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Quantification of fetal heart rate variability by abdominal electrocardiography

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1 Introduction

As fetal electronic monitoring has become a routine practice in modern obstetric units, rapid and accurate interpretation of the cardiotocograph tracings has become important. Decreased fetal heart rate (FHR) variability is the most constant finding observed in severe fetal distress in the ante partum period. An experienced obstetrician, if acquainted with electronic monitoring, can recognize the silent pattern predicting imminent fetal death. Whether there is a gradual diminution of FHR variability in correlation with hypoxia from normal to silent pattern is not known.

Quantification of less severe changes in the variability by visual inspection of the cardiotocograph tracings is problematic, even when electrocardiography is used for processing [5]. Computer methods for quantification of FHR variability from direct fetal electrocardiography (FECG) [1, 2] and fetal magnetocardiography (FMCG) [4] have been presented. These methods are based on statistical analysis of the sequential intervals measured from fetal electric or magnetic QRS complexes. Since fetal magnetocardiography is not yet generally applicable clinically, there has been no accurate method available for ante partum use.

This paper presents a computer system for the statistical analysis of fetal QRS intervals measured from abdominal FECG.

Curriculum vitae

VEIKKO KARINIEMI was born 1937 in Lapland. He graduated 1965 from the Medical Faculty of Helsinki University and was the resident of the Department I of Gynecology and Obstetrics of Helsinki University Central Hospital 1969–1972 (Head: Prof. SAKARI TIMONEN). Since 1973 he has been a senior consultant of the Midwifery Hospital of Helsinki and of the Departments of Gynecology and Obstetrics of Helsinki University Central Hospital. Main topics of research have been fetal electro- and magnetocardiography. Thesis Helsinki University 1978: Quantification of fetal heart rate variability by electro- and magnetocardiography.



2 Patients and methods

In order to compare the variability indices obtained by abdominal FECG with those obtained by direct FECG, both indices were calculated simultaneously from four fetuses during labor. A HEWLETT-PACKARD (HP) 8030 A cardiotocograph was used as an amplifier for the abdominal FECG and an HP 8020 cardiotocograph for the direct FECG. Both signals were also recorded simultaneously on magnetic tape (Instrumentation recorder HP 3960).

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3 Processing the signals

The block diagram for the QRS interval analysis system is shown in Fig. 1. A console printer is

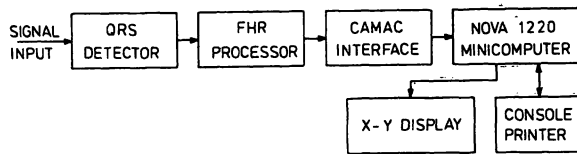


Fig. 1. Block diagram of the fetal QRS interval analysis system. The incoming signal is the FECG amplified by a cardiograph and reproduced from magnetic tape.

used to operate the system. From the console the operator can select e.g. the measurement time and store intervals on cassette tape if necessary. The signal to be analyzed is fed into the QRS detector, the output of which is connected to the FHR processor [3]. The FHR processor calculates the QRS interval lengths in digital form (in units of 0.5 ms, accuracy $\pm 0.6\%$). Both the detector and the processor contain logic for selecting correct fetal QRS intervals for the analysis. When an interval has been calculated and accepted it is triggered into a digital input register which is a standard module in the CAMAC interface. A NOVA 2 minicomputer reads the contents of the register into its memory. It also calculates the corresponding heart rate and appends it to the FHR pattern which is shown on the x-y display unit.

In order to be able to choose only the successive intervals for statistical calculations, a CAMAC clock module is used. If the time that has elapsed from the previous trigger pulse is equal to the interval length, the intervals are successive. When the abdominal FECG is analyzed, some of the intervals are nonsuccessive although they are probably of fetal origin, because two or more fetal intervals between them are lost in the rejection of the maternal QRS complexes. However, statistical calculations are possible, if nonsuccessive intervals are rejected. The NOVA program calculates two parameters of variation, the interval index (II) and differential index (DI) [6]. For definition of the indices, see the Appendix.

The analysis program also contains logic for rejection of the erroneous intervals that are not found by the detector and the processor. The maximum difference of successive intervals can

be selected manually by a keyboard command. In the analyses performed here, the maximum difference accepted was 5 bpm. After the analysis the FHR pattern on the x-y display is revised to the intervals which were used for calculating II and DI. From this improved FHR curve the operator can check the validity of the calculated parameters. Finally, the console printer prints out the number of intervals used (N_I), the number of differences used (N_D) and the variability indices II and DI.

4 Results

189 statistical analyses from four unselected fetuses in labor were performed. The sample time varied from 60 to 180 seconds. The percentage of the successive intervals was $97 \pm 2\%$ in direct FECG and $67 \pm 3\%$ in abdominal FECG.

The II and DI, calculated from 60-second samples of direct and abdominal FECGs during 14 minutes of a patient's labor, are shown in Fig. 2.

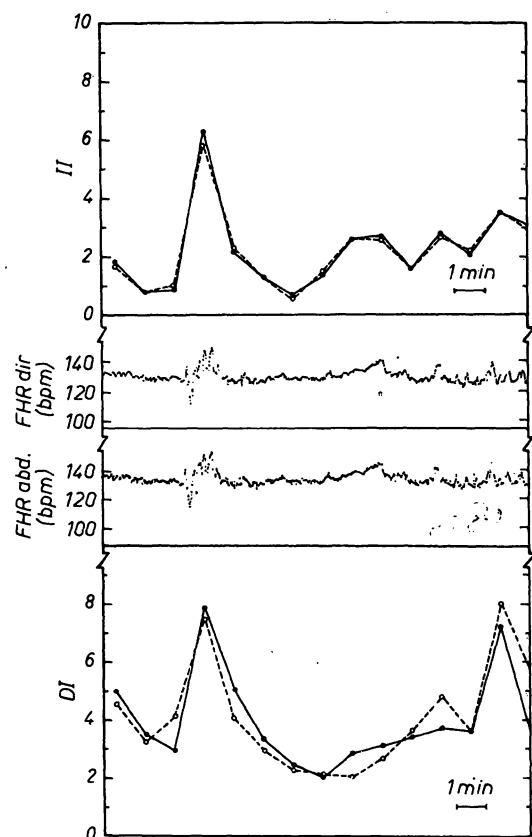


Fig. 2. Interval index (II, upper diagram) and differential index (DI, lower diagram), computed from simultaneously recorded 60 sec. samples of direct FECG (upper FHR trace) and abdominal FECG (lower FHR trace) (— = direct FECG, - - - = abdominal FECG)

The correlation between abdominal and direct FECG in the calculation of II and DI from 37 samples of simultaneous recordings during another labor is presented in Fig. 3.

The correlation analysis for four labors are presented in Tab. I.

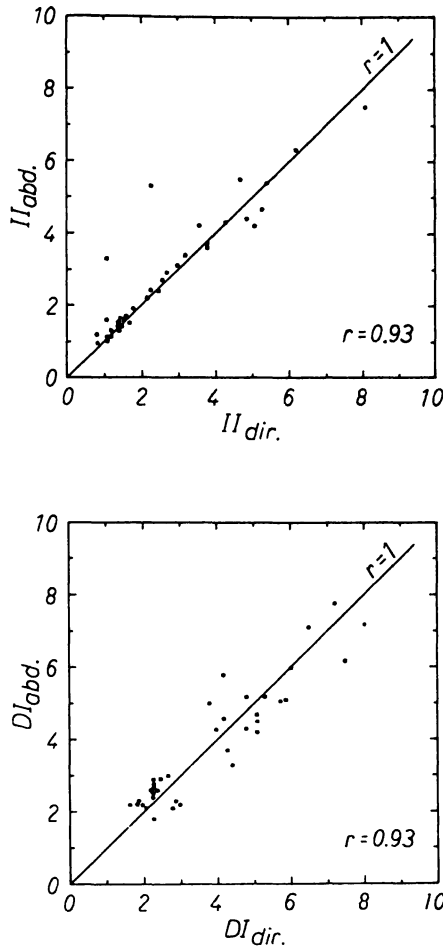


Fig. 3. Correlation between the variability indices (II = interval index, DI = differential index) computed from simultaneously recorded direct (dir.) and abdominal (abd.) FECG during labor.

5 Discussion

The correlation between the statistical indices measuring the long- and short-term variabilities, computed from abdominal and direct FECGs, is good and linear, somewhat better for II or long-term variability ($r = 0.95 \pm 0.02$) than for DI or the short-term variability ($r = 0.83 \pm 0.08$). The correlation coefficients are essentially better for the abdominal interval analysis than for the visual semiquantitative evaluation of the cardiotocograms recorded by direct FECG [5]. Estimation of the long-term variability is easier than that of the short-term variability by both methods. It is to be noted that a reliable statistical analysis is achieved, although a considerable number of fetal intervals ($\approx 33\%$) is lost due to overlapping maternal QRS complexes.

A perfect correlation between the abdominal and direct methods would show $r = 1$, y-intercept = 0 and slope = 1. Linear regression of the calculated data suggests that it would be beneficial to use a correction formula,

$$DI_{true} = 0.9 \times DI_{abd} - 1 \quad [1]$$

to find a better approximation of the true index DI_{true} (obtained by direct FECG). The material of calculations presented is, however, too small to be a basis for optimal corrections. The need for corrections may depend on the equipment used for the analyses. A considerable number of analyses (one in five) was found unusable mainly because of a noisy signal. These analyses were omitted by visual monitoring of the x-y display in the CAMAC crate. The main source of error in the indices

Tab. I. Correlation of direct and abdominal FECG in the QRS interval analysis of FHR variability for four patients in labor. (r = correlation coefficient, II = interval index, DI = differential index)

Patient	Total number of analyses	Percentage of usable analyses	r		y-intercept		slope	
			II	DI	II	DI	II	DI
1.	64	74	0.95	0.80	-0.11	0.74	1.00	0.84
2.	47	81	0.93	0.93	0.39	0.55	0.90	0.86
3.	42	81	0.94	0.84	0.10	0.87	1.02	0.96
4.	33	70	0.97	0.74	0.02	1.95	1.04	0.87
mean		77	0.95	0.83	0.10	1.03	0.99	0.88
S.D.		5	0.02	0.08	0.21	0.63	0.06	0.05

accepted was the noise present in the abdominal FECG. The FHR tracings obtained by abdominal-FECG from these four fetuses were of fairly good quality except in patient 4 who had a higher noise level. Consequently, this patient had a higher y-intercept than the others. Most of the errors produced by the noise were rejected by the logic limits in the QRS detector, FHR processor and the analysis program. The maximum interval difference limit accepted in the program was 5 bpm in these calculations. In our experience, using this limit only a negligible number of true intervals is lost.

The variability indices, especially DI, tend to become too high when calculated from a noisy signal. Consequently, the noisy signal creates a problem of false negative results, since good variability is a sign of a well functioning fetal autonomous nervous system. There seems to be no problem of false positive, i.e., artificially low indices when this system is used in assessing the fetal condition. There have been doubts about the usefulness of the abdominal FECG. With the aid of the modern microprocessor technology it is possible to construct a small size, portable equipment to be used on line with a cardioclograph.

6 Appendix

Definitions of the statistical parameters used in the text:

Summary

A silent pattern of a cardioclogram is a visually recognizable marker of imminent fetal death. Visual evaluation of less marked changes in the fetal heart rate (FHR) variability is more problematic [5]. Statistical quantification of the FHR variability during pregnancy has succeeded previously with the aid of fetal magnetocardiography [4]. Since fetal magnetocardiography is not yet clinically applicable, this paper presents a method for quantification of the FHR variability from abdominal fetal electrocardiography (FECG). This minicomputer-based QRS interval analysis system calculates the interval index (II) measuring the long term variability of FHR from all accepted intervals and the differential index (DI) measuring the short term (beat-to-beat) variability of the FHR utilizing only successive fetal intervals and their differences.

The signal to be analyzed, the abdominal FECG, is fed into a QRS detector, the output of which is connected

Interval index (II) is the standard deviation of the fetal heart beat-to-beat intervals I_i , in percentage of the mean interval \bar{I} ,

$$II = 100 \cdot \bar{I}^{-1} \sqrt{\sum_i \frac{(I_i - \bar{I})^2}{N_I - 1}}, \quad (A1)$$

where N_I is the total number of intervals accepted. The II describes the long term variation only, the sequential order of the intervals does not influence this parameter.

Differential index (DI) is defined with the aid of relative interval differences D_i (of a pair of successive intervals I_i and I_{i+1}),

$$D_i = \frac{I_{i+1} - I_i}{I_{i+1} + I_i}, \quad (A2)$$

as a standard deviation of the relative interval differences, given in per mil,

$$DI = 1000 \sqrt{\sum_i \frac{(D_i - \bar{D})^2}{N_D - 1}}, \quad (A3)$$

where \bar{D} is the average D_i and N_D is the number of pairs of successive intervals (number of D_i 's). Hence the DI describes only the scatter of subsequent interval lengths.

The original proposal for the indices presented above was made by YEH et al. [6] The scaling factors, 100 and 1000, were used to reach indices with practical values between about 1 and 10.

to a FHR processor (Fig. 1). The accepted interval is triggered into a digital input register, the contents of which again are read into the memory of a minicomputer. A clock module of the interface is used to choose only the successive intervals in calculation of the DI. The console printer prints out the number of intervals used, the number of differences used, and the indices of variability.

The validity of the variability indices computed from the abdominal FECG was verified by comparing them with indices computed from the simultaneously recorded direct FECG for four fetuses during labor. The percentage of successive intervals was $67 \pm 3\%$ in the abdominal FECG and $97 \pm 2\%$ in the direct FECG. Hence the results calculated from the direct FECG can be used as reliable estimates of the true values.

The II and DI, calculated from 60-second samples of both direct and abdominal FECGs, during 14 minutes of a

patient's labor are shown in Fig. 2. The correlation between abdominal and direct FECG in the calculation of II and DI from 37 samples of simultaneous recordings during another labor is presented in Fig. 3. The correlation analyses for four labors are presented in Tab. I. The correlation coefficients for these two methods were 0.95 ± 0.02 for II and 0.83 ± 0.08 for DI. It is concluded,

that the abdominal FECG can be used for quantification of FHR variability if suitable data processing system is available. In clinical use, the method presented is the only practical so far. With the aid of modern microprocessor technology it is possible to construct a small-size, portable equipment to be used on line with a cardiotocograph.

Keywords: Computers, electrocardiography, fetal heart, heart rate.

Zusammenfassung

Quantitätsbestimmung der Variabilität der fetalen Herzfrequenz durch abdominale Elektrokardiographie

Ein silentes Muster eines Kardiotokogramms ist ein sichtbares Zeichen eines drohenden fetalen Todes. Die visuelle Auswertung weniger deutlicher Veränderungen der Variabilität der fetalen Herzfrequenz ist problematisch [5]. Eine statistische Quantitätsbestimmung der Variabilität der fetalen Herzfrequenz während der Schwangerschaft gelang mit Hilfe der fetalen Magnetokardiographie [4]. Da diese Methode klinisch noch nicht anwendbar ist, wird in dieser Arbeit eine Methode vorgestellt zur Quantitätsbestimmung der Variabilität der FHR durch abdominale fetale Elektrokardiographie (FECG). Dieses auf einem Minicomputer basierende QRS-Intervall-Analyse-System berechnet den Intervallindex (II), der die Langzeit-Variabilität der FHR von allen gemessenen Intervallen darstellt, und den Differentialindex (DI), der die Kurzzeitvariabilität (Schlag-zu-Schlag) der FHR darstellt und nur die aufeinanderfolgenden fetalen Intervalle und ihre Differenzen benutzt.

Das Signal, das analysiert wird, das abdominale FECG, wird in einen QRS-Detektor gegeben, dessen Ausgang mit einem FHR-Prozessor (Fig. 1) verbunden wird. Das gemessene Intervall löst ein digitales Input-Register aus, dessen Inhalt in die Speicherung des Minicomputers gelesen wird. Eine modulierende Uhr des Interface wird benutzt, um nur die aufeinanderfolgenden Intervalle zur Berechnung des DI zu wählen. Der Konsolenschreiber zeichnet die Zahl der benutzten Intervalle auf, weiter die

Zahl der gebrauchten Differenzen und die Variabilitäts-Indices.

Die Zuverlässigkeit der aus dem abdominalen FECG errechneten Variabilitäts-Indices wurde durch einen Vergleich mit denjenigen Indices bestätigt, die man bei gleichzeitiger Registrierung aus dem direkten FECG ermittelte (4 Fälle sub partu). Der Prozentsatz aufeinanderfolgender Intervalle war $67 \pm 3\%$ im abdominalen und $97 \pm 2\%$ im direkten FECG. Die berechneten Ergebnisse können daher als zuverlässige Schätzungen der wahren Werte angesehen werden.

Der II und DI – berechnet nach 60-Sekunden-Proben von direktem und abdominalem FECG – werden während 14 Minuten einer Geburt in Fig. 2 gezeigt. Die Korrelation zwischen abdominalem und direktem FECG in der Berechnung von DI und II wird bei 37 Beispielen von simultanen Aufzeichnungen während einer anderen Geburt in Fig. 3 dargestellt.

Die Korrelationskoeffizienten waren $0,95 \pm 0,02$ für II und $0,83 \pm 0,08$ für DI. Daraus wird gefolgert, daß das abdominale FECG zur Quantitätsbestimmung der FHR-Variabilität verwandt werden kann, wenn ein geeignetes Datenverarbeitungssystem verfügbar ist. Im klinischen Gebrauch ist diese Methode die einzige, die praktisch verwandt werden kann. Mit Hilfe der modernen Mikroprozessor-Technik ist es möglich, ein kleines tragbares Gerät zu konstruieren, das On-Line mit einem Kardiotokograph benutzt werden kann.

Schlüsselwörter: Computer, Elektrokardiographie, Herzfrequenz (fetale).

Résumé

Quantification de la variabilité du rythme du coeur foetal par électrocardiographie abdominale.

Un cardiotocogramme plat est un indicateur d'imminence de mort foetale reconnaissable visuellement. Cette reconnaissance est plus aléatoire lorsque les modifications sont moins marquées [5]. La quantification statistique de la variabilité du rythme cardiaque foetal pendant la grossesse a pu être réalisée par magnéto-cardiographie foetale [4]. Cette technique n'étant pas encore disponible cliniquement, on présente ici une méthode applicable à l'électrocardiogramme foetal abdominal.

Il s'agit d'un système de mini-ordinateur qui à partir de la détection des intervalles entre les complexes QRS successifs calcule l'indice d'intervalle (II) qui mesure la variabilité

dite à long terme, concernant tous les intervalles acceptés, et l'indice différentiel (DI) qui mesure la variabilité à court terme (de battement à battement) concernant uniquement des intervalles consécutifs.

Le signal électrocardiographique est introduit dans un détecteur de QRS, dont la sortie est reliée au calculateur (Fig. 1). L'intervalle accepté est dirigé vers un registre à entrée numérique, dont le contenu est lu dans la mémoire d'un mini-ordinateur. Un module de temps permet de choisir seulement les intervalles consécutifs pour le calcul de DI. L'imprimante fournit le nombre d'intervalles consécutifs pour le calcul de DI. L'imprimante fournit le nombre d'intervalles utilisés, le nombre de différences et les indices de variabilité. La validité de ceux-ci a été vérifiée

par comparaison avec des indices calculés à partir d'enregistrements cardiographiques foetaux directs, réalisés pendant le travail, dans 4 cas.

Le pourcentage d'intervalles consécutifs fut $67 \pm 3\%$ pour l'ecg abdominal et $97 \pm 2\%$ pour l'ecg direct.

Les résultats obtenus à partir de l'ecg direct peuvent donc être considérés comme représentatifs des valeurs exactes.

Les indices DI et II, calculés à partir d'échantillons de 60 secondes d'enregistrements directs et abdominaux pendant 14 minutes d'un travail sont montrés sur la figure 2. La corrélation entre les calculs de DI et II, sur enregistrements

directs et abdominaux simultanés de 37 échantillons dans un autre cas, est représentée sur la fig. 3.

Les coefficients de corrélation furent $0,95 \pm 0,02$ pour II et $0,83 \pm 0,08$ pour DI. L'électrocardiogramme abdominal peut donc être utilisée pour la quantification de la variabilité à condition d'utiliser un système de traitement adéquat. C'est la seule méthode utilisable jusqu'à présent en clinique. Grâce au développement des microprocesseurs modernes on peut construire un équipement plus encombrant, portatif, adaptable en temps réel au cardiogramme.

Mots-clés: Coeur foetal, électrocardiographie, ordinateur, rythme cardiaque.

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