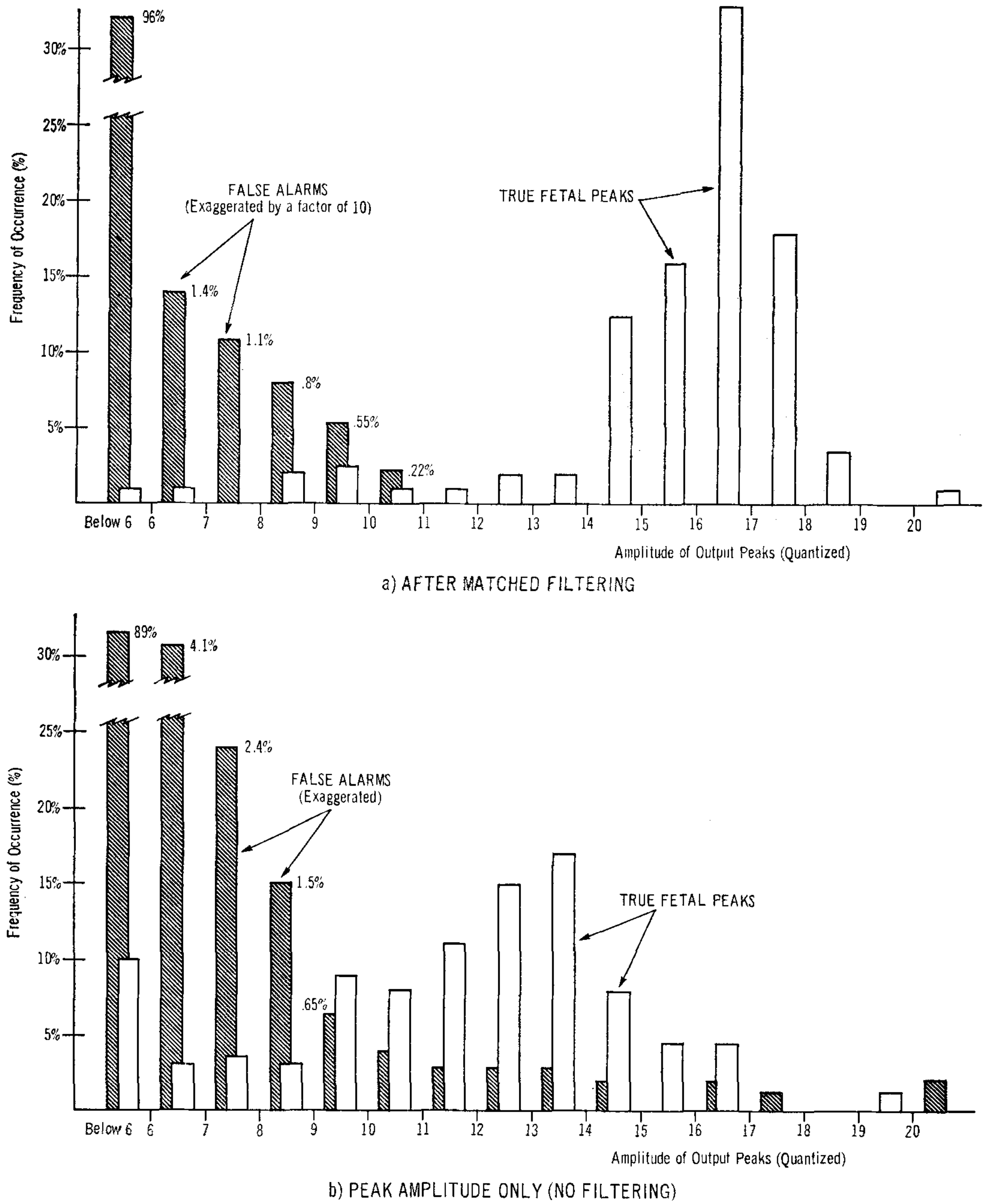

FIG. 3. Histograms comparing output amplitude levels associated with true peaks and false alarms with and without matched filtering. (case 121).

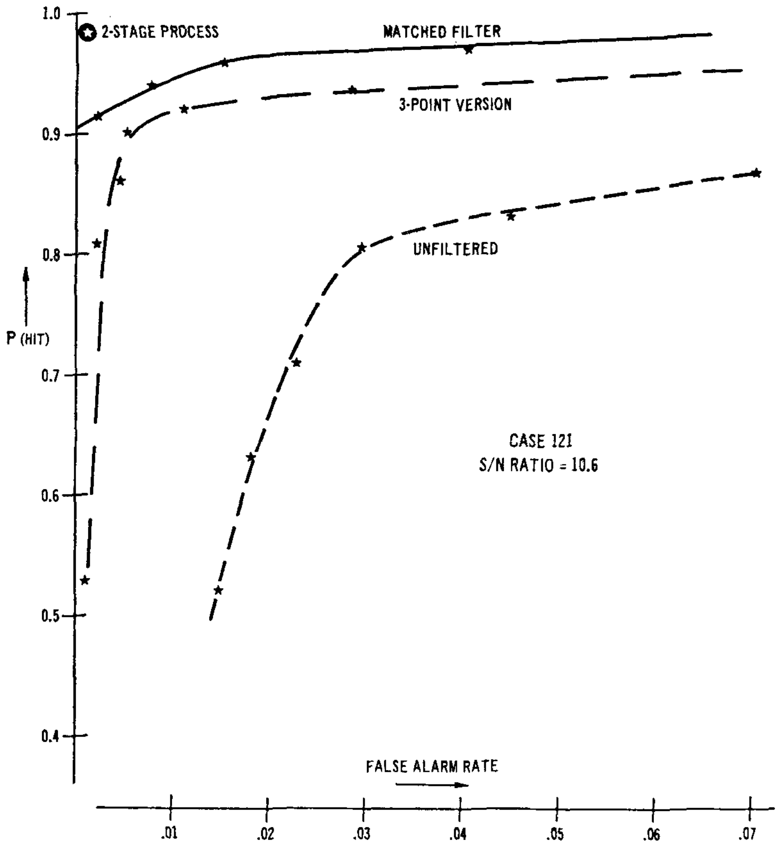

FIG. 4. Receiver Operating Characteristic for case 121 (good signal-to-noise ratio) showing improved performance obtained by matched filter.

It was necessary to investigate relative performance over a range of signal-to-noise ratios. This necessitates some quantitative measure of signal-to-noise ratio. This was done by averaging several hundred fetal complexes and using the ratio of peak-to-peak fetal signal to the root mean square value of the competing noise. The latter is found by computing the standard deviation of points in the averaged waveform (FAVRET and MARCHETTI, 1966). In the signals we have analysed the signal-to-noise ratio has varied from 3·0 (marginally positive tracings) to 12·0. For case 121 it was 10·6.

Figures 5 and 6 are ROC curves which show the relative performance for poor (case 94, S/N = 4·0) and moderate (case 124, S/N = 6·2) signal-to-noise ratios. The moderate S/N ratio represents the same signal shown in Fig. 1a. A typical curve is based on the occurrence of at least 100 fetal peaks or an input signal of 10,000 points representing a 45 sec recording. To do this the computer calculated an output score for about 1000 potential peaks. As can be seen from the histograms of Fig. 3, most of the false peaks fall far below any reasonable threshold.

The general effect of S/N ratio is apparent by comparing Figs. 4, 5, and 6. A big change in optimum performance occurs in going from low to moderate S/N ratio, but only a slight improvement in going from moderate to good. The main difference occurs at low false-alarm rates. In all three cases there is a distinct but rather slight

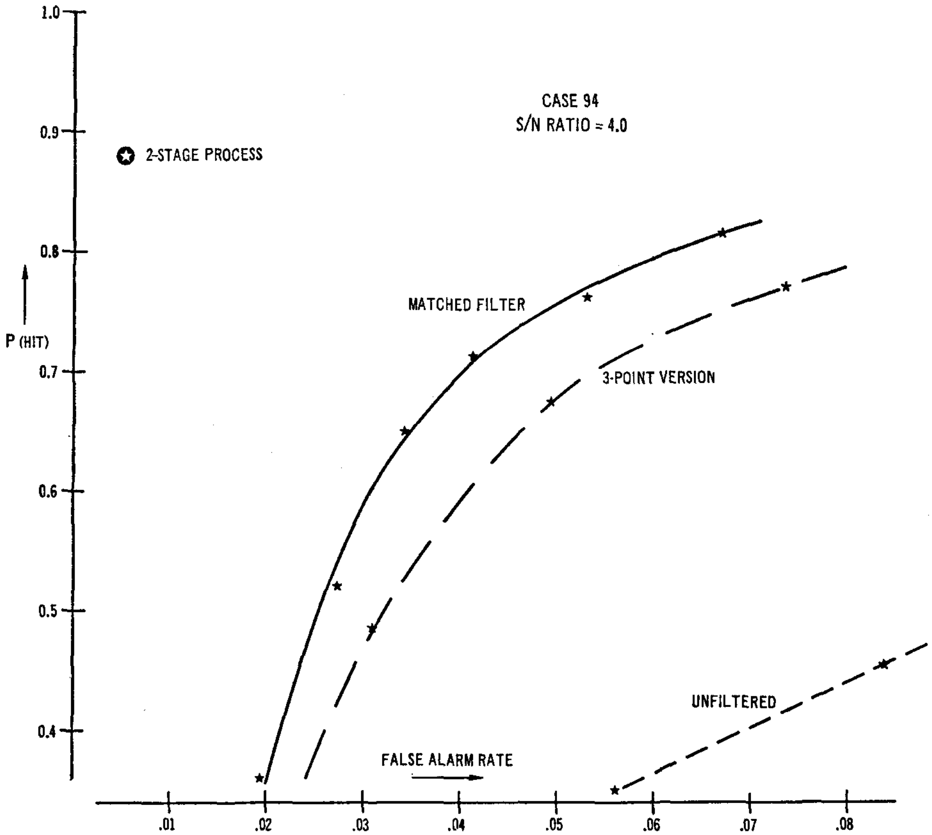

FIG. 5. Receiver Operating Characteristic for case 94 (poor signal-to-noise ratio).

difference in performance between the matched filter and the 3-point version. There is always a big difference in performance between the unfiltered signal and either of the digitally filtered signals. Several cases were processed for each class of S/N ratio and all produced similar results. In the low S/N ratio it was noticed that there is more variation between cases than in the moderate or good categories.

In Figs. 4 and 6 a considerable increase in false-alarm rate is necessary in order to detect the last 5 per cent of the fetal peaks. Invariably these are the fetal peaks that corresponded with a maternal QRS complex. Although they are still identifiable after the maternal elimination they are frequently attenuated or distorted in the process (see Fig. 1b). Hence the threshold must be lowered significantly in order to detect them.

If the signal is processed in a digital computer, it is possible to improve the performance further by taking advantage of the almost periodic characteristic of the fetal ECG. After using the matched filter with an appropriate threshold, the computer then analyses the remaining peaks to see how they fit into the almost-periodic pattern expected from a fetal ECG. Those that fail this test are rejected. Typical operating points with this improvement are shown by the asterisk in Figs. 4, 5, and 6 (referred to as two-stage process). It should be noted that the success of the second stage depends on the first, since the computer is required to "track" the fetal peaks despite fluctuations in the period and occasional missed peaks. If there are too many missed peaks and/or too many false peaks, the automatic tracking technique may not work for the entire sequence.

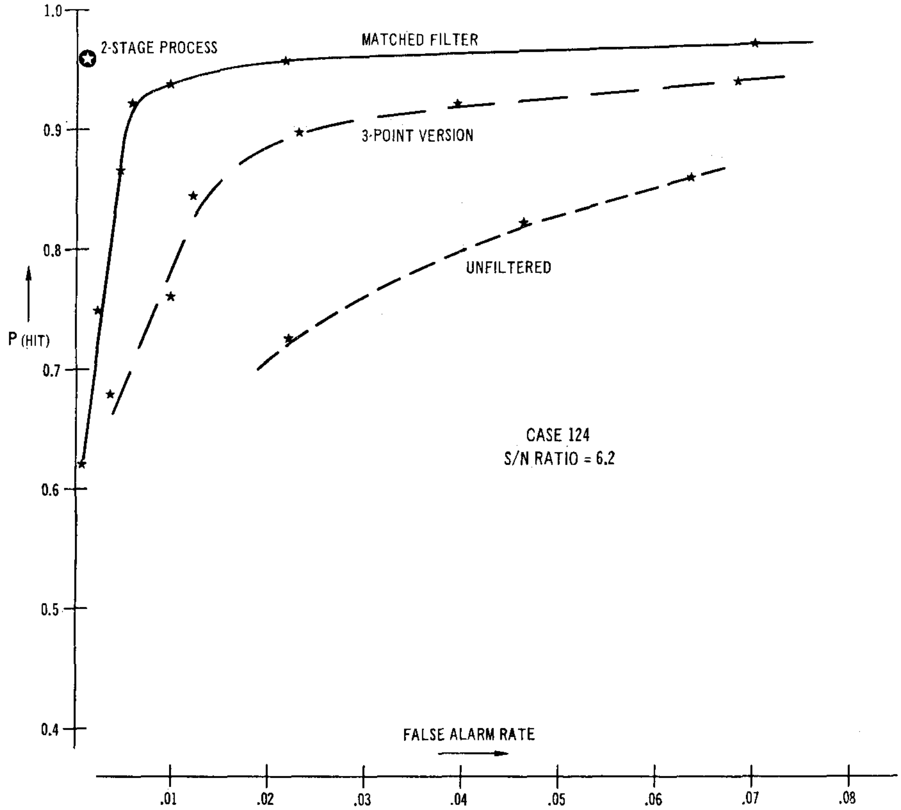

FIG. 6. Receiver Operating Characteristic for case 124 (moderate signal-to-noise ratio).

Similar two-stage processing (MAIO, 1967) has been accomplished using a more precise version of the matched filter and a different method of exploiting the approximate periodicity. This also resulted in significant improvement in the performance.

4. CONCLUSIONS

When it is desired to detect or locate fetal R-waves automatically, the use of a matched filter technique provides significant improvement over the use of the amplitude of the unfiltered R-wave. A simplified 3-point version provides almost as much improvement as the matched filter with the added advantage that *a priori* knowledge of the fetal waveshape is not required. Either version can be implemented easily if the fetal ECG is being processed in a digital computer. It is also possible to implement such filters for on-line processing without using a computer.

It is possible to improve the performance further by taking advantage of the almost-periodic characteristic of the fetal ECG. Such a two-stage process permits the automatic detection and location of fetal R-waves with a high degree of confidence.

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DETECTION DE L'ONDE R D'UN ECG FOETAL AU MOYEN D'UN FILTRE ADAPTE SIMULE PAR CALCULATEUR

Sommaire—Le calcul statistique montre que la meilleure façon de localiser un signal de forme d'onde connue est d'utiliser un filtre adapté. Le degré de résolution réellement atteint est obtenu enutilisant des signaux réels dont le rapport signal sur bruit est variable, et dans lequel le complexe maternel a été automatiquement éliminé par calculateur. On montre qu'une version simplifiée due filtre adapté offre une aussi bonne résolution, avec l'avantage qu'il n'est pas nécessaire de connaître à l'avance la forme de l'onde foetale. Il est possible d'améliorer encore la performance en utilisant un processus èn deux étapes qui exploite la caractéristique quasi-périodique de l'ECG foetal.

COMPUTERZUORDNUNG VON FETALEN R-WELLEN MIT ANGEPASSTEN FILTERN

Zusammenfassung—Aus der Entscheidungstheorie der Statistik geht hervor, daβ ein Signal bekannter Wellenform am besten mit Hilfe eines angepaβten Filters lokalisiert wird. Der gegenwärtig erreichte Stand wird mit Signalen verschiedenen Signal/Rausch-Verhältnisses untersucht dabei wird der mütterliche Komplex durch Datenverarbeitung automatisch eliminiert. Es wird gezeigt, daβ eine vereinfachte 3-Punkte-Version des angepaβten Filters fast diesen Stand erreicht. Ein zusätzlicher Vorteil ist, daβ die fetale Wellenform nicht im voraus bekannt sein muβ. Eine weitere Verbesserung ist durch Benutzung eines Zweistufenverfahrens möglich, bei dem die fast periodische Charakteristik des fetalen EKG ausgenutzt wird.