

Central Computerized Automatic Fetal Heart Rate Diagnosis with a Rapid and Direct Alarm System

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Abstract: *Aims:* This study aimed to simplify fetal monitoring, reduce inter-observer differences and false-positive diagnosis and monitor a large number of births simultaneously. *Methods:* Fetal signals from several births were transmitted to a central computer via local area network (LAN) or telemetry and analyzed using a multichannel timesharing system. Fetal heart rate (FHR) abnormalities were detected by using three programs: the experts' knowledge system, power spectral analysis and artificial neural network. Abnormal results were automatically communicated directly to the attending doctor. Instead of an FHR chart recorder, the original fetal signals were stored on the computer and re-processed on demand. *Results:* a maximal FHR score in the first stage of labor indicated a low Apgar score, and correlated with umbilical blood pH. The fetal distress index derived from the FHR score was three or more in cases of fetal acidosis. The neural network yielded probabilities of fetal outcome that coincided with the FHR score, and the neural index derived from these probabilities predicted fetal outcome. Pathological sinusoidal FHR and severe loss of FHR variability were automatically diagnosed by power spectral analysis. Perinatal mortality was 1.1 in 1,000 births, which was significantly lower using this central computerized system than the previous system, and no cases of cerebral palsy were reported 2 months after delivery. *Conclusion:* The central computerized automated fetal monitoring system improved fetal outcomes even in institutions dealing with a large number of births.

Keywords: Fetus, FHR monitoring, Computer, Experts' Knowledge System, Neural Network, Power Spectrum, Direct Report.

INTRODUCTION

Fetal hypoxic states can be detected during intrapartum cardiotocogram (CTG) monitoring, which records fetal heart rate (FHR) and uterine contractions using external FHR meters. This method is advantageous due to its high FHR traceability and feasibility, which have led to improved perinatal outcome [1-3]. However, these favorable results were achieved by zealous observation of the intrapartum CTG, instantaneous FHR diagnosis and exclusion of false-positive results. There is also a degree of inter-observer variability in the visual recognition of FHR patterns. In addition, it is difficult to monitor individual cases in hospitals with a large number of births. These problems were expected to be solved by the introduction of quantified FHR analysis [4] and a central computerized automatic FHR monitoring system.

METHODS

Detection of FHR and Input into a Central Computer

The FHR was obtained initially by listening to the fetal heart tone. The Doppler ultrasound method was then adopted, and the fetal heart signal was processed by an autocorrelation FHR meter commonly used in external fetal monitoring. Uterine contraction signals were obtained by a

guard-ring type transducer placed on the maternal abdomen. FHR was sampled every 250 milliseconds over a 5-minute period, and averaged every 2 seconds to determine 150 FHR data: 150 uterine contraction data were obtained and stored at the same time. In the 1970s, an experts' knowledge system program was developed by Maeda using Hewlett-Packard (HP)'s technical BASIC interpreter for use on the HP 2100A minicomputer [5], and this has progressed to the modern timesharing computer used in the present study.

Central Computerized System (Fig. 1)

Continuous wave (CW) Doppler ultrasound fetal heart rate and movement signals as well as uterine contraction signals, were transmitted to a central computer via a local area network (LAN) system or radio-wave telemetry.

FHR signals obtained by the autocorrelation FHR meter and uterine contraction signals were converted from analog to digital data before input into a 100-channel timesharing computer. The data were then analyzed in fault-tolerant servers, which consisted of 4 GB working memory, three HD drives (160 GB), the CPU of the Intel Xenon processor E55505 (2.26 GHz). Microsoft Windows server 2008 Standard and two external HD drives (200 GB). There was neither a CTG recorder nor chart, instead the original signals stored in the HD were re-processed and hard-copy of CTG readings were printed from the computer on demand. The 16-channel display was able to show each CTG undergoing analysis, and the results from each 5-minute analysis period could be shown on demand.

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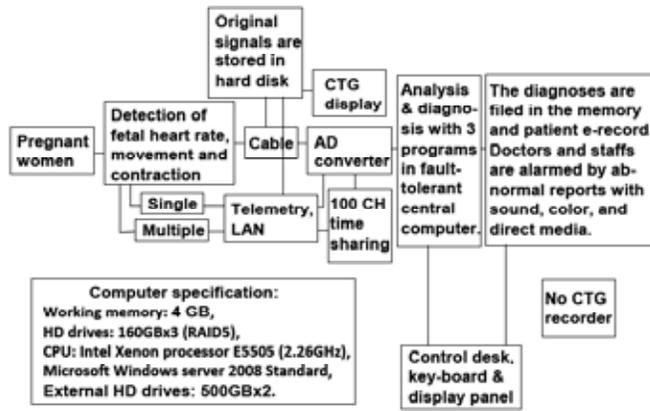


Fig. (1). The block diagram of central-computerized FHR monitoring system which enabled the monitoring of simultaneous multiple births with the time sharing input of the central computer (Maeda-TOITU, 2010).

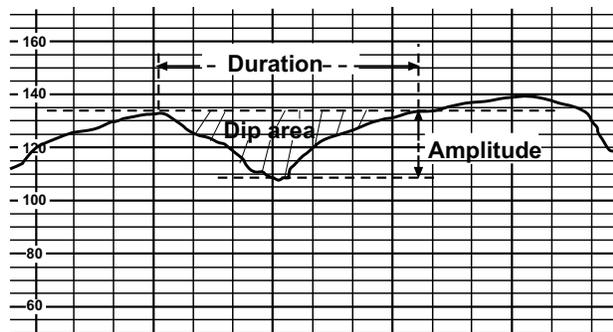


Fig. (2). DIP SHAPE value is the Dip Area ((sum of FHR amplitude) x 2) divided by (Duration (sec) x Amplitude (bpm)) which was applied to define late deceleration, early deceleration and variable deceleration.

Abnormal FHR findings were filed in the computer memory and in electronic patient records. Abnormal results were informed attending doctor immediately and automatically by means such as i-systems and mobile phones. Computer staff were also communicated with the information.

Determination of FHR Parameters

FHR Baseline

FHR data were counted in intervals of 10 beats per minute (bpm) ranging from 0 to 200 bpm. The data in the interval with the most frequent FHR data was then averaged to determine the FHR baseline.

Reference Line

Data-to-data difference in FHR were averaged (F bpm) and added to the baseline data to define the upper reference line (FHR baseline + F/2), and subtracted from the baseline data to define the lower reference line (FHR baseline - F/2).

Deceleration

A transient FHR decrease of more than 15 bpm below the lower reference line lasting longer than 15 seconds was defined as a deceleration. An FHR decrease appearing during transient tachycardia with a nadir of 110 bpm or more was not considered a deceleration but instead a transient recovery to the normal baseline.

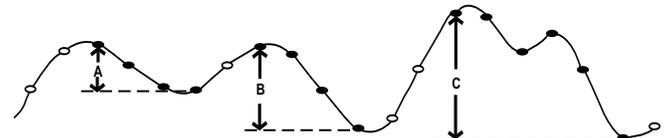


Fig. (3). Long term FHR baseline variability was defined by the mean of A, B, C, --- N. Severe loss of variability was defined by the power spectrum [8].

Late Deceleration

The DIP SHAPE value was applied to the classification of deceleration, and was calculated by dividing the dip area ((sum of the FHR data in the deceleration) x 2) by ((deceleration amplitude x duration (seconds)) (Fig. 2). A decrease in FHR was defined as late deceleration (LD) if the following four conditions were met within 15 minutes: (1) the lag time between the contraction peak and FHR nadir was longer than 20 seconds in 60 % or more decelerations: (2) the number of deceleration was more than the contraction number - 1: (3) the DIP SHAPE value was less than 0.5: and (4) the dip variability (sum of $FHR_n - FHR_{n-1}$ in the deceleration) was less than 60 bpm [5]. A decrease in FHR was defined as early deceleration (ED) if the DIP SHAPE value was less than 0.5, dip irregularity was less than 60 bpm and the lag time was almost zero.

Variable Deceleration

A decrease in FHR was defined as a variable deceleration (VD) if the DIP SHAPE was greater than 0.6 and dip variability was greater than 60 bpm [5].

Severe variable Deceleration

A variable deceleration with a nadir heart rate less than 100 bpm and duration longer than 60 seconds was defined as severe variable deceleration (SVD) [5].

Prolonged Deceleration

Deceleration lasting longer than 2 minutes was defined as prolonged deceleration [14].

Acceleration

A transient rise in FHR of 15 bpm or more above the upper reference line lasting 15 seconds or more, after 30 weeks of pregnancy, was defined as FHR acceleration [5].

Long-term Variability (LTV)

The downhill amplitude of each FHR increase above the baseline, excluding FHR acceleration, was measured (Fig. 3). The amplitude of FHR baseline variation was determined by calculating the difference between the maximum and minimum FHR values. The measurement was reset at the start of each FHR increase and the same procedure was repeated. The mean of variations (ranging from 1 to n) was defined as the LTV. When the LTV was less than 5 bpm in 20 minutes, the condition was defined as loss of variability [5]. Severe loss of variability was defined by power spectral analysis of FHR [6].

FHR Score Determination

Evaluation scores were calculated for every FHR change detected by the quantified analyses in accordance with the

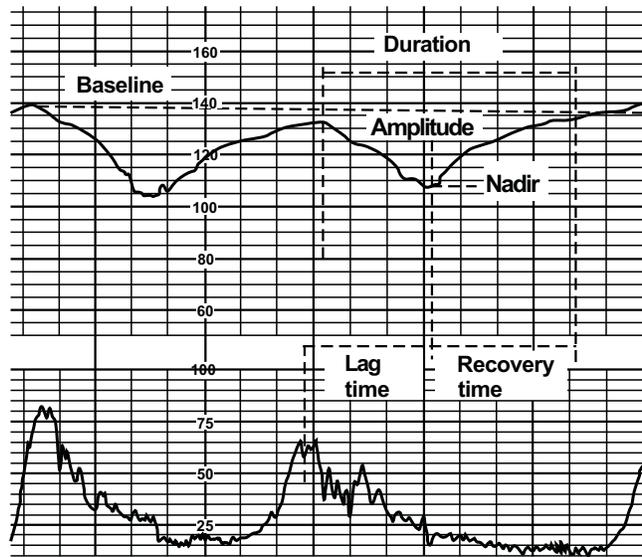


Fig. (4). Quantitative analysis of FHR changes which was utilized in various evaluations of FHR instead of visual recognition of FHR pattern. FHR score of sample deceleration was 11 due to long duration, long lag time, long recovery time and no acceleration, showing abnormal FHR score according to Table 1.

Table 1. FHR Score Calculation

Parameter	Abnormal Signs	Evaluation Score
Baseline FHR	110-130 or 160-180 bpm	1
	<110 or 180 < bpm	3
Deceleration		
Duration	> 60 seconds	3
Amplitude	> 50 bpm	2
Nadir heart rate	< 100 bpm	2
Recovery time	> 40 sec	3
Lag time	> 40 sec	3
Acceleration	No associated acceleration	2
Shape	W-shaped without variability	4

FHR SCORE; Sum of evaluation scores in 5 minutes

incidence of Apgar scores lower than 7 (Fig. 4). Changes in the baseline FHR, each deceleration parameter (duration, amplitude, nadir FHR, lag time (the time between the contraction peak and nadir FHR), recovery time (the time between nadir to the baseline FHR), acceleration and W-shaped deceleration were analyzed, and used to determine the evaluation score. The accumulated evaluation scores in all of the decelerations were used to obtain FHR score every 5 minutes (Table 1) [4, 7].

Fetal Distress Index (FDI)

One point was added the FDI if the FHR score was 10-19, there was a loss of variability, there was bradycardia (100-110 bpm lasting 10-30 minutes), there was tachycardia (>180 bpm, 30 minutes) or LD. Two points were added if the FHR score was 20 or more or if there was bradycardia (100-110 bpm lasting more than 30 minutes). Three points were

added if bradycardia was below 100 bpm. The sum of the points was defined as the FD index [6].

FHR Power Spectral Analysis

The spectrum of the FHR baseline was studied to detect sinusoidal FHR and severe loss of FHR baseline variability. The power spectrum was obtained using Fast Fourier Transform (FFT) frequency analysis of the FHR. Diagnostic parameter were the ratio of the area under the low frequency (0.03125-0.1 Hz) power spectrum to the area under the whole power spectrum (La/Ta), and peak power spectrum density (PPSD) [8,9].

Artificial Neural Network (ANN) System

The network program was added to our computer system due to its very objective nature. The ANN software is composed of three layers: the input, intermediate and output layers. Information which trained the system 10,000 times to analyze FHR using back-propagation system was consisted of eight FHR parameters (baseline FHR, variability, sinusoidal FHR, deceleration number, deceleration duration, nadir heart rate, recovery time and lag time) obtained in 20 known outcome cases in three succeeding 5 minutes. Internal check of the software was totally correct after the training. Trained software was installed onto other computers and used for the diagnosis of new cases, where the eight FHR parameters in three succeeding 5-minutes periods were entered into the software, with the output results being the probability that an outcome would be normal, intermediate or pathological. The results were objective and easily understood without education because they were reported as a percentage [7, 10, 11].

Neural Index

The neural index was obtained by subtracting the past mean probability for a pathological outcome from the past mean probability for a normal outcome every 5 minutes, and plotted [12].

RESULTS

FHR Score

The maximal FHR score in the first stage of labor correlated to the 1-minute Apgar score at delivery: an Apgar score of 6, indicating mild neonatal asphyxia, corresponded to an FHR score of 10. Apgar score of 3, indicative of severe neonatal asphyxia, corresponded to an FHR score of 20, if no intervention was performed during labor (Fig. 5) [7]. Therefore quantitative FHR analysis and the FHR score can predict fetal outcome, and interventional delivery will be indicated in cases with a high FHR score.

The maximal FHR score in the first stage of labor also correlated with the umbilical arterial blood pH and base excess at birth [7]. The second stage FHR score correlated with fetal scalp blood pH [4]. The FD index 30 minutes before delivery was three or more if there was acidosis in the umbilical arterial blood [6]. These facts show that fetal acidosis may be estimated by detailed quantitative FHR analysis.

Power Spectral Analysis

The sinusoidal FHR with an ominous outcome was diagnosed when the La/Ta ratio was larger than 39% and the

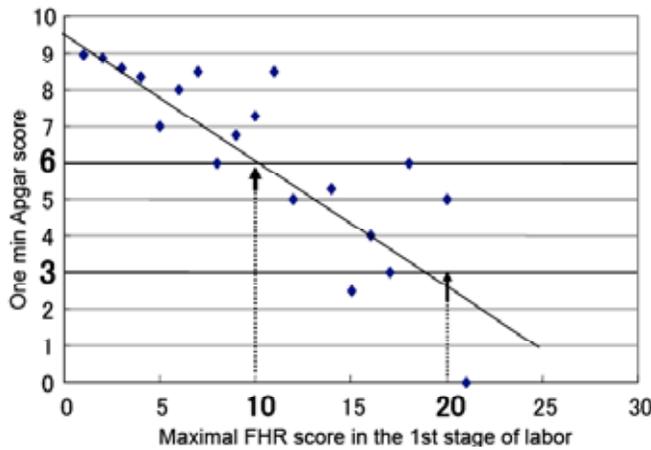


Fig. (5). Maximal FHR score in the first stage of labor correlated 1 min Apgar score, i.e. Apgar score was 6 when FHR score=10; Apgar score was 3 when FHR score was 20. Apgar score = 9.361 – FHR score x 0.351, R²=0.71, p<0.01.

PPSD was larger than 300 bpm²/Hz simultaneously, whereas false positive physiological sinusoidal FHR was diagnosed if the La/Ta ratio was less than 39% or the PPSD was less than 300bpm²/Hz even in high value of another spectrum parameter. The power spectral values were low in normal FHR tracings [8]. The La/Ta ratio was 15% or more and the PPSD was 60 bpm²/Hz or more in cases with normal resting state FHR baseline, whereas the hypoxic LD and anencephalic fetus showed lower than normal FHR baseline values. Severe loss of variability was diagnosed when both power spectral values were lower than the normal FHR [9].

Artificial Neural Network

The accuracy of neural network diagnosis was confirmed by simultaneously obtained FHR score in new cases. The FHR score was significantly higher in the group with a probability of a pathological outcome, intermediate in the group with a probability of an intermediate outcome and significantly low in the group with a probability of a normal outcome [10,11].

Neural Index

If the final neural index was higher than zero, then the fetal outcome was normal, the Apgar score was higher than 6 and the umbilical arterial blood pH was normal. If the final neural index was lower than zero, then the neonate suffered from asphyxia and acidosis. This technique was suitable to estimate fetal outcome after prolonged monitoring [12].

Automated, Immediate and Direct Reporting to the Attending Doctor

Abnormal FHR findings were reported to the attending doctor. These included bradycardia, tachycardia, sinusoidal FHR, loss of variability due to reduced LTV and severe loss of variability detected by power spectral analysis, late deceleration, prolonged deceleration, severe variable deceleration, loss of FHR acceleration, non-reactive FHR (loss of acceleration for 30 minutes), FHR score (10-19 or >19), FD index of three or more, probability of a pathological outcome (> 50%), non-reassuring fetal status (NRFS), uterine hyperactivity, noisy FHR tracings and a detached transducer

Table 2. Abnormal FHR Signs Obtained by the Computer System and Reported Attending Doctors

Discrete FHR Parameters:
Continuous bradycardia* (<110 bpm; L4) (<70 bpm; L5)
Continuous tachycardia >180 bpm and >30 min* (L3 or L4)
Loss of variability by small LTV <5 bpm and >20 min* (L4)
Severe loss of variability diagnosed by frequency spectrum* (L5)
Sinusoidal FHR diagnosed by frequency spectrum* (L5)
Late deceleration diagnosed by automatic analysis* (L4 or 5)
Prolonged deceleration >2 min* (L4 or L5)
Severe variable deceleration >1 min and nadir < 100 bpm* (L4 or 5)
Loss of acceleration (non-reactive if >30 min; L2 or 3)
Comprehensive Evaluation:
Large FHR score 10-19* (L4 or 5), >20* (L5)
Large FD index >=3* (L4 or 5)
Probability to be pathologic outcome >50 %* (L4 or 5)
Others:
Uterine hyperactivity (area under the contraction curve >70 min g/cm ² in external CTG)
Adjust probe setting (increased miss-counts)
Detached probe
Discrete FHR parameters:

L2: careful monitoring, L3: conservative therapy, L4: preparation or execution of rapid delivery, L5: rapid delivery [14].
*: Non-reassuring fetal state (NRFS)

(Table 2). The L4 severity level indicated preparation or execution of rapid delivery. The L5 severity level indicated urgent and immediate execution of rapid delivery by emergency C-section during pregnancy or in the first stage of labor, and by a forceps or vacuum extraction in the second stage of labor [13].

Clinical Improvements in the Central Computerized Fetal Monitoring

Dr. Utsu compared the clinical results obtained using the following different methods from the Seirei Mikatahara hospital: individual fetal monitoring with visual CTG analysis, central computerized monitoring with an indirect reporting system and central computerized monitoring with a direct reporting system (Table 3). Although there were insignificant differences (NS) between various statistical parameters among the three methods, there was a significant (S) decrease in the incidence of perinatal death to 1.1 in 1,000 births and no reports of cerebral palsy within 2 months after delivery using the central computerized monitoring system in which abnormal FHR results were communicated directly to the doctor. These favorable results were thought to be obtained by the shortened interval between diagnosis and interventional delivery due to the direct reporting system.

DISCUSSION

There are various risk factors in the fetus and its environment. The intrauterine fetus tends to be hypoxic because the fetal PaO₂ is lower than the maternal PaO₂, with the um-

Table 3. Clinical Results in Conventional and Central Computerized Fetal Monitoring with and Without Direct Alarm in 1994-2011 at the Seirei-Mikatahara Hospital (M. Utsu)

Clinical Results	1994-1996	1996-2009	2009-2011
	Conventional Monitoring	Central Computerized Monitoring	
		Without Direct Alarm	Direct Alarm
N of births	1,280	10,346	1,767
N of maternal deaths*	0	2#	0
Apgar score <7 (N)* (%)	49 3.8	505 4.9	88 4.9
Perinatal deaths (N) (/1,000 births)	9 7.0	55** 5.3	2** 1.1
Cerebral palsy (N)* (/1,000 births)	1 0.8	10 1.0	0 0

*Non-significant difference, **Significant difference, N; Number, # 1 cancer and 1 sarcoma

bilical PaO₂ usually measuring less than 50 mmHg [4] even in normal cases due to oxygenation through the placental villous chorionic membrane. Fetal PaO₂ levels depend on the maternal PaO₂ level, which can be reduced due to maternal shock, anemia, maternal placental flow reduction in supine hypotensive syndrome, iliac artery compression or hyperactive uterine contractions. If the placenta is damaged it may lose its gas-exchange function as seen in maternal pregnancy induced hypertension (PIH), developed fibrin deposit in intervillous space as seen in fetal growth restriction (FGR) [14] or result in sudden placental abruption. In particular, fetal hypoxia can be a consequence of fetal anemia during fetomaternal transfusion, fetal hemolytic disease, some viral infections and congenital hemoglobin diseases. Furthermore, fetal blood flow in the umbilical cord vessels tends to be interrupted not only in the prolapsed cord but also in various occasions. Unfortunately, fetal hypoxia can damage multiple fetal organs, in particular fetal central nervous system, which can cause hypoxic-ischemic encephalopathy and its sequelae.

Therefore, the purpose of fetal monitoring during pregnancy and labor is to detect fetal hypoxia in its early stages and to protect the fetus from its effects through intervention.

All pregnant and parturient women should be monitored, even in cases that appear normal, because hypoxia can occur unexpectedly in normal cases as well as in cases of PIH, FGR, fetal and maternal abnormalities. Full intrapartum monitoring during the entire delivery would be ideal, particularly since abnormal conditions due to uterine contractions, the cervical dilatation, rupture of membrane, fetal descent and expulsion.

Although traditional fetal monitoring with visual diagnosis of the intrapartum CTG has resulted in favorable outcomes, full monitoring of all deliveries can only be achieved if easier, more detailed and reliable fetal monitoring techniques are available. Many simultaneous births occur in large obstetric institutions: more than 30 cases can deliver at the same time in a hospital with 10,000 annual births. In these cases, there may be insufficient numbers of FHR monitoring experts available to fully monitor all cases. A central computerized automated FHR monitoring system is capable of

supporting a large number of births with 100 channel time-sharing system, and the direct and rapid abnormality reporting system can shorten the interval between diagnosis and a rapid delivery.

The detection of fetal signals using the Doppler ultrasound method is reliable for antepartum diagnosis. The same method can also be used for intrapartum monitoring to ensure a smooth transition from pregnancy to labor. The CW ultrasound intensity is weak enough at SATP 1 mW/cm² to satisfy safety requirement, even for prolonged monitoring. The central computer was prepared for possible disturbances with a fault-tolerant server. The three analysis systems supported each other and did not overlook any hypoxic abnormality, as seen in Table 2. False-positive FHR changes were rejected from the table. These included cases of non-hypoxic variable deceleration, early deceleration, resting fetal state. FHR decrease to baseline in transient tachycardia and benign physiological sinusoidal FHR.

Since a sudden change from normal FHR to bradycardia below 70 bpm, caused by obstructed umbilical cord vessels or placental abruption, frequently results in fetal brain damage, its occurrence is communicated rapidly, automatically and directly to the attending doctor even in the first five minutes of monitoring to indicate an emergency C-section. Continuous bradycardia caused by atrio-ventricular block or sick sinus that does not need an emergency C-section should be diagnosed before the onset of labor using ultrasonic M-mode for the atrio-ventricular block, and an actocardiogram to determine the FHR rise associated with fetal movement bursts for the sick sinus [15].

CONCLUSION

The central computerized automated FHR analysis and diagnosis system was effective in improving fetal outcomes. Perinatal mortality was significantly reduced to 1.1 in 1,000 births, and no CP was noted 2 months after delivery. This direct reporting system contributed to the favorable results when compared to the central computerized system using a conventional indirect reporting system. The experts' knowledge system, power spectral analysis and artificial neural network system incorporated into the computer correctly

diagnosed FHR abnormalities without the need to visually diagnose FHR patterns. A large number of deliveries were able to be monitored as the computer input was composed of a 100 channel timesharing system.

CONFLICT OF INTEREST

None declared.

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None declared.

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