Fetal Electrocardiography

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SINCE Cremer first recorded the fetal electrocardiogram (FECG) over fifty years ago there have been cycles of clinical interest when attempts were made to apply the technique to clinical obstetrics. In the early 1940's a number of investigators began to use the abdominally recorded FECG for the diagnosis of fetal life, presentation, and multiple pregnancy.[1-5] Diagnosis was based on the identification of the fetal R wave. Because the apparatus was inconvenient and diagnosis not always accurate, the technique was not widely used. Later investigators proposed additional uses for fetal electrocardiography; and some have believed that they could evaluate FECG baseline changes in a manner similar to the techniques employed for adult electrocardiography, and to use the tracings as indicators of fetal well-being.[6-12]

Unfortunately, assessment of the baseline of the abdominally recorded FECG is hampered by a poor signal-to-noise ratio. To minimize this disadvantage some investigators have turned to intrauterine or other types of direct electrode recording.[13-20] Electrodes of this type may be introduced transabdominally into the uterine cavity and placed against the fetus, or inserted into the fetal tissues. These techniques have the advantage that they can be used before rupture of the membranes. Another method is to introduce an electrode transcervically and place it outside the amnion, but in contact with the fetus. The most widely used type of direct electrode is made from a surgical skin clip and attached to the presenting part of the fetus after the patient is in labor, when partial dilatation is present and the membranes have been ruptured.[17, 21, 22]

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Since the techniques and problems associated with fetal electrocardiography vary with the time of gestation, it is advantageous to consider the antepartum and intrapartum periods separately, although the indirect techniques used before parturition may on occasion be used intrapartum.

Antepartum Fetal Electrocardiography

In the antepartum period, fetal electrocardiography is used primarily for the diagnosis of fetal life, fetal presentation and multiple pregnancy. The recording is made from the maternal abdominal wall with suction cup or an adhesive type of electrode which feeds a preamplifier attached to a standard adult electrocardiograph. An electroencephalograph may also be used for this purpose. With present techniques an FECG of 5 to 15 microvolts amplitude is obtained. In most instances a distinctive configuration of the FECG cannot be made out and the only portion that can be identified with certainty is the R wave. Figure 1 shows examples of tracings obtained with this technique.

While this technique is simple, nonhazardous, and relatively inexpensive the accuracy of no more than 80 to 90 per cent is a drawback for clinical use. One of the major problems is the poor signal-to-noise ratio which becomes of increasing significance if, in addition to fetal viability determination, FECG configuration studies are planned. Other related problems are the difficulty of determining the exact spatial relationship of the fetal heart to the electrodes and the nature of the transmission pathways from the fetal heart to the maternal abdominal wall.[23] If the latter do not agree with the simple volume conductor concept, it will be more difficult to determine the significance of FECG waveform changes.

In recent years, as interest has increased in fetal heart rate (FHR) in both the antepartum and intrapartum periods, attempts have been

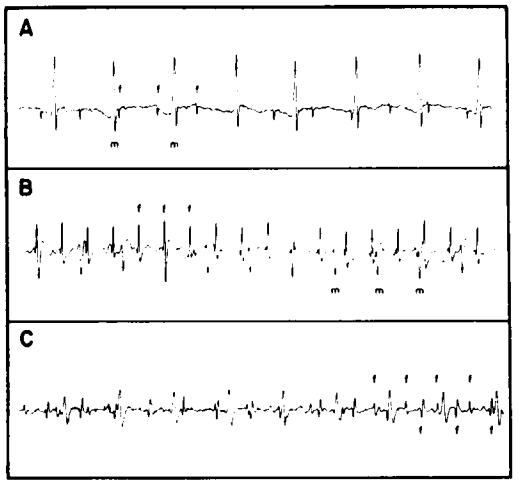

FIG. 1. *A.* Average quality FECG's recorded from the maternal abdominal wall. Maternal ECG labelled with an "m," FECG labelled with an "f." *B.* Abdominal recording of better than average quality. In this case the FECG is of equal amplitude to the maternal ECG. *C.* FECG's recorded from the maternal abdominal wall of a patient who had twins. One twin is labelled with a series of "f's" above the tracing and the other labelled in a similar manner beneath the tracing.

made to use the FECG as a trigger for a cardiotachometer in order to graph automatically the FHR. With the indirect electrodes that are presently used for fetal electrocardiography, it is necessary to attenuate or eliminate the maternal ECG from the combined maternal-fetal ECG complex. While a number of attempts [24-28] have been made to achieve this goal, none has been sufficiently successful to permit routine FHR determinations from the abdominally recorded FECG. This is primarily due to the low amplitude of the FECG and the high noise levels resulting from the electromyogram and the maternal R wave.

Intrapartum Fetal Electrocardiography

During the intrapartum period it is feasible to use electrodes directly attached to the fetus, with a marked improvement in signal-to-noise ratio. With certain types of electrodes the maternal ECG is remarkably attenuated or eliminated completely.[13-20] Earlier studies were done with silver wires passed into the amniotic sac either transcervically or through

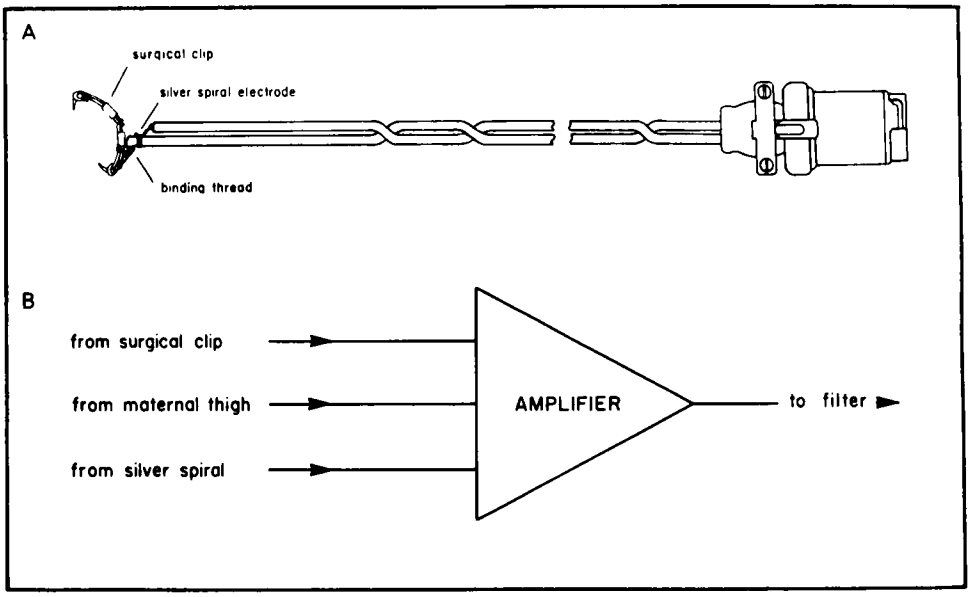

FIG. 2. *A.* Electrode for direct fetal electrocardiography. The surgical clip is attached to the presenting part of the fetus. The spiral electrode is connected to the mother through the vaginal and cervical sections. The binding thread around the connecting wire reduces the mechanical strain on the soldered joint. *B.* Block diagram of amplifier and connections. The patient's thigh is connected to the "ground" terminal on the amplifier.

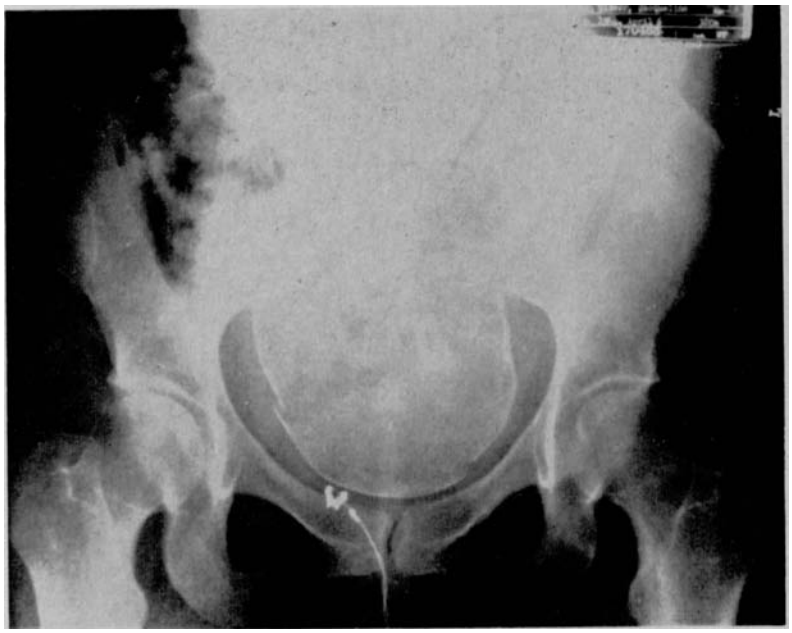

FIG. 3. Roentgen-ray photograph showing attachment of the electrode to the fetal scalp.

the maternal abdominal wall. Unfortunately, good results could not be consistently obtained throughout labor and delivery. More recently, transabdominal techniques, where a fine silver wire is inserted directly into the fetal buttocks, have been used with better success.[18] For the transcervical approach the skin clip electrode is simple and most effective.[17, 22]

Following rupture of the membranes, the electrode is attached to the fetus with a special pair of forceps introduced through the partially dilated cervix. The second electrode of the bipolar pair is a silver spiral wrapped around the insulation of the wire which connects the surgical clip to the amplifier. Figure 2*A* is a drawing of the electrode and figure 2*B* shows the connections to a high gain differential amplifier which is connected to a filter to provide a trigger for automatic counting of the FHR. The electrode is simple to use and the placing of the silver spiral electrode high in the vaginal vault where there is little skeletal muscle, eliminates almost entirely the electrical interference by the electromyogram. Figure 3 is of a roentgenogram showing a vaginal electrode attached to the fetal scalp. In this instance the fetus was being studied during a prolonged labor.

Figure 4*A* is an example of the quality of FECG tracing obtained with this type of electrode. On the relatively clean FECG baseline a small maternal R wave is seen occasionally. This is labelled with an "m." The large fetal FECG and its labelled P wave are identified easily. Figure 4*B* is a tracing of the waveform after filtering the FECG through a 30 cycle peaked filter and further conditioning the signal to provide a trigger for automatic counting of the FHR.

Many of the FECG studies being done at the present time use the FECG as a trigger for FHR determinations; and while the direct FECG vaginal electrode is a convenient way to do this, it is not always convenient or desirable to rupture membranes and apply the electrode. Attempts, therefore have been made to use the abdominally recorded FECG for this purpose. Unfortunately, in these circumstances, the lower amplitude of the FECG, the presence of the maternal ECG and interference from the electromyogram obscure the FECG a large portion of the time so that it is not possible to obtain consistently a clean FECG trigger for FHR counting. Figure 5 shows the FECG recorded with a vaginal electrode attached to the fetal scalp, and the simultaneous abdominal record made during situations where the patient is lying quietly, moving, having

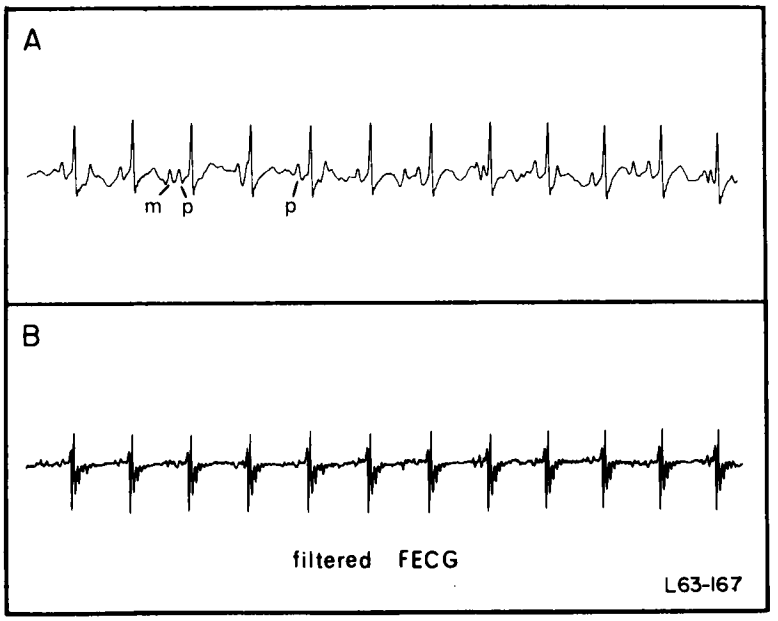

FIG. 4. *A*. FECG recorded from the fetal scalp. Maternal R waves are marked with "m." Fetal P waves marked with a "p." *B*. Filtered FECG conditioned for automatic counting of the FHR.

contractions, and bearing down with contractions. The upper trace (vaginal electrode) in each case is much cleaner than the lower trace (abdominal electrodes).

Another difficulty with the abdominally recorded FECG is the inability to detect changes in configuration with any real assurance. The tracings in figure 6 were recorded simultaneously from the maternal abdominal wall and fetal scalp, respectively. In figure 6*B* the bizarre FECG configuration associated with a premature ventricular contraction is clearly seen, whereas in the simultaneous abdominal tracing (fig. 6*A*) this alteration is less apparent.

Figure 7 shows examples of FECG configuration changes that were recorded with a direct FECG vaginal electrode and indicate that, with the resulting improvement in signal-to-noise ratio, it may be possible to evaluate FECG configuration changes. Figure 7*A* is an example of the FECG change that may be observed during compression of the umbilical cord. This tracing was made at the time of cesarean section. In figure 7*B*, widened notched R waves and prolonged P–R interval are clearly seen. This record was made from an anencephalic fetus as it approached death. The FECG of figure 7*C* was also recorded from anencephalic fetus in early labor. The small P waves are identified readily. As labor progressed and the condition of the fetus deteriorated, a fetal tachycardia developed and the P waves became high, peaked and biphasic (fig. 7*D*).

Signal Enhancement

While there is a marked improvement in the signal-to-noise ratio when direct FECG electrodes are used, even then it is not always possible to see the FECG baseline clearly. To assess this more adequately some method of signal enhancement must be used. Figure 8 shows examples of FECG's recorded from the fetal scalp where it is not possible to make out the FECG baseline clearly. In the first portion of figure 8*A*, interference from the maternal R wave makes study difficult. The second portion of figure 8*A* is a tracing of the group average of 50 consecutive FECG's. Here a large peaked fetal P wave and the remainder of the FECG can be clearly seen. Figures 8*B* and *C* are further examples of the use of group averaging techniques to improve signal-to-noise ratio.[29-30]

Figure 9 shows further examples of alterations in FECG configuration which are shown before (first section) and after group averaging of 20 complexes (second section); (i) recorded at 25 mm./second and (ii) at 50 mm./second. In each case the abnormal QRS complex is seen quite clearly. While it is occa-

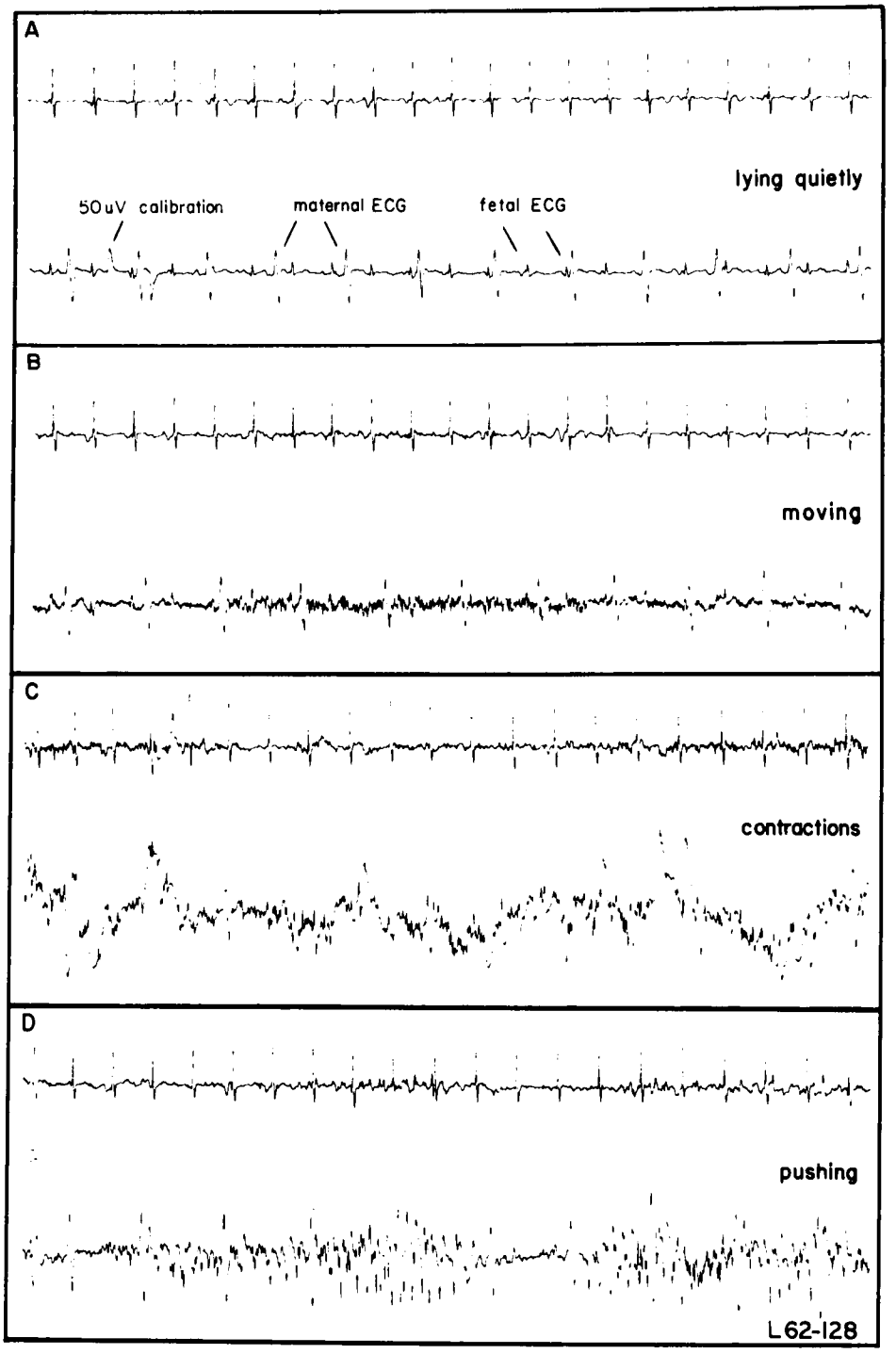

FIG. 5. *A*, *B*, *C* and *D*. Upper traces: FECG recorded with an electrode attached directly to the fetal scalp. Lower traces; simultaneous record made from the maternal abdomen during periods when the patient is lying quietly, moving, having contractions, or pushing with contractions. In the latter three instances the quality of the abdominal tracing is compromised significantly by noise. (Reprinted from Hon, E. H.: Instrumentation of fetal heart rate and fetal electrocardiography. II. A vaginal electrode, Amer. J. Obstet. Gynec. **86**: 772, 1963, with permission of the C. V. Mosby Company.)

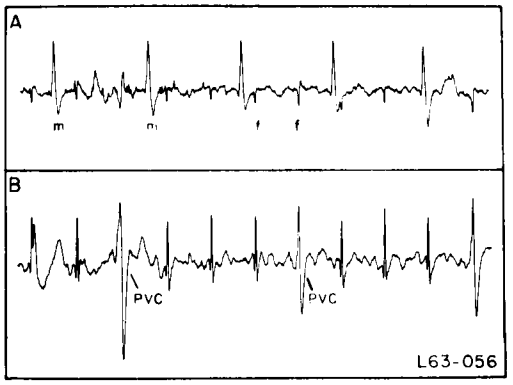

FIG. 6. *A*. Abdominally recorded FECG where PVC's can be identified with difficulty. *B*. Simultaneous FECG recording from the fetal scalp. The marked change in FECG configuration at the time of premature ventricular contractions is seen readily. This is one of the important advantages of a direct FECG electrode.

sionally difficult to identify the FECG baseline with direct FECG electrodes, employment of indirect abdominal wall electrodes makes this difficulty practically insurmountable; however, if group averaging techniques are employed, it is frequently possible to see baseline changes with clarity. Figures 10*A* (i), 10*B* (i) and 10*C* (i) are examples of FECG's recorded from the abdominal wall. Immediately to the right of each tracing is the group average of 32 complexes where the baseline details can be seen clearly. Figures 10*A* and *B* were recorded from a vertex presentation and figure 10*C* from a breech presentation.

Another method of improving the signal-to-noise ratio with the abdominally recorded FECG's is to sum the inputs from a number of pairs of separate but adjacent electrodes.[31, 32, 33] With this technique a number of FECG's are summed in parallel rather than in series, as was the case with the previous technique. Figure 11*A* is an example of an abdominally recorded FECG in which there is a moderate amount of baseline noise so that the fetal R wave (marked with an "f") is partially obscured. Figure 11*B* is a recording made from the same patient using a multielectrode technique. The marked improvement in signal-to-noise ratio is quite apparent.

Data Display

While group averaging is a useful tool and improves the signal-to-noise ratio in fetal electrocardiography, the large number of FECG's (about 9,000) which accumulate during each hour of labor, makes assessment difficult. Methods for displaying and analysing these data have therefore been developed to minimize the problem. In figure 12 two examples of group averages of FECG's are shown in a raster display which permits easy comparison. In the upper display the alterations in fetal Q–T interval can be seen clearly while in the

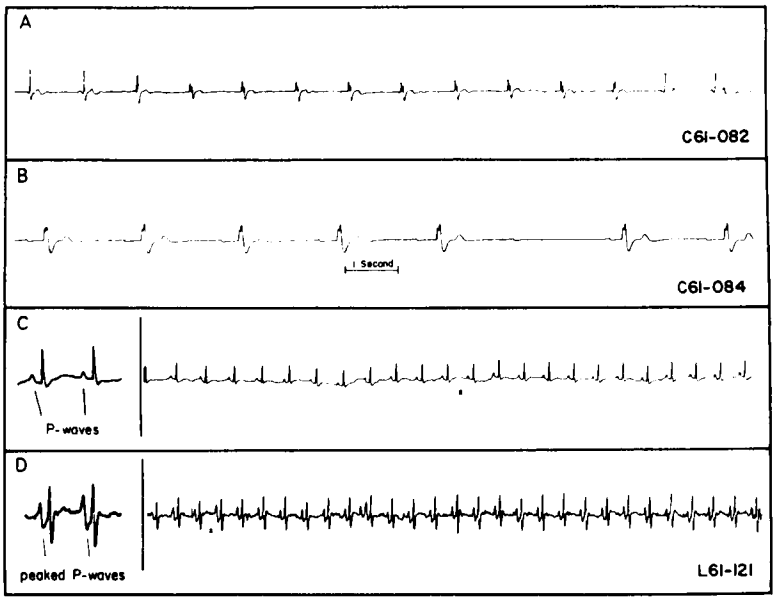

FIG. 7. *A*. Changes in FECG configuration associated with compression of the umbilical cord. *B*. Changes in FECG configuration with approaching fetal death (anencephalic). *C*. Small fetal P waves recorded during early labor. *D*. Same patient as *C* but later in labor. Note fetal tachycardia and marked change in fetal P wave.

lower presentation the alterations in the P wave configuration and duration of the P–R interval are readily identified.

While this method of display provides a convenient method of studying FECG configuration changes, it is difficult to correlate these data with other events of labor. To overcome the disadvantages of an uncorrelated FECG raster display, a more adequate display technique has been developed.[34] Figure 13 is a photograph of a section of microfilm which illustrates this technique. The uppermost channel is a BCD code which aids in localizing the data on the magnetic tape record. When used with a searching technique this provides ready access to the stored data. The remainder of the microfilm shows in descending order, a record of the fetal heart rate tracing (FHR), amniotic fluid pressure (UC) and FECG arranged in a vertical presentation. The overall system provides an efficient method of storing and retrieving data.

Conclusion

With the application of modern electronic techniques to fetal electrocardiography and the

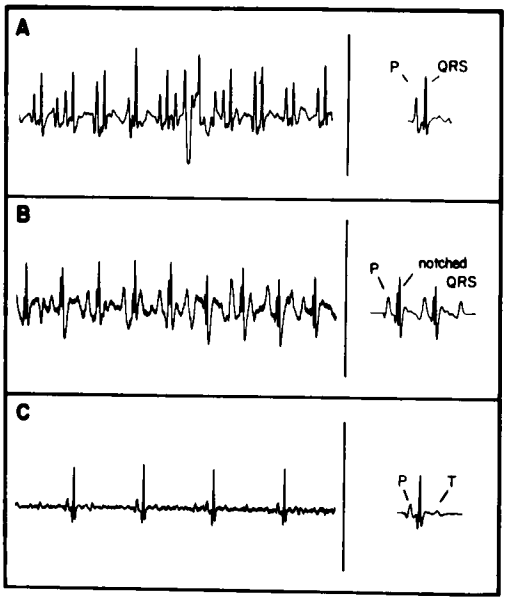

FIG. 8. *A*, *B* and *C*. The first portion of each figure shows FECG tracings made from the fetal scalp. The second portion of each figure is group average of 50 consecutive FECG complexes. Note the high degree of signal enhancement in the averaged signals.

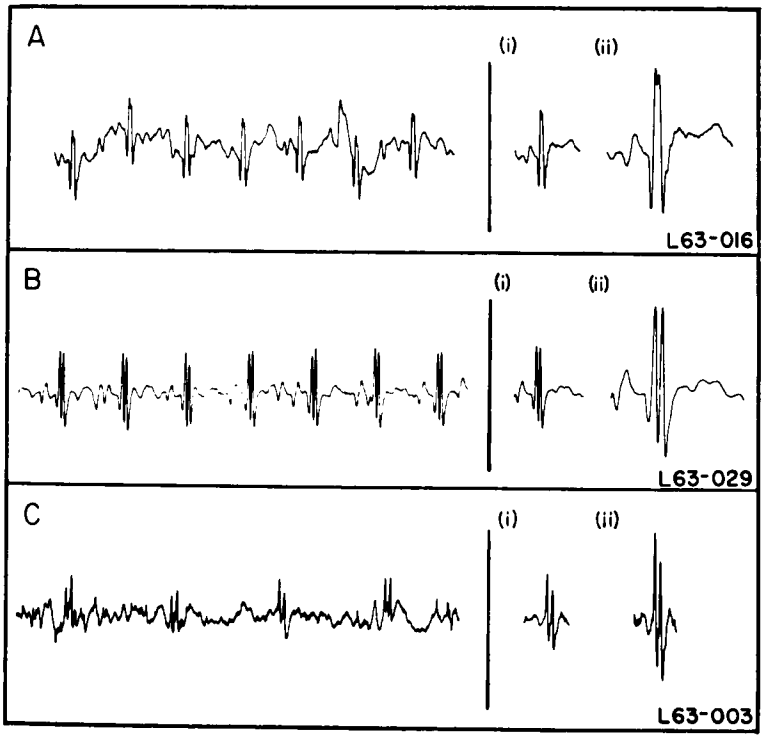

FIG. 9. *A*, *B* and *C*. First section of each tracing are FECG's recorded with a direct electrode attached to the fetal scalp. The second section is the group average of 20 complexes recorded at 25 mm. (i) and 50 mm./sec. (ii), respectively. Note the bizarre QRS complexes.

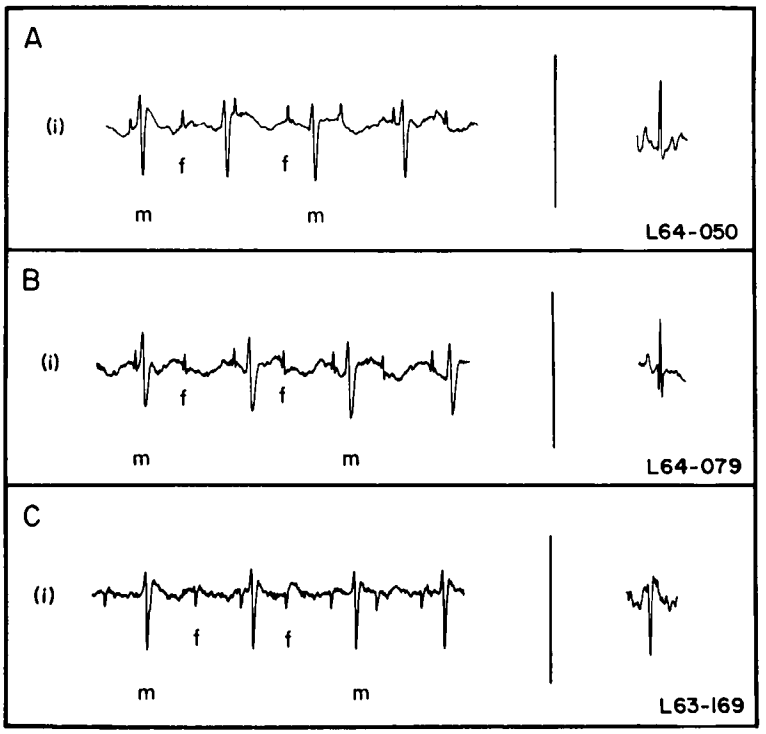

FIG. 10. *A*, *B* and *C*. The first portion of each figure show tracings of abdominally recorded FECG's. Those in *A* and *B* were recorded from the fetal scalp and that in *C* was made from the fetal buttocks. The tracings to the extreme right of each of the figure are group averages of 32 FECG complexes where the marked improvement in signal-to-noise ratio is easily seen.

resulting improvement in FECG signal-to-noise ratio, it is now possible to detect consistently FECG baseline changes with clarity. As a result the role of fetal electrocardiography in clinical obstetrics is significantly broadened. The accuracy of indirect techniques for the diagnosis of fetal life, presentation and multiple pregnancy will be improved with sum-

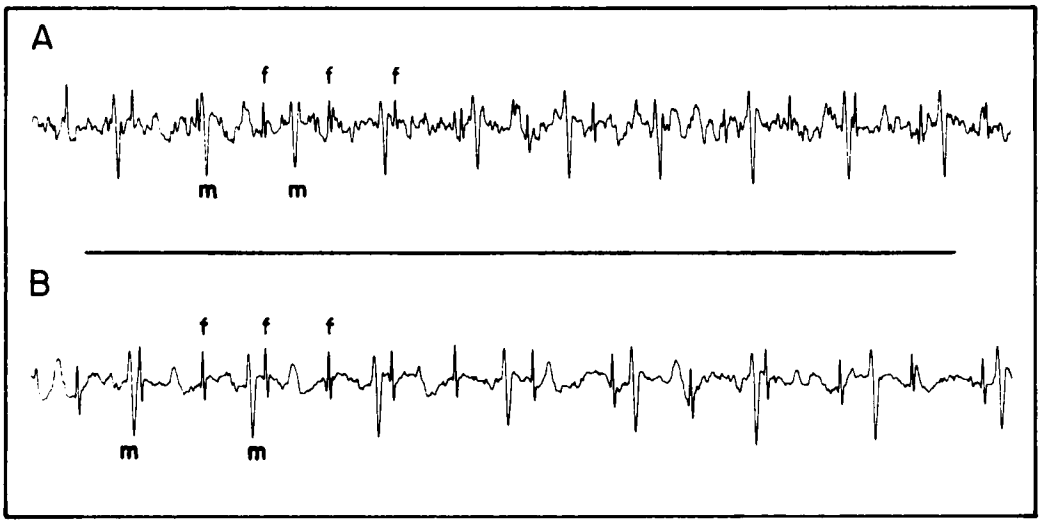

FIG. 11. *A*. FECG recorded from the maternal abdominal wall. The fetal R wave is partially obscured by baseline noise. *B*. Abdominally recorded FECG made from the same patient but using a multielectrode summing technique. The marked improvement in signal-to-noise ratio is clearly seen. FECG's are marked with an "f" and the maternal ECG with an "m."

ming techniques and the use of direct FECG electrodes alone, or with group averaging techniques. These indicate that definite FECG waveform changes are present with impending fetal death and in some complications such as diabetes mellitus, erythroblastosis fetalis and congenital heart disease. Although more extensive studies are needed, early clinical results suggest that even at this juncture the FECG is occasionally of value in managing difficult clinical cases. It seems likely, therefore, with the simplification and improvement of current signal enhancing techniques that fetal electrocardiography will become of increasing clinical value.

Summary

1. If fetal electrocardiography is confined to simple amplifier techniques and indirect electrodes, poor signal-to-noise ratio is a significant problem.

2. With direct electrodes there is a marked improvement in FECG signal-to-noise ratio and it is possible to detect with certainty unusual waveform changes.

3. Group averaging of a number of FECG's with a small digital computer remarkably improves the signal-to-noise ratio of both indirect and direct recordings.

4. Evaluation of FECG during many hours of recording can be facilitated with modern electronic data processing methods.

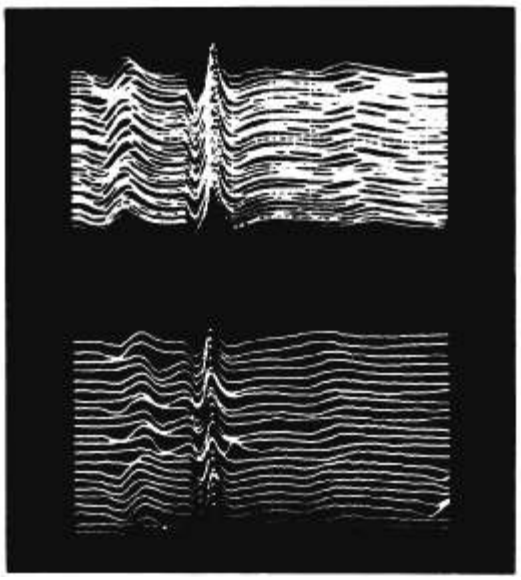

FIG. 12. Raster display of group averages of FECG's. In the upper display, the alterations in Q–T interval are clearly seen and in the lower display the alterations in the P–R interval and fetal P wave configuration changes are easily identified.

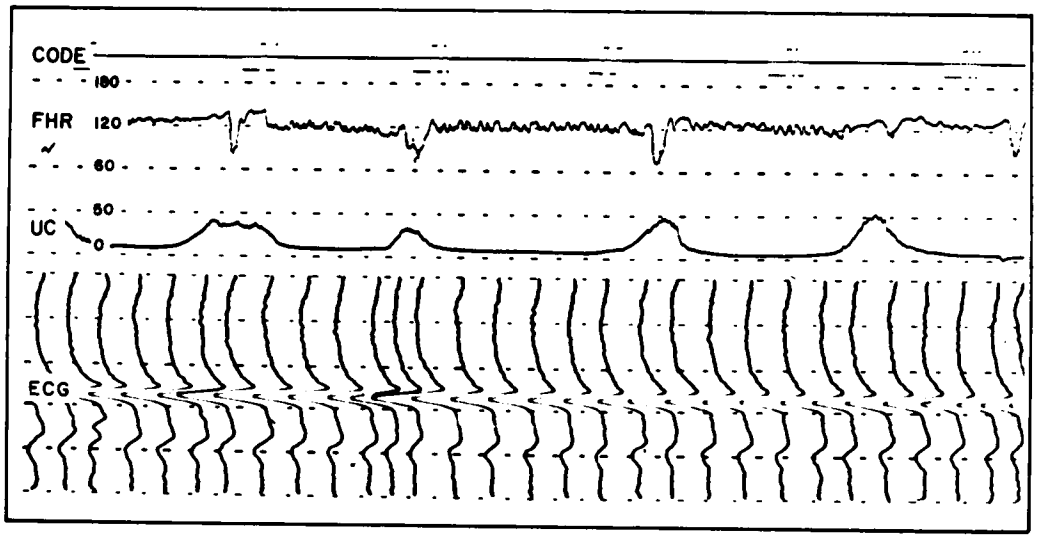

FIG. 13. Photograph made from microfilm. Code: three digit BCD code. FHR: fetal heart rate patterns. UC: amniotic fluid pressure. The FECG is presented in a vertical manner and can be more readily evaluated by rotating the figure clockwise through 90°. This type of display permits easy correlation of the data. (Reprinted from Hon, E. H., and Lee, S. T.: The fetal electrocardiogram. III. Display techniques, Amer. J. Obstet. Gynec. **91**: 56, 1965, with permission of the C. V. Mosby Company.)

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