PhD Thesis

COMPUTER RESEARCH METHODS IN THE ANTE- AND INTRAPARTUM CARDIOTOCOGRAPHY

Antepartum computer monitoring of twin pregnancies and data structure analysis of beat-to-beat cardiotocographic records

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PAPERS AND LECTURES RELATED TO THE THESIS

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ABBREVIATIONS

2D	two-dimensional
Ac	accelerations
A/D	analogue/digital
API	application programming interface
ASCII	american standard code for information interchange
AT	the third generation of IBM standard computers
B	byte
BHR	basal heart rate
BL	baseline
bpm	beats per minute
CD	compact disk
cm^2	square centimetre
CPU	central processing unit
CTG	cardiotocography
D/A	digital/analogue
DIO	digital input output
DLL	dynamic link library
DMA	direct memory access
DOS	disk operating system
DX	referring to 32-bit processor
ECG	electrocardiography
FDD	floppy disk drive
FECG	fetal electrocardiography
FHR	fetal heart rate
FHRV	fetal heart rate variability
FM	fetal movement(s)
HDD	hard disk drive
Hz	Hertz
IBM	International Business Machines Corporation
IUGR	intrauterine growth retardation
K	kilo
LCD	liquid crystal display
M	mega
m	mili
μ	micro
MASM	macro assembler
MECG	maternal electrocardiography
MS	Microsoft
PC	personal computer, and the name of first generation of IBM standard computer
RAM	random-access memory
s	second
STV	short-term variation
SVGA	super video graphics array
ULT	ultrasound
V	Volt
Vo	variation overall
W	Watt
WHO	World Health Organization

THE STRUCTURE OF THE THESIS

The present thesis is comprised of work related to two principal topics. These are:

I A method of the prenatal computer CTG monitoring of twin pregnancies

II A method of obtaining strictly continuous and highly precise beat-to-beat FHR data suitable for spectral and chaos theory analysis

The main aim was to establish the hardware and measuring technique basis of two future research projects, namely:

I CTG parameters of the intrauterine well-being and behaviour-physiology of twin fetuses

II Study of the fetal heart rate using spectral and chaos theory analysis

As regards the main aim both items, especially the latter, involve studies which are mainly methodological. Because of the relatively high number of studies (some seeming disparate) the thesis structure had to be slightly modified.

Chapter 1 Introduction: the rationale of the study objectives and a brief account of spectral analysis and nonlinear dynamics theory.

Chapter 2 Objectives: the initial study plan.

Chapter 3 Research tools: the list and description of the commercially available and self-developed hardware and software products used. The description is more detailed when the role of the given device or program was crucial to a study.

Chapter 4 Methods: the description is divided into two parts corresponding to the main topics I and II.

Chapter 5 Studies and results: this format was chosen to allow an easier overview. The sequence of the study description attempted to adhere to a linear process of logical thinking. It is divided into two parts, corresponding to the main topics I and II.

Chapter 6 Discussion and conclusions: the most important results from the viewpoint of theory and practice are evaluated. Afterwards future research plans and perspectives in the light of the current state-of-art are discussed.

Chapter 7 New findings and results: a brief summary that is divided into two parts, corresponding to the main topic-items I and II.

1 INTRODUCTION

In its constitution the WHO declares [1]:

"Health is a state of complete physical and social well being, and not merely the absence of disease or infirmity" and "The enjoyment of the highest attainable standards of health is one of the fundamental rights of every human being without distinction of race, religion, political belief, economic or social condition."

With the above in mind the primary objective of perinatology is to ensure a state of health to human beings according to the constitution of WHO in the fetal, intrapartum and postnatal period of life. Perinatal mortality in itself can no longer be the measure of success, but only morbidity and the "quality" of growing-up generations can establish standards to strive after.

Intrapartum asphyxia is a common cause of neonatal morbidity and mortality. Intrapartum hypoxia may occur in any pregnancy, but is more common in cases at high risk. In a study of 91 children with newborn encephalopathy [2] intrapartum fetal hypoxia accounted for 12 % of cases with mild to moderate encephalopathy, and 22 % of cases with severe encephalopathy. Intrauterine hypoxia and fetal cerebral injury prior to labour may account for a mortality rate of 53-59 % and a subsequent cerebral palsy rate of 36-57 % in normally developed term infants having Apgar scores of 3 or less 15 minutes after delivery [3]. Other findings suggest a relatively small incidence during labour and a larger incidence of hypoxia prior to labour [4].

Fetal surveillance covers all tools that aim to detect fetal distress and its consequences. Methods to assess fetal welfare should however be as noninvasive as possible, clinically informative and predictive, relatively harmless and cause little bother to the mother and fetus. Cordocentesis, a technique intended to directly determine fetal oxygenation in the antenatal period, does not meet these requirements. Current noninvasive fetal surveillance methods include the following: fetal heart rate monitoring, objective FHR analysis, FECG, phonography, biophysical profile scoring, Doppler velocimetry, fetal-scalp blood sampling, and biochemical methods. Other approaches which are not yet widespread include: fetal $tcpO_2$ monitoring, continuous pO_2 and pH measurement, fetal pulse oximetry, fetal scalp circulation monitored by laser Doppler flowmetry, measuring fetal scalp heat flux, magnetic resonance imaging and spectroscopy, and near infra-red spectroscopy.

Undoubtedly, antenatal and intrapartum cardiotocography is the most widely used method today to assess fetal well-being. The first milestone in the history of FHR monitoring came in 1821 when a Breton internist, JA Le Jumeau de Kergaradec, recognized fetal heart beats by auscultation using Laennec's stethoscope [5]. Fetal electrocardiograms were first recorded by Cremer in 1906 [6]. In the 1950s Hon and Hess in the USA managed to eliminate maternal

ECG complexes superimposed on fetal signals using a second ECG recorder. In the late 1950s Caldeyro-Barcia and coworkers implanted an electrode in the fetal skin through the maternal abdomen. In 1960 Hon introduced an ECG electrode to the uterine cavity through the cervix, and clipped it on the fetal head. The first clinically usable cardiotocograph was developed by Hammacher and the Hewlett-Packard company in 1968 [7]. According to the results of the National Natality Survey in 1980, continuous electronic FHR monitoring had been used in 48 % of 10 thousand births in the USA [8]. A large amount of experimental and clinical data has also been collected upon normal and abnormal FHR patterns for medical studies. Several classification and scoring systems have been developed to provide a (semi-) quantitative assessment of the FHR tracing. In hospital populations, the predictive value for a negative test ranges from 93 % to 99 %, while for a positive test from 8 % to 26 % [9]. According to the same study, sensitivity ranges from 16 % to 52 %, while specificity ranges from 91 % to 96 %. The unreliability of visual assessment of FHR recordings has been demonstrated in a classic study by Trimbos and Keirse [10], and has been confirmed by others subsequently. To reduce inter- and intraobserver variation of the visual assessment, which can vary from 20 % to 30 %, the development of computer systems to cope with this problem were started as early as the 1970s [11, 12, 13, 14]. Up to the 1980s only three advanced systems were available in Europe: the Oxford System 8000 [15, 16, 17], the Porto [18], and the Kompor [19] system. The largest database is used by System 8000, which currently has over 43,000 records. Since its introduction in clinical trials, collective experience has shown that antepartum measurement of STV proved to be a better guide to the outcome at birth than decelerations [20]. At present, there is no convincing evidence that labour measurement of FHR variables offers a better prospect of accurate prediction of the outcome [21]. However, it must be remembered that this statement concerns System 8000 and the procedures it employs.

Although it occurs in only about 1 % of pregnancies progressing beyond 20 weeks, twin births represent 11 % of all neonatal deaths and 10 % of perinatal mortality [22]. Due to prematurity and fetal intrauterine growth retardation, the risk of perinatal death is 3-11 times higher in twins than in single-born infants [23, 24]. IUGR values range between 12-47 % in twin pregnancies compared to a value of 5-7 % in singleton pregnancies [25, 26]. The introduction of clomiphene citrate to the treatment of female infertility has increased the incidence of multiple pregnancies to a value of 6.8-17 %. Other sources report even higher rates (18-53 %), with ovulation induction by exogenous gonadotropins [22]. These results thus provide ample reasons for a close surveillance of twin pregnancies. In the past simultaneous CTG recording of both members of a twin gestation using two external monitors was difficult due to Doppler interference. In the recent years, however, various manufacturers have solved this problem by issuing cardiotocographs equipped with two ultrasound transducers each operating at different frequencies (1.5 MHz and 2 MHz). The benefits of simultaneous twin monitoring are the following: 1/ both fetuses can be monitored simultaneously, 2/ less time is needed to obtain important antenatal data, 3/ simultaneous FHR changes can be observed and documented, 4/ by collecting data on the behaviour-rhythm of fetuses in utero the mother-twins and twin-twin communication can be examined in more detail.

Fetal heart rate variability derives from the varying lengths of heart beat intervals. But the measurement of this beat-to-beat variability requires an accurate identification of cardiac events. Functional integrity of the autonomic and probably the whole fetal nervous system is currently thought to be reflected in FHR. The central nervous system in particular is the most sensitive organ to hypoxia, which means that either acute or chronic hypoxia may be expected to appear in some form of fetal heart rhythm. The FHRV is influenced, on one hand, by beat-to-beat changes in stroke volume (fluctuations in venous return predominantly due to respiratory movements), and on the other by longer-term changes in the activity of the autonomic nervous system. The ability to give an adequate response to the conditions of different behavioural and physiological states suggests that a sensitive and effective control mechanism is involved [27]. For quantitative measurement of FHRV a large number of derived formulae exist originating from the 1970s, but none of them has acquired general acceptance.

Circulation and respiration are both based on discontinuous events, and oscillations of various orders characterize them, particularly cardiovascular variables. The description of such oscillations and understanding their origins may reveal links between neural and cardiovascular rhythms. In the recent years it has been shown that for a quantitative analysis of short-term variability of fluctuations in haemodynamic parameters such as heart rate, blood pressure or flow, spectral analysis is a powerful natural tool [28, 29, 30]. By definition, spectral analysis transforms any steady fluctuating time series into its corresponding functional form in the frequency domain, from which the power (amplitude squared) of the signal components at predetermined frequency values can be computed. Here two classes of technique can be distinguished - nonparametric and parametric. The latter one has two main advantages over nonparametric procedures. The first is a high resolution spectrum from relatively short signal samples, while the second is that the number of parameters defining the power spectrum density curve is completely independent of the signal length. Spectral analysis was first employed in the 1970s to study normal adults' heart rhythm [31]. From studies three typical peaks of heart rate frequency have been observed [32, 33, 34] namely, (i) 0 - 0.05 Hz: peripheral vasomotor regulation; (ii) 0.05 - 0.15 Hz: arterial pressure oscillations, and (iii) 0.15 - 0.20 Hz: respiratory sinus arrhythmia. In the case of the fetus it is more uncertain [35]. To date the precise physiological origin of the frequency band of 0 - 0.05 Hz is not fully understood. The significance of the band of 0.05 - 0.15 Hz remains a subject of debate, but is usually regarded as the representative of arterial blood pressure control. The third frequency band of 0.15 - 0.50 Hz has been demonstrated to be associated with fetal movements. After administrating a curare-based drug, this band disappears [35]. It cannot be stressed enough, however, that strict continuity of the measured input data (i.e. FHR values) is a necessary prerequisite for spectral analysis. If this requirement is ignored, the results can be highly misleading [36].

Beside spectral analysis another mathematical technique has recently appeared in the analysis of FHR values [37, 38]. The theory of nonlinear dynamics, alias Chaos Theory, studies systems where the output is disproportionate to the input (i.e. there is a nonlinear connection between the two), and whose state can change with time. This revolutionary theory has had a profound effect on many different branches of science, among them medicine. It in part derives from the work of the 19th-century French mathematician Henri Poincaré on dynamical systems theory. The term 'chaos' here can best be understood by mentioning two everyday types of behaviour, namely randomness and periodicity. A random pattern never repeats itself, and is inherently unpredictable and disordered except in one particular way. This is that average changes can be predicted with absolute precision, but individual behaviour can never be. On the contrary, periodicity, that always repeats itself over some finite time interval, is highly predictable because it is governed by deterministic processes. But while chaos is distinct from periodicity and randomness, it has the characteristics of both. It is also true that there are different degrees of chaos. Taking the example of the Bernoulli map [39], a simple chaotic system: $x_{n+1} = 2x_n$ (mod 1) (mod 1 means to keep only the decimal value; e.g. mod 1 of 2.25 = 0.25), and choosing the starting value of 0.85, the result will be: 0.85, 0.7, 0.4, 0.8, 0.6 .... If one knows the rule, the next number in the seemingly random series can be predicted with complete confidence. Chaotic phenomena have a highly-sensitive dependence on initial conditions. This means that very small changes in initial conditions will result in large differences in behaviour at a later point in time (Figure 1-1, 1-2.). Despite its random appearance, chaotic behaviour is generally constrained to a relatively narrow range and has a definite form.

The sensitivity of chaotic systems to initial conditions was rediscovered [40] almost a century after Poincaré first described it, when Lorenz studied the behaviour of a simple microclimate system via computer simulations. After repeating some of his calculations to three significant digits instead of six he found, to his surprise, that his data corresponded exactly for a while, but later diverged widely from the previous case. This phenomenon is called the "Butterfly effect" [41], where under critical conditions the flutter of the wings of a butterfly in Peking can change the weather in New York.

The survival of the human race may depend on its ability to predict the behaviour of the local and wider environment, and to meet its changes adequately. At the same time, the needs of the modern era require ever more precise predictions over increasing longer periods of time. By the end of the 20th century the accuracy of statistical descriptions may have become insufficient to answer all our needs. The study of the general environment shows that most phenomena of the nature are nonlinear. The discovery of chaos has created a new paradigm in two aspects. On the one hand, it implies new fundamental limits on the ability to make predictions. In principle, the future is completely determined (statistically at least) by the past, but in practice, small uncertainties in the measurement of past events can be amplified to an extent that, even though the behaviour is predictable in the short term, it is unpredictable in the long term. On the other hand, however, the determinism inherent in chaos allows one to predict many random phenomena more precisely than had previously been thought. Apparently random data gathered in the past and shelved because of its complexity can now be explained more clearly. Looking at the question from an information theory viewpoint, without new measurements the behaviour of a nonlinear system can only be predicted with increasing uncertainty, that is, with every change in the state of the system we loose some information. In other words, each measurement gives a new piece of information on the behaviour. That is why chaotic systems are also called information generators. Similar to spectral analysis, chaos theory has been already successfully applied to adult cardiology [42].

It is a well-known fact that the perinatal period is the most dangerous stage of a person's life. The primary objective of obstetrics is to ensure a healthy birth to everyone in the sense declared in the WHO constitution. At present, intrauterine hypoxia is thought to be the main cause of intrauterine distress and consequent collapse of fetal homeostasis. To predict a catastrophe in time, that is, long before the onset to prevent or avoid it, we must be able to recognize the warning signs as early as possible. We assume that the variability of heart beat intervals carries the information of the actual and expected behaviour-state of the given biological system. Provided this is true, chaos theory may be expected to offer an effective tool for recognizing the warning signs much earlier than at present. However, it cannot be stressed enough that strict continuity and high precision of the measured input data (i.e. FHR values) is an indispensable prerequisite for spectral and chaos theory analysis. If one overlooks this requirement the results will be misleading.

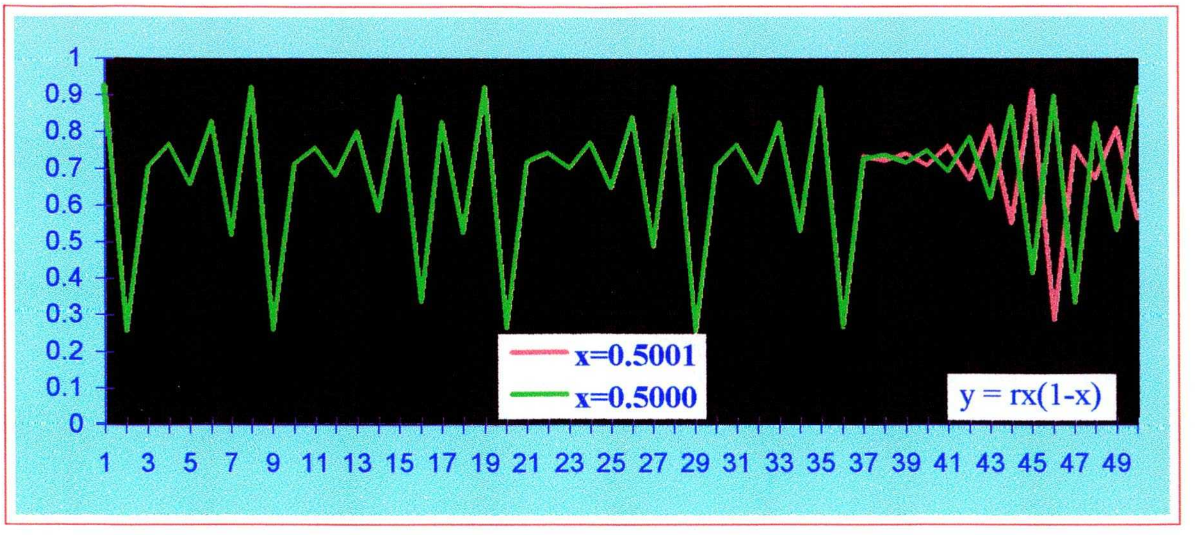


Figure 1-1
A simple iterative function showing chaotic dynamics, the logistic map (r=3.7)

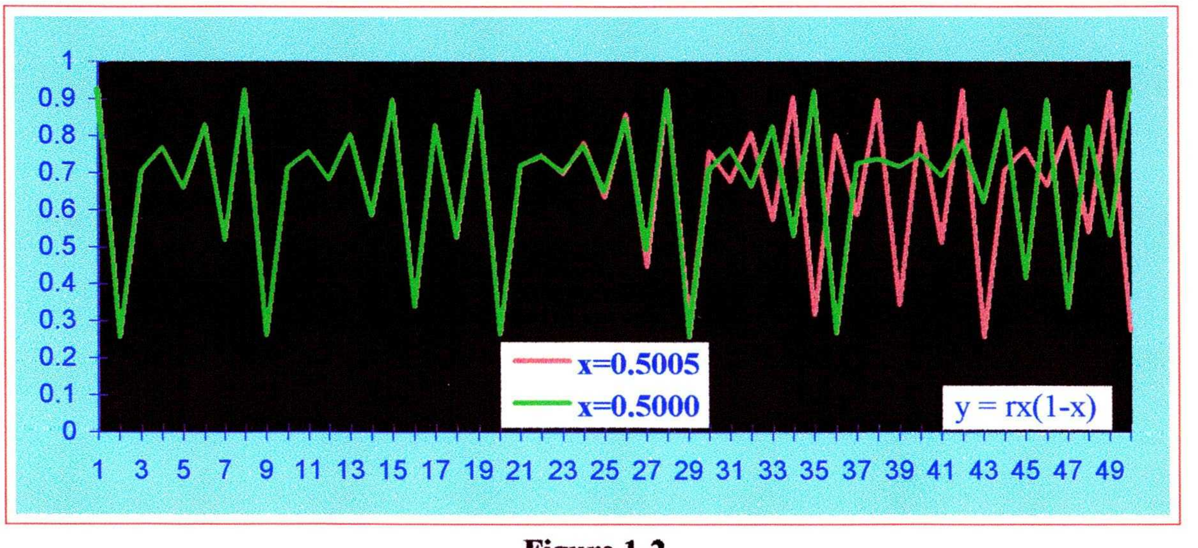


Figure 1-2
The logistic map (r=3.7): its sensitivity to initial conditions

2 OBJECTIVES

The work present here had two main objectives:

I To develop the method of simultaneous objective computer CTG monitoring of twin pregnancies in the antepartum period.

II To find a method that provides strictly continuous and highly precise beat-to-beat FHR values suitable for spectral and chaos theory analysis.

To achieve these two objectives the following sub-tasks were decided upon:

I - 1. To study the movement distribution of twin fetuses to decide whether it is necessary to register the movements of both fetuses separately or not.

I - 2. To work out the technique of simultaneous antepartum CTG monitoring of twins analysed by objective computer analysis software.

I - 3. To make an initial screening study to determine which CTG parameters seem relevant in the assessment of twins' intrauterine well-being.

I - 4. To study how the trend analysis of the Oxford System 8000 should be modified to get standardized and comparable results.

I - 5. To improve current baseline fitting methods to get more stable, quick and reliable results.

I - 6. To work out the technique of the detection of synchronous accelerations by objective computer analysis.

I - 7. To look for an independent variable to characterize FHR tracings.

II - 1. To solve the problem of serial communication with Oxford Sonicaid fetal monitors in real time.

II - 2. To study the data structure of CTG records made by abdominal transducers from the point of view of continuity.

II - 3. To study the data structure of intrapartum direct FECG recordings from the point of view of continuity.

II - 4. To study the data structure of intrapartum direct FECG recordings from the point of view of accuracy.

3 RESEARCH TOOLS

3.1 COMMERCIALLY AVAILABLE HARDWARE PRODUCTS

3.1.1 Fetal monitors

3.1.1.1 Sonicaid Meridian 800 cardiotocograph

The Sonicaid Meridian 800 (Figure 3-1) is a complete fetal and/or maternal monitoring system for use during either the antepartum or intrapartum period. It provides information using mainly non-invasive ultrasound and external toco facilities.

Fetal heart rate monitoring can operate both in the single and dual mode. The dual heart rate mode allows simultaneous monitoring of two heart rates - twins (Ultrasound/FECG or Ultrasound/Ultrasound) and maternal-fetal (MECG/Ultrasound or MECG/FECG) monitoring.

The quality of ultrasound recordings is achieved using pulsed Doppler ultrasound and auto-correlation of the received Doppler shifted signals.

Three interconnected microprocessors provide the optimization and co-ordination of these facilities, together with alphanumeric display and chart recording facilities.

The mode of operation is automatically sensed from the type and number of transducers in use connected at the correct front panel socket. Multi-crystal, wide-angled ultrasound transducers are employed for either antepartum or labour fetal heart rate monitoring, operating at frequencies of 1.5 MHz and 2 MHz respectively. The maximum ultrasonic power output densities are 0.6 mW/cm^2 and 1.2 mW/cm^2 respectively.

The external contractions transducer is a tocodynamometer whose central section is pushed down by the patient's abdominal muscles during a contraction. It is used for assessing the timing, duration and relative strength of contractions but only gives a subjective indication of contraction pressure or baseline tone.

The Meridian 800 can take fetal ECG samples as well. In this case the FECG electrode is attached to the fetal scalp, and the two wires leading from the electrode are connected to the terminals on the FECG leg electrode assembly.

The MECG electrodes enable the Meridian 800 to measure maternal ECG, too. The Maternal ECG lead is connected to the yellow MECG socket.

An isolated ECG front-end gives an ECG waveform output. Inside the device a filtering procedure rejects frequencies outside the range 10 to 80 Hz to give a true ECG waveform for subsequent signal processing. This mode operates both a 'lamp-flash' and 'bleep' for direct monitoring.

Safety design: Direct FECG Protection Category BF, scalp. min. signal threshold: 20 μV; Direct MECG Protection Cat. BF, min. signal threshold: 200 μV.

There are two types of event marking available with the Meridian 800. One is a front panel key with a pen symbol on it for the midwife or obstetrician to mark the chart (a larger solid sharp triangle at the top of the FHR scale) at a clinically significant point. The other event marker connected to the rear panel is a hand-held push-switch operated by the patient when she senses a fetal movement (a smaller triangle printed at the top end of the contractions scale).

A thermal dot-matrix chart printer is used which prints its own grid lines on blank paper. This allows a wide choice of printed formats for clear dual-mode annotation.

A 2-line, 20-character per line vacuum fluorescent display reports all the mode and heart-rate display functions.

External connections include outputs for digital FHR, Contractions and other signals to interface with a Sonicaid System 8000 Objective CTG Analysis computer.

The Meridian 800 was designed to comply with safety standards IEC601-1 Part 1, Class 1 BS5724 Part 1, Class 1 UL544, CSA 22.2 No. 124, and VDE 0750.

3.1.1.2 Sonicaid TEAM Fetal Monitor System

The Sonicaid TEAM Fetal Monitor System is a complete fetal cardiotocograph system for use during the antepartum period, which employs non-invasive ultrasound and external toco facilities.

The monitor consists of two modules; the ultrasound (1.5 MHz or optionally 2 MHz) and contractions transducers, electronics in the base unit, and a printer in the second module, which can all be joined together and easily separated if needs be (Figure 3-2).

The FHR and external contractions transducers, patient event marker, and printer are basically the same as described in Section 3.1.1.1. The selected frequency of ultrasound transducer is optional, being either 1.5 MHz or 2 MHz. However, simultaneous monitoring of twins requires both a 1.5 MHz (yellow transducer) and a 2 MHz Ultrasound TEAM unit (blue transducer).

The LCD display operates in two main modes. The alphanumeric display shows the FHR, heart rate lamp, signal quality indicator, contractions, and messages/system status. The graphics display shows a full-size FHR trace, compressed toco information, real-time or reviewed trace, and message/system status.

The storing mode is a unique feature of the TEAM base unit. If the module is used without a System 8000 Objective CTG Analysis program or the printer module, all data can be stored in the internal memory. Six hours of cardiotocograph data can be saved in this way, and printed or transmitted to the System 8000 at any later time.

The safety design is the same as described in Section 3.1.1.1.

3.1.2 Computers employed

3.1.2.1 IBM PC/AT compatible Intel 486 DX 33 MHz computer

Hardware configuration: 4 MB RAM, 5.25" and 3.5" FDD, 88 MB SYQUEST removable cartridge HDD, Trident SVGA board (512 KB), and 14" SVGA colour monitor.

Collectively this equipment was used for recording and digital analysis of FECG and adult ECG wave signals, and development of software programs in Assembly language.

3.1.2.2 IBM PC/AT compatible Intel 386 SX 25 MHz notebook computer

Hardware configuration: 2 MB RAM, 3.5" FDD, 85 MB HDD, 8" LCD monitor.
Used for bed-side intrapartum beat-to-beat fetal heart rate recordings reading the serial port of fetal monitors, by a computer program of mine, according to the Sonicaid Serial Protocol.

It was used to measure time intervals between bleeps of the Meridian 800 during recordings in the direct FECG mode to a precision of 0.1 ms with the help of self-developed hardware equipment.

3.1.2.3 ESCOM Intel Pentium PCI 60 MHz computer

Hardware configuration: 16 MB RAM, 3.5" FDD, 540 MB HDD, Creative Labs Discovery Multimedia Upgrade Kit, V7-MERCURY Lite (PCI) true-color VGA compatible graphics accelerator, 14" SVGA low radiation colour monitor.

This equipment was used for software development, and antepartum beat-to-beat fetal heart rate recordings reading the serial port of cardiotocographs using software written by me, in accordance with the Sonicaid Serial Protocol.

The computer was also used for data analysis, word processing, creating of charts, figures, tables, spreadsheets and illustrations.

3.1.3 Analogue/digital input/output board

3.1.3.1 ITK-341 Metrabyte DAS-16 compatible A/D D/A DIO board

The ITK-341 is a multifunctional analogue/digital input/output board that can be plugged into one of the available slots of an IBM PC/AT or compatible computer.

The analogue input characteristics of the ITK-341 were designed to allow high rate data sampling. The combination of hardware auto-scanning multiplexer, high-speed sample/hold and A/D converter enables an input sampling rate up to 60 KHz. The converted data may be collected through software commands, interrupt service routines or DMA channels.

A/D subsystem specifications: Number of inputs - 16 single-ended; Resolution - 12 bits; Sampling rate - 60 KHz maximum; A/D conversion time - 15 μs maximum; Channel acquisition time - 5 μs maximum; System accuracy - ± 0.03 % FSR; Output coding - offset binary.

3.1.4 16-bit Sound Card

3.1.4.1 Creative Labs Sound Blaster 16

This card offers 16-bit sound capability and has a maximum sampling rate of 44.1 KHz. It was used to record and replay bleep patterns made by the Meridian 800 fetal monitor in the FECG/MECG mode.

3.2 COMMERCIALLY AVAILABLE SOFTWARE PRODUCTS

3.2.1 Operating systems

3.2.1.1 Microsoft MS-DOS 5.0, 6.0, 6.2

Three successive versions of the most widely-used operating system for personal computers were employed. Some of the features that provided benefits during hardware, software development, and signal recording or processing include the following:

Mem.exe (and its enhanced version) give more information about the memory the computer is using and the programs that are loaded in memory;

MemMaker.exe, a memory-optimization program that makes easy to move device drivers and memory-resident programs from conventional memory into the upper memory area;

MemMaker.exe maximizes available conventional memory so that programs run faster and more efficiently;

Defragmenter.exe, a program that reorganizes files on the hard disk to minimize the time it takes the computer to access files;

Smartdrv.exe, a program that establishes a disk cache, then temporarily stores information to be written to the hard disk and writes it to the disk after system resources are in less demand.

3.2.1.2 Microsoft Windows 3.1 for MS-DOS

Windows 3.1 is the most popular graphical user-interface environment for MS-DOS. It provides a multitasking, graphics-based window environment that runs programs especially designed for Windows.

For the program developer himself, Windows provides a wealth of built-in routines that allow the use of menus, dialogue boxes, scroll bars, and other facilities of a friendly user-interface. Besides this an extensive graphics programming language is provided by the package. Programmers can also treat the keyboard, mouse, video display, printer, system timer, and communication ports in a device-independent manner. Finally, since Windows 3.1 is a platform for programs, Windows programs run the same way on a variety of hardware configurations.

3.2.2 Software development systems

3.2.2.1 Microsoft Visual Basic 3.0 Professional Edition

Microsoft Visual Basic offers a quick and easy way to create applications for the Microsoft Windows operating system, providing appropriate tools for exploiting the graphics user-interface and computer hardware features.

The first step available is the creation of a user-interface for the application by drawing objects, called 'controls', in a graphical way.

Next, the properties of these objects are fixed so as to refine their appearance and behaviour.

Finally, a user-interface interaction is set up by writing program code that responds to events that occur in the interface.

The main feature of theVisual Basic is that it can be extended by adding custom controls and calling procedures from any dynamic-link libraries. In this way it provides a powerful access to the Windows API functions when needed.

3.2.2.2 MS Visual Basic Programming System, Applications Edition for MS Excel 5.0

This software tool offers a powerful and easy-to-use programming language used in Microsoft Excel. It also provides access to the Windows API. It was used for automating repetitive tasks like performing complex custom functions on a large number of spreadsheet data sets.

3.2.2.3 Microsoft Visual C++ 1.5 Professional Edition

MS Visual C++ and its integrated development environment, Microsoft Visual Workbench, together provide a powerful tool for building and debugging MS-DOS, and Windows-based applications and libraries as well.

This was utilised for C/C++ language development of DOS applications and Windows DLLs to speed up Visual Basic programs.

3.2.2.4 Microsoft MASM 6.1

The MS MASM 6.1 is an assembly-language development system for MS-DOS and Windows operating systems. It includes the Programmer's WorkBench and provides an integrated software development environment to edit, build, debug, and run a program.

3.2.3 CTG Analysis Computer Program

3.2.3.1 Sonicaid System 8000

The Sonicaid System 8000 CTG Analysis System is a computer program, that runs on an IBM PC compatible computer, which provides detailed analysis of an antepartum CTG record (Figure 3-3).

The program and its analysis algorithms originate from work carried out by Professor GS Dawes and Dr CWG Redman at the Nuffield Department of Obstetrics and Gynaecology, John Radcliffe Hospital, Oxford in England.

The program analyses many aspects of CTG traces, calculates a number of indices and compares them with the normal range. It then stores the data and plots the indices to give the clinician trend information.

The CTG record is usually obtained via a serial link from a fetal monitor while it is connected to a patient. The computer evaluation includes the analysis of FHR and contractions signals. Maternally-sensed fetal-movement marker data are also used in the analysis.

Upon executing the program the user gets a main menu display with the following options to choose from: New record; Re-plot an existing record; Trend display; System maintenance menu; Receive telephone data; Stop program.

During a CTG recording, System 8000 analyses the data collected so far after ten minutes, and every two-minute interval thereafter. The results are then summarized on the screen and a printed report is obtained. If the record appears normal, the computer displays "Dawes/Redman Criteria Met". Otherwise the advice "Continue" is given. The first time the Criteria are met, the computer gives a double bleep as a signal to the user.

The main criteria used are the detection of a high FHR variation episode (in the absence of large deceleration) and registering of at least 1 fetal movement or 3 accelerations.

The program offers advice based on a statistical analysis of a large number of records (currently over 43,000). The system also measures the short-term variation of the fetal heart rate, which has been shown to be a better guide to the outcome at birth than decelerations [20, 21]. The FHR monitoring parameters used include: signal loss, contraction peaks, number of fetal movements, basal heart rate, accelerations, decelerations, high and low variation episodes, overall and short-term variations.

If a patient has two or more records filed on the System 8000, then a visual trend display can be generated of the last four weeks' records about her with a printout if required. The parameters analysed in this trend display form are fetal moves per hour, overall FHR variation, and basal fetal heart rate.

One of the most important features of the System 8000 is the option of receiving CTG data from an external source, for instance the memory of a Sonicaid TEAM fetal monitor connected to the system via an RS232 link.

It has been found in practice that a thirty-minute record takes about forty five seconds to send and that the System 8000 ignores the last two minutes of the original CTG record. After receiving the raw data from the TEAM cardiotocograph, a routine computer analysis is performed (the minimum of a 10-minute record is required). Other possible options have already been mentioned.

An interesting option is the "Re-plot an existing record" menu choice. The computer gives the record length and asks whether the whole record is needed. Any number of minutes can be removed from the start and/or end, but at least ten minutes must be retained.

3.2.4 Other programs

3.2.4.1 FractalVision for Windows

This commercially available software package was developed to let the user design his own fractal models, or modify any of over 200 fractal designs included. It contains a fractal dimension computing function as well based on the box-counting method.

3.2.4.2 CSS

This DOS-based program provides a complete and high-quality graphic and statistical environment to analyse any data-set, and can be used to create phase-space reconstructions of measured FHR values.

3.3 SELF-DEVELOPED HARDWARE PRODUCTS

3.3.1 Fetal heart rate measurement

3.3.1.1 HRMIC - FHR measuring unit

The HRMIC unit was developed to detect bleeps given by the Sonicaid Meridian 800 during FECG or MECG recording, and to measure time intervals between successive bleeps to 0.1 ms precision. It includes a small black box containing a microphone and appropriate electronics. The device, which can be connected to the COM1 serial port of a notebook computer, was developed by Péter Liszli of the Albert Szent-Györgyi Medical University, Institute of Physiology.

3.4 COMMERCIALLY NOT AVAILABLE SOFTWARE PRODUCTS

3.4.1 Self-developed programs

Listed here are commercially unavailable programs used by me during the studies, and unless otherwise indicated were developed by myself.

3.4.1.1 Readout.com

The program reads out the FHR, tocodynamometer, and fetal movements data from System 8000 CTG recording files, and writes them into standard ASCII text files. It was written by me in Assembly language based on knowledge about the structure of System 8000 data files provided by Róbert Zeller of the Scientific Hungarian Academy, Institute of Automata Theory.

3.4.1.2 Com.exe

Com.exe reads the FHR, tocometer, FM, signal quality, and new beat flag data in real time from the Sonicaid Meridian 800 and TEAM fetal monitors via their RS232 serial port during antepartum CTG recordings. The program was developed in MS Visual Basic using the Mscom.vbx custom control which enabled serial communications and allowed the transmission and reception of data through a serial port, done according to the Sonicaid serial protocol. FHR, toco and FM data values were stored in ASCII text files.

3.4.1.3 Missbeat.exe

This piece of software was written using MS Visual Basic. Missbeat.exe not only reads the new beat flag (thus calculating the beat-to-beat FHR values) and other data of Sonicaid cardiotocographs, but checks the FHR values provided by the fetal monitor using an internal time measuring method. In this way, the program recognizes the number of missed fetal heart beats during antepartum CTG records with a precision of 95 % or better.

3.4.1.4 Missbeat.xls - Excel 5.0 workbook

This was used to determine the length of unfragmented data (without missed fetal heart beats) segments of antepartum beat-to-beat CTG records made by Missbeat.exe. Its macro module, which performs the search and calculation algorithm, was developed using Excel Visual Basic.

3.4.1.5 FECG.exe

The functions of this program are similar to that of Missbeat.exe. It can be used to make intrapartum beat-to-beat CTG records, and was developed using MS Visual Basic.

3.4.1.6 MECG.exe

MECG.exe measures the same parameters as Missbeat.exe during adult ECG recordings made by the Sonicaid Meridian 800. Like the above the program was developed via MS Visual Basic.

3.4.1.7 Hrmic.exe

The program modifies the timer tick rate and specifications of the COM1 serial port of the computer. When the Hrmic unit (described in Section 3.3.1.1.) detects a bleep, it sends a signal to the COM1 serial port which immediately gives an interrupt request of first priority to the CPU, and the time between successive bleeps is measured to 0.1 ms precision. The error bar is better than 0.3 %. Hrmic.exe, which stores time data values in ASCII text files, was developed in Assembly language by Péter Liszli of the Albert Szent-Györgyi Medical University, Institute of Physiology.

3.4.1.8 Baseline.exe

This program employs a modified algorithm of the method suggested by Dalton and Dawson [43]. It requires an input ASCII text file containing the FHR values in ms intervals (Readout.com was used to do this) of a System 8000 data file. The program stores FHR and baseline values in an ASCII text file. As before the code was written and developed using MS Visual Basic.

3.4.1.9 Fractdim.exe

The program estimates the fractal dimension of FHR tracings based on the modification of the graphical box counting method [44], and was developed using MS Visual Basic and Visual C++.

3.4.1.10 Twins.xls - Excel 5.0 workbook and macro module

Used to determine the synchronous accelerations with or without FM of simultaneous twin CTG records. The macro module was developed using Excel Visual Basic.

3.4.1.11 Adacq4.exe

This program, written in Assembly language, controls the ITK-341 A/D D/A board. Intrapartum direct FECG and adult ECG recordings can be made using the Sonicaid Meridian 800 cardiotocograph, the data being read via the analogue output, with a sampling rate that can be as high as 20 KHz. The length of records is restricted only by the capacity of hard disk drive. The code was written by Péter Liszli of the Albert Szent-Györgyi Medical University, Institute of Physiology.

3.4.1.12 RRECG.exe

The program reads the data of Adacq4.exe output binary files, then searches for R peaks and determines the number of data samples between them. Knowing the original sampling rate the R-R intervals can then be calculated.

Figure 3-1

The Sonicaid Meridian 800 cardiotocograph

Figure 3-2

The Sonicaid Team fetal monitor (base and printer unit)

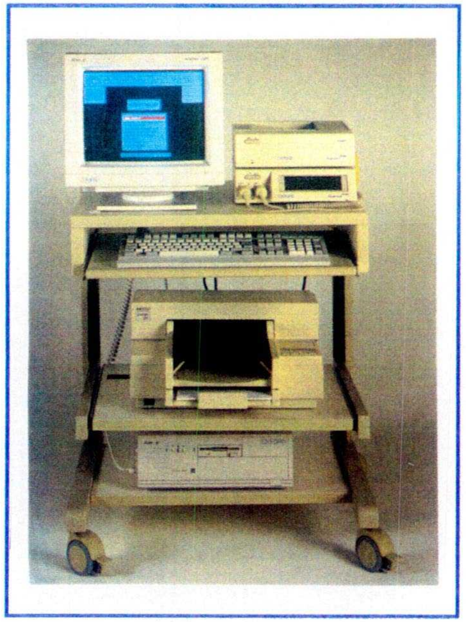


Figure 3-3

The System 8000 objective CTG analysis system

4 METHODS

Topic I

I - 4.1 PSEUDO-SIMULTANEOUS OBJECTIVE CTG RECORDING IN TWIN PREGNANCIES

I - 4.1.1 Antenatal monitoring of twins by Meridian 800 - the standard way (visual analysis)

In the dual operation mode the Sonicaid Meridian 800 cardiotocograph allows simultaneous monitoring of two heart rates. For antepartum twin CTG records two separate ultrasound transducers should be used to minimise cross-interference. Fetus A can be monitored by the 1.5 MHz ultrasound transducer connected to the yellow socket, while Fetus B can be monitored by the 2 MHz transducer connected to the blue socket (Figure 4-1/b).

An aquasonic coupling medium was applied to the pregnant's abdomen over the fetal site and the face of the transducer. The ultrasound transducer was then placed on the abdomen over the fetal site and slowly moved until the characteristic hoof-beat sound of the fetal heart was detected, then the volume level was adjusted. The same procedure was repeated for the other fetus as well. Once achieved all three horizontal segments of the signal quality indicator should be lit up, with the fetal heart pulse lamp flashing for each fetal heartbeat as its heart rate is displayed. The stretch belt was placed around the abdomen and each transducer was fixed in the optimum fetal heart signal position. The external contractions transducer was then placed over the uterus fundus in the middle line (Figure 4-1/a). When the patient subsequently sensed fetal movement, she pushed the hand-held event marker.

Once set up the two heart rate traces are printed side-by-side with equal scale settings, which allows for a clear and straightforward comparison during visual assessment.

I - 4.1.2 Evaluation of the fetal movement distribution of twins by maternal perception

In trials the patients were asked to listen to fetal movements for two hours in the morning, at noon, and in the evening over three successive days. They filled in a form where they noted the number and location of movements of Fetus A and Fetus B separately every 10 minutes over the three two-hour periods (Figure 4-2). In the daytime a qualitative description was used (i.e. very high, high, medium, low, very low, none).

I - 4.1.3 Pseudo-simultaneous objective monitoring of twins with separately registered fetal movements

In this case the Meridian 800 cardiotocograph was connected to the System 8000. The program, however, is such that it can only receive and analyse data (FHR, toco, fetal movement) from only one ultrasound channel (Fetus A) at a time. Consequently visual assessment was only supported by automatic numerical analysis of data from one of the two fetuses. But using the hand-held event marker operated by the pregnant, and the clinical event marker operated by the mid-wife when the patient gave a sign, fetal movements could be registered separately on the printed CTG chart (Figure 4-3). This provided additional information for analysis.

After 30 minutes of recording the transducers and button-pushing roles were interchanged, so that the System 8000 received and analysed data from Fetus B. In this way, visual assessment for both fetuses was supported by an impersonal computer CTG analysis, but unfortunately without a parallel control.

I - 4.2 REAL SIMULTANEOUS OBJECTIVE CTG RECORDING IN TWIN PREGNANCIES

The key to the method is the Sonicaid TEAM fetal monitor and its internal RAM memory which is able to store FHR, toco and FM data.

Fetus A was monitored by the Meridian 800 using its 2 MHz ultrasound transducer connected to the System 8000, then the computer analysis of Fetus A's data (FHR, toco, FM using the standard event marker of the Meridian 800) was performed on-line and in real time. Fetus B's data samples (FHR, toco, FM) were downloaded to the memory store of a TEAM cardiotocograph equipped with a 1.5 MHz ultrasound transducer and a conventional event marker.

Once set up both fetal monitors were activated and halted at the same moment. At the end of the recording the FHR, toco and FM data of Fetus B were transferred to the System 8000 via a serial link. The data processing software immediately analysed and saved the received input record set. This method thus provides computer-analysed simultaneous CTG records from Fetus A and Fetus B, including separated fetal movement data (Figure 4-4). On the parallel printed reports of Fetus A and B synchronous accelerations with or without FM can be precisely detected manually using a ruler.

I - 4.3 BASELINE FITTING TO FHR DATA

In this section two baseline fitting methods which served as basis of a modified numerical algorithm presented in the study section are elaborated upon, especially their advantages and disadvantages.

I - 4.3.1 The Dalton-Dawson-Dawes method [43] [45]

The first method [43] uses FHR values averaged over intervals of 3750 ms (i.e. System 8000 data format). The baseline is calculated via a first-order autoregressive filter, twice applied to the recording: first in the forward direction and then the backward direction. Such bi-directional processing cleverly eliminates phase shift.

The FHR values are loaded into a linear array A ($A_1 \ldots A_n$) then, using a three-stage iteration process with arrays B and C, an array D ($D_1 \ldots D_n$) is calculated. This gives the baseline or trendline of the original heart rate recording held in A.

$$B_n = R * B_{n-1} + (1 - R) * A_n$$ forward direction

$$C_n = R * C_{n+1} + (1 - R) * B_n$$ backward direction

$$D_n = C_n - (1 - Q) * A_n$$

where

$$n = 1,2,3 \ldots N$$

$$R = 0.95$$

and

$$Q = \frac{2 * R}{1 + R^2}$$

To keep the units primary wherever possible, it is advised that the processing of FHR values be done in the time domain (ms).

The best estimates of B_0 and of C_{N+1} are obtained from a dummy-run of the autoregressive algorithm in the appropriate direction. However, the description of the method gives no mention of the appropriate starting values of the dummy runs [43]. According to Mantel *et al.* [46], the method does not provide a baseline which meets general expectations. The BL does not fit well at the beginning of the recording, is slightly elevated in the environment of groups of accelerations, and repeated large swings of heart rate cause a distinct elevation of baseline level. Besides this the BL does not adequately follow shifts in basal heart rate.

Dawes *et. al.* [45] calculate the theoretical starting point of the digital low-pass filter mentioned previously using the first 64 data points [15]. A slow and steady declining or rising trend at the beginning of a CTG record causes the initial BL value to be too low or too high. To minimise these unwanted effects, Dawes *et al.* keep the output constant when the input signal reaches values beyond the range of P $\pm$ 60 ms. Here P represents a relative peak in the frequency distribution of the signal where either the modal value or a prominent peak near the higher end is chosen. According to Mantel *et al.* [46], narrowing the operating range of the filter or a cut-off frequency sufficiently low to have any real effect does not solve the problem because the filter would then no longer adequately cover a physiological drift in basal heart rate over a longer time interval.

I. - 4.3.2 The method of Mantel et al [46]

With this procedure FHR signals are averaged over 2.5-s periods, stored in an array $A(A_1...A_N)$ then copied to another array B for programming reasons. The frequency distribution of array data (between 300 and 600 ms, class width 1 ms) is scanned from high to low values to find a relative peak P near the higher end, P acting as a reference guide.

The BL value fitting is done using a low-pass filter and trim function of a five-run iterative process. The filter with attenuation 50 % is centred at 0.1 min^{-1}, and is limited where necessary, according to the following:

Backward dummy pass:

$B_0 = P$
For i running from N to 1:
If $|B_i - P| \leq 60$ then $B_0 = 0.95 * B_0 + 0.05 * B_i$

Forward pass:

For i running from 1 to N:
If $|B_i - P| \leq 60$ then $B_i = 0.95 * B_{i-1} + 0.05 * B_i$
else $B_i = B_{i-1}$

Backward pass:

For i running from N-1 to 1:
$B_i = 0.95 * B_{i+1} + 0.05 * B_i$

The trim function copies to array B all segments of the original signal in array A which, in terms of fetal heart rate, lie either above or below the baseline and never touch BL + U, or - L respectively. The U and L values are upper and lower limits expressed in beats per minute (bpm).

The five-run trim procedure is given by the following:

run1: Initial application of the baseline filter;

run2 Trimming at U = 20 bpm and L = 20 bpm, followed by application of the BL filter;

run3: Same as run 2, except U = 15 bpm;

run4: Same as run 2, except U = 10 bpm;

run5: Same as run 2, except U = 5 bpm.

According to the authors this iterative procedure provides more stable and better baseline fitting than that of Dawes et al. However, in the case of records substantially longer than 2 hours or shorter than half an hour the P value becomes statistically less reliable. Another disadvantage is that the method is only retrospective, while the method of Dalton-Dawson-Dawes operates on-line, gives immediate results, and operated well when tested on really large amounts of data (System 8000).

I - 4.4 DETECTION OF SYNCHRONOUS ACCELERATIONS WITH OR WITHOUT FM IN TWIN PREGNANCIES USING A COMPUTER PROGRAM

After fitting a baseline to the FHR values the detection of synchronous accelerations with or without FM by computer analysis is in general straightforward. In the first step FHR and FM data are read from the corresponding System 8000 files and written into output ASCII text files using Readout.com. The next step is the baseline fitting to both FHR tracings. Finally FHR, FM and baseline data of both Fetus A and B are loaded into the data sheet of the Twins.xls Excel 5.0 workbook, after which the macro module finds the synchronous accelerations with or without FM.

I - 4.5 ESTIMATION OF THE FRACTAL DIMENSION

The computation of fractal dimensions is presently something of an art, and the numerical algorithms used for the analysis of any type of signal are still evolving. Currently the most common algorithm employed is that developed by Grassberger and Procaccia [47, 48]. They turned the so-called correlation dimension into a useful algorithm as follows:

$$I_2(\varepsilon) = -\log \sum_{i=1}^{N(\varepsilon)} P_i^2 = -\log C(\varepsilon)$$

where $C(\varepsilon)$ is the probability of points having distance $|x_i - x_j| < \varepsilon$, since each P_i^2 is the probability of x_i, x_j being in the same ε-sphere. $C(\varepsilon)$ can be calculated explicitly using a numerical approximation of the Heaviside step function. Analytically the step function is defined by the series summation.

$$C(\varepsilon) = \lim_{n\to\infty} \frac{1}{n^2} \sum_{i,j=1}^{n} \Theta(\varepsilon - |x_i - x_j|), \qquad \Theta = \begin{cases} 1, & x>0 \\ 0, & x<0 \end{cases}$$

Several modifications have been proposed to improve the speed and accuracy, but to date several problems remain outstanding, such as the speed of computing.

I - 4.5.1 Box-counting method

This algorithm [44], originally developed to estimate the fractal dimension of anything on the screen, is also employed in the FractalVision for Windows software package.

The screen is divided into boxes 8 pixels wide, then the number of boxes that contain part of the curve is counted. Next, the screen is divided into boxes 6 pixels wide and counting is repeated. By comparing the difference between the two counts, the roughness or irregularity of the image can be estimated. This roughness is called the fractal dimension. To obtain a more accurate estimate, the algorithm repeats this procedure for box sizes down to 2 pixels wide and averages the results overall (Figure 5-19).

Fractdim.exe is based on the graphical box-counting method but it calculates a theoretical estimate without any screen operation. After reading the data value the program places the given value into an imaginary Euclidean coordinate system, then immediately calculates which 2-pixel wide box should contain this point if it were drawn on a screen. This is repeated for boxes 4, 6, 8 pixels wide. In this way, the time needed for finding the fractal dimension estimate is only a fraction of the original graphical approach and there is no restriction involved with the screen size or graphics resolution.

I - 4.6 INTERNAL TREND ANALYSIS OF SYSTEM 8000 CTG RECORDS

In addition to the standard analysis, System 8000 also provides quantitative information on FHR parameters by furnishing a trend analysis of the FHR baseline, overall variations, and fetal movements over days or weeks. However, since records cannot always be made in the same fetal behavioural, state this form of trend analysis does not always give comparable results.

Using the "Re-plot an existing record" menu selection of the System 8000 program each tracing can be cut into shorter segments by getting all corresponding analysis data for the given segment. After giving the necessary identification numbers the computer gives the record length and asks whether the whole record is needed. Any number of minutes can be removed from the start and/or end, but a period of at least ten minutes must be kept. This means that a sixty-minute record has to be recalled six times. Thus specifying the number of minutes to be removed from the start and end of the record (0,50 10,40 20,30 30,20 40,10 50,0 respectively) six ten-minute segments are obtained. However, six points often does not provide sufficient trend information.

I - 4.6.1 Internal trend analysis after baseline fitting using mean minute range and FM values

To break the ten-minute restriction of the System 8000, a baseline fitting method should be used. About this baseline the range of FHR variation (the mean minute range) can be determined. The mean minute range is defined as the difference between the max and min FHR value when the rate rises above and falls below the baseline in the one-minute section. If the rate continually exceeds the baseline then the range is calculated from the baseline [17].

In the first step, the FHR and FM data of the System 8000 CTG records were read and written to an ASCII text file. For this purpose the Readout.com program was utilised. In the second step, after fitting a baseline [45] the mean minute range and 1-min section FM values were calculated and displayed on the screen monitor.

I - 4.6.2 Internal trend analysis of twin CTG records using STV and FM values

After reading out the FHR and FM values of real simultaneous twin CTG records using Readout.com, the STV (short term variation, which is defined as the average datum-to-datum variation over a given period of time) and FM values can be displayed and analysed with an optional zoom facility for both Fetus A and Fetus B.

This form of trend analysis provides the opportunity to study longitudinal twin behaviour more precisely because it is based on STV values. This parameter does not depend on the calculation of a hypothetical baseline value that may depend upon the precise numerical algorithm employed.

Topic II

II - 4.1 SIGNAL LOSS OF BEAT-TO-BEAT CTG RECORDS MADE BY AN ABDOMINAL ULTRASOUND TRANSDUCER

II - 4.1.1 Beat-to-beat CTG recording

Sonicaid fetal monitors provide additional information about all measured quantities and their actual operation mode in serial form transmitted via an RS232 connector. It therefore allows a computer system to collect monitor data for research, remote display or further processing.

The hardware involved is a simple three-wire connection. All the messages are small enough to be collected without losing data.

The monitor itself acts as a slave device and operates on request from the host computer with a delay of only a few ms. The reply given is always the latest information available to the monitor. The protocol procedure is the same as that used by the System 8000, and it is compatible with Hewlett-Packard serial monitors.

The Com.exe program, written by me using Visual Basic 3.0 and an Mscom.vbx custom control, regularly reads (every 55 ms) the so-called Beat Flag of the fetal monitor via the COM1 RS232 serial port. This bit toggles with every new beat recognized by the cardiotocograph. It can be used to determine whether the FHR value just obtained from the monitor is a new FHR, or the same as the previous value.

If Com.exe finds the Beat Flag has been toggled, it reads and writes the FHR, toco, fetal movement, signal quality and Beat Flag values to a displayed window on the monitor screen. Except for the latest one, values are written to an ASCII text file for safe keeping.

This method provides beat-to-beat FHR and other values in real time, and later processing is also possible using text file data.

II - 4.1.2 Detection of missed fetal heart beats

When the fetus is moving, the fetal heart often goes outside of the range of the ultrasound beam. During this interval, which sometimes lasts for several seconds, the Beat Flag does not toggle. At the first recognized fetal heart beat the flag toggles again.

Missbeat.exe, written by me using Visual Basic 3.0, measures the elapsed time between every successive, recognized fetal heart beat, and compares this time value to the FHR value provided by the cardiotocograph. In this way, the fact as well as the number of missed beats can be recognized and stored in an output text file. At the end of the record, the program automatically gives the signal loss rate and writes it into an output file.

The procedure can readily be verified by a crude simulation. Taking the ultrasound transducer in one hand with its abdominal surface towards the palm, and tapping this hand with the other one a simulation of the fetal heart beating was obtained. At every tap the cardiotocograph provides the appropriate "FHR" value. When the hand is tapped at a frequency around 140 to 150 per minute (the average human rhythm sense is inaccurate enough to produce a variation in the intervals between tappings similar to that of a real FHR), and eventually tapped, instead of a hand, on the chest two, three, four or more times in a random way, one can check whether the program recognizes the fact and number of missed beats. Using this simulation technique a precision of better than 95 % was obtained.

II - 4.1.3 Determination of the length of segments without missed fetal heart beats

The macro module of the Missbeat.xls Excel 5.0 workbook determines the length of unfragmented segments, and writes out the precise values in descending order. The module uses output text files of beat-to-beat antepartum or intrapartum CTG records. The FHR values (in ms) must be loaded into the first column of Data Sheet. After activating the macro module, it searches for "beats missed!?" strings, and totals up the FHR values between them, then automatically writes out the time duration of unfragmented segments in minutes and seconds.

II - 4.2 DATA STRUCTURE OF BEAT-TO-BEAT INTRAPARTUM CTG RECORDS MADE BY A SCALP ELECTRODE

Basically the same procedure was used as that described in Section II - 4.1. The FECG.exe program employed here allows beat-to-beat CTG recording and numerical analysis of missed beats during intrapartum monitoring made by a scalp electrode. In this case the cardiotocograph toggles the Beat Flag at every new recognized fetal QRS complex and uses a modified communication command set.

II - 4.3 HIGH PRECISION MEASUREMENT OF HEART BEAT INTERVALS

In the FECG and MECG modes the Meridian 800 cardiotocograph gives a bleep at every recognized fetal or adult QRS complex.

Here using the self-developed HRMIC unit, time intervals between bleeps were measured to 0.1 ms precision.

The HRMIC contains a microphone that sends a signal to an electronic device at each bleep. The electronics produces an interrupt request of first priority at the COM1 serial port, which then starts a timer that measures the elapsed time to 0.1 ms. Heart beat interval data are simultaneously stored in an ASCII text file for later processing.

The accuracy of measurements performed was checked by two independent methods. During the first test, 1-s, 500-ms, and 250-ms signals of a crystal oscillator were measured (a high-quality piezoelectric quartz crystal was employed as the frequency controlling element). The crystal oscillators are actually some of the most precise devices currently available with tolerances of better than one part per million. The accuracy in trials proved to be better than 0.1 %.

In the second test a 16-bit SoundBlaster board was utilised to record a part of an original FECG intrapartum monitoring (a series of bleeps given by the Meridian 800). The sampling rate of the board is 44.1 KHz which provides CD-quality. Moreover the fact that a digital technique is employed to store data means that replaying the recorded file gives exactly the same sound result from bit to bit, regardless of how many times it is played. In this test fifty measurements were taken from the recorded sound file, and in two cases a difference of less than 0.1 % was found.

II - 4.4 DIGITAL RECORDING OF DIRECT FETAL ELECTROCARDIOGRAMS

The Meridian 800 allows intrapartum direct FECG recording to be carried out using any good-quality disposable scalp electrode. The electrode must be attached to the fetal scalp, avoiding face and fontanelles.

After connection of the electrodes a few minutes should be allowed for stabilisation of the electrode and fetal tissue. It is essential that the ECG signal electrodes are in good contact with both the fetal scalp and the vaginal wall.

The ECG waveform output was sampled at the isolated ECG front-end using an ITK-341 A/D converter board controlled by the Adacq4.exe program. The steps involved in the operation procedure of ITK-341 were the following: initialise, set channel, set gain, set timers, select DMA mode, read and save data. The DMA mode is a background operation which means it is processed via system time sharing.

The spectrum and nonlinear dynamics analysis require strictly continuous input data which in practice raises a technical problem. Unfortunately 16-bit operating systems, like that included in DOS 6.2, 6.0, etc, allow the addressing of only 640 KB of conventional memory, which dramatically reduces the maximum buffer size available for use. The management of extended memory, due to lack of sufficient information, is not very easy. For spectrum analysis the minimum record length is two minutes, but chaos theory analysis requires much longer records than this. Adacq4.exe solves the problem using DMA technique, disables the HDD caching, and saves data straight away. It is capable of saving and processing very long files as well.

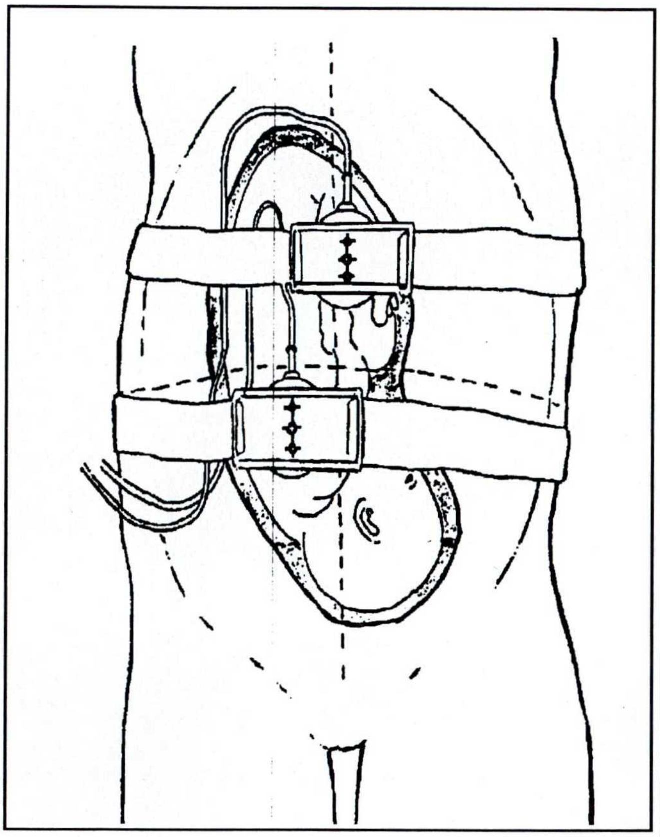
II - 4.4.1 High precision FHR measurements from direct FECG records

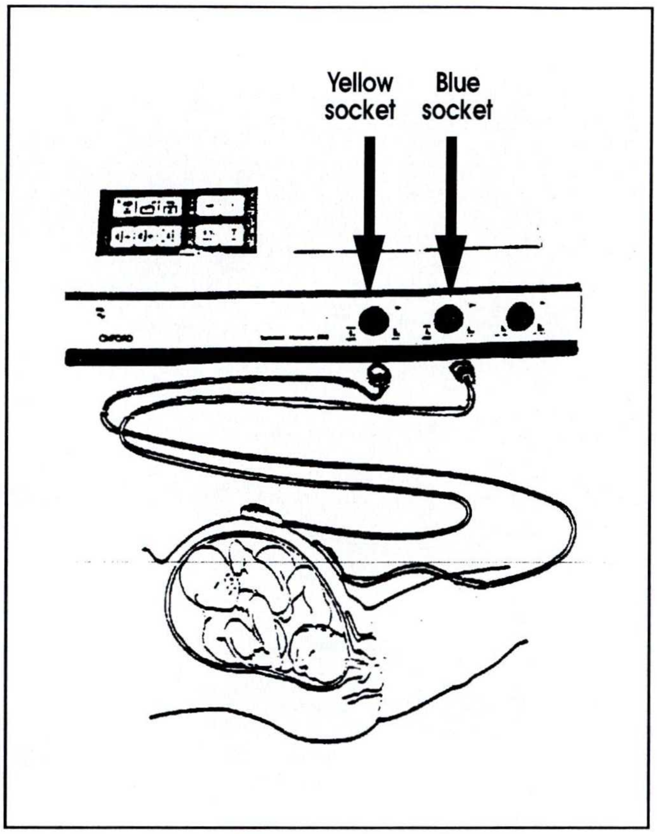
Adacq4.exe is able to load previously recorded file sets and display them on the screen. Using its heart rate function R peaks of the QRS complexes can easily be found (Figure 4-5), and the R-R interval automatically evaluated. This manual technique is suitable for checking automatic algorithms (like RRECG.exe) which search for R peaks in order to determine R-R interval values.

Before starting a new record, a sampling rate must be selected which lies in the range 1 to 20 KHz, say. Setting a 1 KHz sampling rate means that time difference between measured digital data is 1 ms. In this way the number of sampled data values between two R peaks gives the heart beat interval in milliseconds. Actually the higher the sampling rate, the higher the measurment accuracy. However, according to international literature and my own experience, 1 KHz is a reasonable choice.

II - 4.5 SURVEY OF THE HEART RATE DETECTION METHOD OF THE MERIDIAN 800 IN ECG MODE

To avoid any unwanted signal loss beat-to-beat heart rate values were read from the serial port of the Meridian 800 in MECG operation mode using the MECG.exe program, while time intervals between bleeps were measured by the HRMIC-Hrmic.exe program to 0.1 ms precision. At the same time the analogue ECG waveform output was sampled at a frequency of 1 KHz by the ITK-341-Adacq4.exe, and values of the three parallel records were compared.





a/ Transducer positioning

Figure 4-1

b/ Connections for the monitoring of twins - ULT/ULT

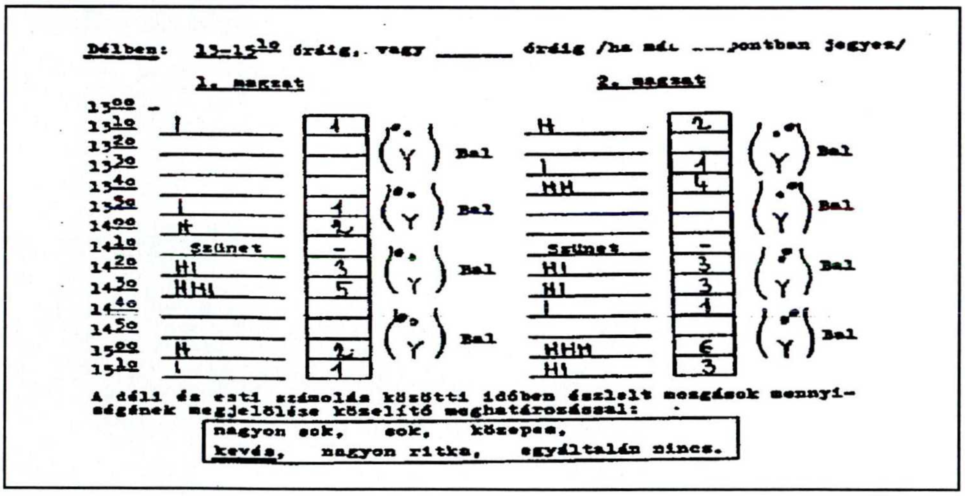


Figure 4-2

A data sheet (a section)

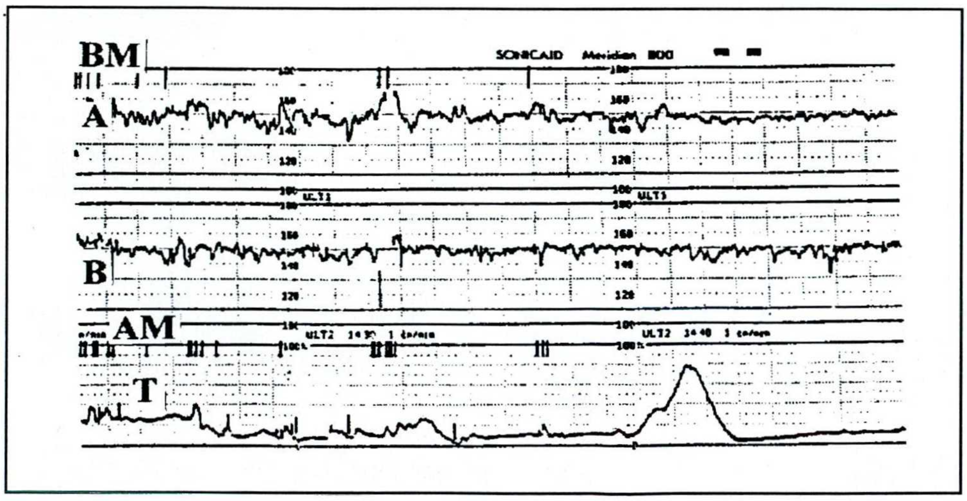


Figure 4-3

A Meridian 800 CTG record with separately registered FM

(BM=FM-Fetus B [clinical event marker], A=FHR trace Fetus A, B=FHR trace Fetus B, AM=FM-Fetus-A [patient event marker], T=tocometer trace)

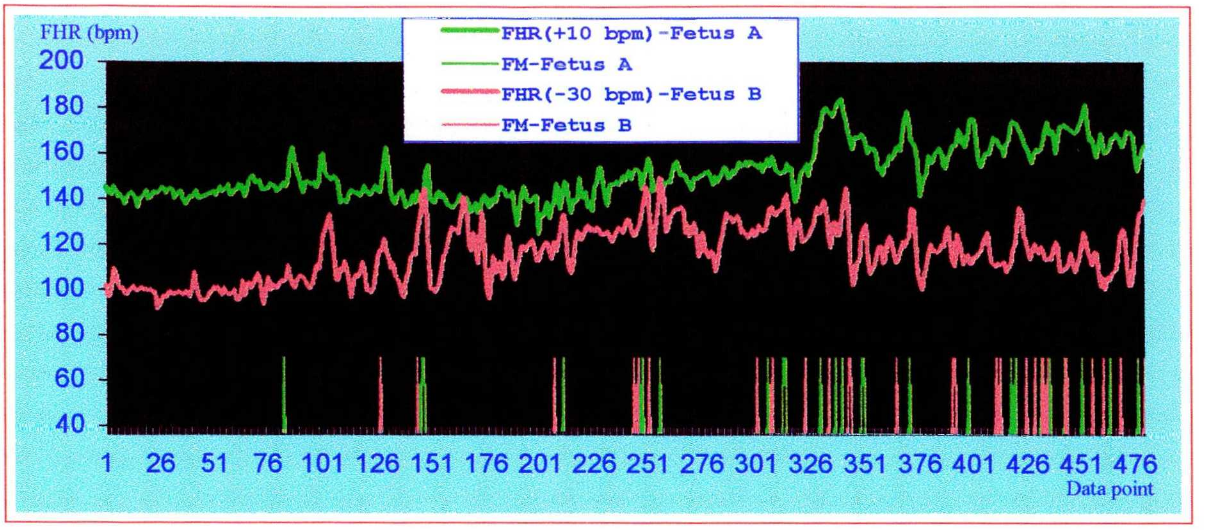


Figure 4-4
A real simultaneous System 8000 record of twins (FHR and FM)

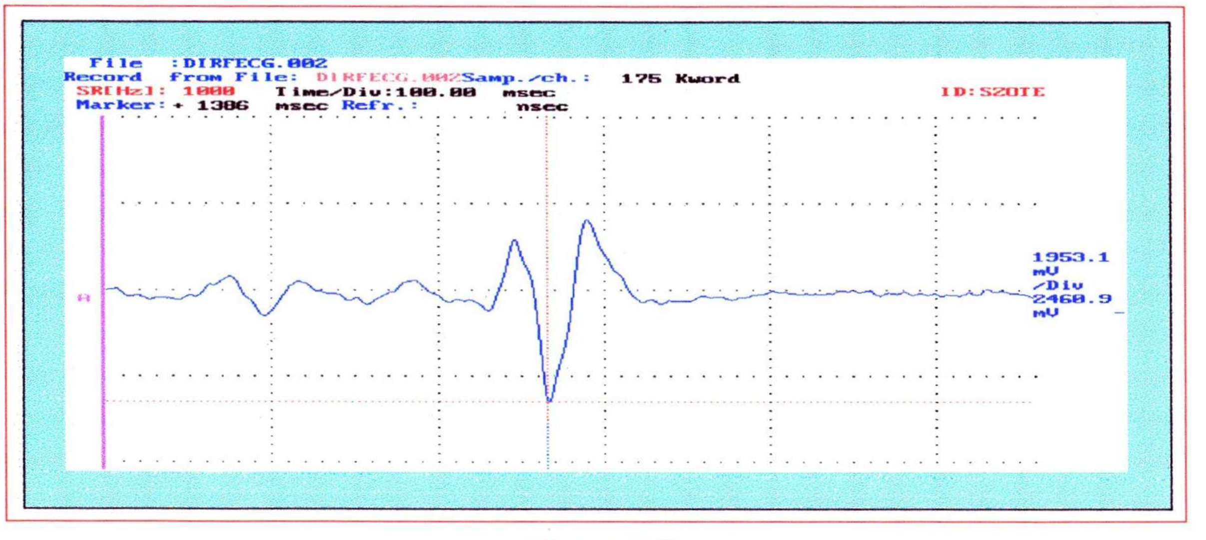


Figure 4-5
An R peak found (direct digital FECG record)

5 STUDIES AND RESULTS

Topic I

I - 5.1 PSEUDO-SIMULTANEOUS OBJECTIVE CTG RECORDINGS OF TWIN PREGNANCIES

I - 5.1.1 Evaluation of the fetal movement distribution of twins by maternal perception

According to the method outlined in Section I - 4.1.2, data sets totalling 47 days in length have been amassed from 12 gravidas. Altogether, 1299 ten-minute periods were analysed from the point of view of two study groups. The first one was where the number of movements of Fetus A and Fetus B was different during the ten-minute period (labelled Group I in the diagrams), while the second group was where the number of movements of both fetuses was equal (labelled Group II in the diagrams). The results are presented here in the Figures 5-1, 5-2 and 5-3.

In the diagrams the movement pattern of Fetus A and Fetus B can be considered different, but highly interdependent. This is surely indicated by the unambiguous difference between Group I and Group II (Figure 5-1), but there was no marked difference in the values of Fetus A and Fetus B within the Group I (Figure 5-2, 5-3).

I - 5.1.2 Pseudo-simultaneous objective monitoring of twins with separately registered fetal movements

Making use of the method described in Section I - 4.1.3, 128 sample records of 50 twin pregnancies were taken. The average recording time was 34 minutes, and average gestational age was 33 weeks. The number of accelerations was 1190, while the number of accelerations per record was found to be 9.3. In the literature accelerations are considered simultaneous if that of one twin occurs within 15 seconds after the onset in the other [49]. Similarly the time limit for FM is 15 seconds before or after the acceleration. The single accelerations of Fetus A and Fetus B, and the simultaneous AB accelerations were counted separately depending whether they occurred with or without fetal movements. Upon medication, the gravidas were divided into a neutral-treatment (Group I) and an oral-tocolysis (Group II) study group.

The results of the findings are presented in Tables 5-1 and 5-2, and in Figure 5-4.

As can clearly be seen, there was a considerable difference in the synchronous AB accelerations in either Group I and II, or the values with and without movements. This suggests that synchronous accelerations with and without movements are of crucial importance in the assessment of twins' intrauterine well-being.

I - 5.2 REAL SIMULTANEOUS OBJECTIVE CTG RECORDINGS OF TWIN PREGNANCIES

Using the technique outlined in Section I - 4.2, 58 recordings of 16 twin pregnancies were performed. The clinical evaluation supported by an impartial simultaneous computer analysis for both Fetus A and Fetus B was as follows: reactive 95 cases (81.9 %), suspect 19 cases (16.4 %), abnormal 2 cases (1.7 %). The average gestational age was 34 weeks, and average recording time 31 minutes. In nearly 88 % of the samples taken signal loss occurred for both fetuses, 8.5 % per record on average.

In the study a total of 714 accelerations were noted in all, while the average number of accelerations per recording was 12.3. The ratio of the accelerations without FM (3.5) was 40 % of the accelerations with FM (8.8), and on average an acceleration occurred every 1.8 movements. A synchronous AB acceleration was noted in 159 cases, while a single Fetus A acceleration and single Fetus B acceleration occurred in 192 cases and 204 cases respectively.

In the case of Fetus A the length of high variability episodes was 41.3 %, while for Fetus B it was 42.6 % of the total recording time (1798 minutes). The ratio of the simultaneous AB high episodes was 21.6 %, while the values of low variability episodes were 11.5 %, 13.9 %, and 3.6 % respectively (Figure 5-5, 5-6).

The data sets were analysed according to whether the single or synchronous accelerations took place with or without movements (Figure 5-7, 5-8).

The average values of other parameters used in the automatic numerical analysis are summarized in Figure 5-9.

The number of AB synchronous accelerations without movement was consistently quite low when compared to the synchronous AB accelerations with movement or the single A or B accelerations without movement. These data plots then suggest that not only are the evaluation of synchronous accelerations important, but so is the analysis of movements present or absent in the assessment of reactivity. However, it should be kept in mind that the recordings presented here were mostly reactive, which can have a significant influence on the results obtained in a study.

I - 5.3 BASELINE FITTING TO FHR DATA

Going over the two methods described in Section I - 4.3, it can be seen that the P starting value plays a crucial role in both procedures. The more precise the P value is, the better are the results obtained (Figures 5-10, 5-11, 5-12).

To find the optimum starting point values is not easy and may become quite time consuming if one has to scan through the frequency distribution of the FHR data to obtain them. In the study two different approaches were applied to overcome this problem. In the first case the forward and backward dummy runs of the Dalton-Dawson-Dawes method were started by selecting the minimum value (in bpm) of the given recording (Figure 5-11). Next, the algorithm looked for the start points, at the beginning and the end of the record, where the dummy baseline was the closest to the FHR tracing and was the most horizontal (Figure 5-12). It should also be mentioned that the beginning and end of a record can have quite different trends, which is why it is necessary to look for the start and end points separately. This method provides good results, but it may take some time to find the starting values.

The baseline itself can be defined as a hypothetical heart rate which might have been observed if accelerations or decelerations had not occurred. However, because of its hypothetical nature only visual assessment can verify whether it has any real validity. A baseline fitting by eye first identifies accelerations and decelerations, which are noted for having considerably different slopes with peaks, and unusually low datum-to-datum FHR variability. A baseline is then built up from the rest of the FHR tracing, which generally has an almost horizontal or moderately wavy trend line, and generally higher variability than that for accelerations.

Choosing the starting value of the Dalton-Dawson-Dawes method by eye the instinctively selected point was normally the average value of the first segment trace where the slope was closest to the horizontal.

In the second approach this method was imitated algorithmically. As can be seen the results indicate good start and end points, and faithful follow the natural baseline shifts (see Figures 5-13 and 5-14). In addition, this procedure does not need dummy runs to determine the best estimates of B_0 and C_{N+1}, because it finds them during the filtering procedure. The other crucial factor which needs to be mentioned here is the stability of baseline, especially in the environment of groups of accelerations or repeated large swings of FHR. Keeping the output constant when the input signal reaches values beyond the range of P $\pm$ 60 ms [45] (P represents a relative peak in the frequency distribution of the signal), does not always provide good results. However, if the output is kept constant according to the criteria of accelerations, and the frequency domain (bpm) is used instead of the time domain (ms), the results turn out to be quite satisfactory (see Figure 5-15).

Another useful modification concerned the value of the R parameter. In the original algorithm it was 0.95. However when its value was changed to 0.97 the baseline estimation was found to be more stable when accelerations occurred, without losing the faithful following of the natural baseline shifts.

The Mantel method [46] is not elaborated upon here because, when employed in practice, it was not found to work properly on recordings less than two hours in duration and its five-run iterative procedure took up too much CPU time as well.

The applied modifications outlined above eliminated all of the drawbacks of the Dalton-Dawson-Dawes method while keeping all its advantages. But to confirm which method provides better estimations is currently only possible using visual assessments that remain as subjective and inaccurate as ever.

I - 5.4 DETECTION OF SYNCHRONOUS ACCELERATIONS WITH OR WITHOUT FM IN TWIN PREGNANCIES USING A COMPUTER PROGRAM

Using the method described in Section I - 4.4 the synchronous accelerations with or without FM were found (see Figures 5-16, 5-17, and 5-18). The results were not really different from that obtained by the manual technique, but the computer method was nicer and faster. However, in the case of high signal loss the automated numerical analysis approach can have difficulties. Therefore it is highly recommended that the location of each fetal heart be determined from a 2D ultrasound scan before commencing the twin CTG recording.

I - 5.5 ESTIMATION OF FRACTAL DIMENSIONS

The objective was to study whether the box-counting method was suitable for estimating the fractal dimension of FHR records.

Analysing the boxcount.c source code [44], it was found that the original program uses the lineto(x, y) function, which means that it interpolates between the data points (Figure 5-19). Unfortunately the algorithm it uses depends on the screen resolution, so the box count values and the dimension estimations will in general vary (see Table 5-3).

In numerical approach used here the lineto(x, y) function was changed to the setpixel(x, y) function which plots only the pixel points of the corresponding FHR values (Figure 5-20). But while real box counts were obtained, fractal estimates changed in a surprising way (Table 5-3).

To see what was happening visually the FHR data sets were entered into a Windows drawing program written by me using MS Visual Basic. The picture was then copied to the screen of the FractalVision for Windows software facility, and its fractal dimension estimation function was activated. The results were that different values were obtained. However, it was recognised that the software used boxes 2, 4, 8, 16, and 32 pixels wide instead of the values given in the original description [44]. After modifying the Fractdim.exe program written by me the average of box size 8, and 16, gave tolerably acceptable estimates. Several FHR tracings were then tested and the results seemed consistent. In some cases the fractal estimates were less satisfactory. This can be seen in the following examples depicted in Figures 5-21 and 5-22. Here, as in the other methods, the problem of window length seemed to arise. After considering the question it was concluded that, not a precise dimension value, but an independent parameter is needed to reliably estimate the irregularity of FHR tracings. When one measures the length of an irregular coastline the precise results depend on the length of the measure ruler applied. Thus a measuring stick 50 scale miles long, say, reports a shorter distance than a 1-mile long measure. Using different ruler lengths the fractal dimension of the coastline can be estimated, which is a procedure first suggested by Mandelbrot [50].

A program was written by me that measured the length of the "coastline" of a FHR tracing using 1, 2, 4, 6, 8-unit long rulers. After taking several measurements, the most reliable results which could be obtained were from that using the ratio of the length of 1-unit ruler and the number of data points. The more irregular an FHR tracing, the longer its length from point to point. However, this method gave exactly the same result as the STV parameter of the System 8000.

I - 5.6 INTERNAL TREND ANALYSIS OF SYSTEM 8000 CTG RECORDS

I - 5.6.1 Internal trend analysis after baseline fitting using mean minute range and FM values

Two 60-minute records are presented here as particular examples for study. The first one met the Dawes/Redman criteria of System 8000 at 44 minutes, and the visual evaluation also found it reactive. The second one was positive, and did not meet the criteria at 60 minutes (Figure 5-23).

In the positive case there were hardly any fetal movements, whereas in the reactive case, especially in the second part of the sample record, there were several (Figure 5-23). As can be seen, the one-minute variability lies below the normal range 86.7 % of the time, and 46.7 % in the abnormal range (Figure 5-24).

In the reactive case variability was outside the normal range for 61.7 % of the time, and in the abnormal range for 40 % of the time (Figure 5-25).

This form of internal trend analysis can also be employed to study the CTG parameters of simultaneous fetal events and twin behaviour physiology.

I - 5.6.2 Internal trend analysis of twin CTG records using STV and FM values

Here the same technique as that described in Section I - 4.6.2 was utilised, from which an STV and FM trend analysis of three good quality, real simultaneous twin recordings are presented for comparison in Figures 5-26, 5-27 and 5-28. In trials the 2-minute STV and FM trend proved the most informative (Figure 5-27).

Topic II

II - 5.1 SIGNAL LOSS OF BEAT-TO-BEAT CTG RECORDS MADE USING AN ABDOMINAL ULTRASOUND TRANSDUCER

Twenty, thirty minute long antepartum CTG records were made using a TEAM fetal monitor, the beat-to-beat data and signal loss being measured in the way described in Section II-4.1. At the same time all records were stored in the TEAM memory buffer, and later transferred to the System 8000 for analysis. The length of the unfragmented segments was determined by the macro module of the Missbeat.xls Excel 5.0 workbook.

The corresponding data obtained from the trials are presented in Table 5-4.

In the case of a signal loss of 0.0 % according to the System 8000, beat-to-beat signal loss ranged between 2.6 % and 10.4 %. It might seem surprising at first to see that, say, the 4th record where the corresponding value of 0.1 % was 15.2 %. The reason for this is that the 1/16 min interval technique used by the System 8000 calculates one data value as the average of all heart-beat intervals detected over 3.75 s. If three to four detected intervals are regularly followed by one or two missed intervals, then the signal loss of System 8000 will be quite low because the system recognizes data as valid over almost every 3.75-s period. But in the 7th record it is just the opposite. At the beginning of the record there were two nearly 2-minute long segments without input data from the transducer, also detected by the Oxford system. But during the rest of the record the beat-to-beat signal loss was not too high, so the total signal loss remained relatively low.

In the third column of the Table 5-4 the length of the longest segments of the given record can be seen to be without any beat-to-beat signal loss.

II - 5.2 DATA STRUCTURE OF BEAT-TO-BEAT INTRAPARTUM CTG RECORDS MADE USING A SCALP ELECTRODE

Here using the FECG.exe program four intrapartum recordings were performed on pregnancies judged to be at high risk. The FHR data sets were obtained from good-quality disposable direct scalp electrodes, and the beat-to-beat signal loss was less than 1 %. During the four intrapartum records 18 abrupt decelerations were observed.

At each abrupt deceleration, without exception the signal loss (which during the whole record was negligibly low) suddenly became unacceptably high. Watching directly on the computer monitor screen how the new-beat flag toggled, it could clearly be seen that the Meridian 800 recognized this dramatic frequency decrease only after a considerable delay (3 to 4 seconds).

Due to lack of space here only one case is presented immediately before the Cesarian section was performed (see Table 5-5).

II - 5.3 HIGH PRECISION MEASUREMENT OF HEART BEAT INTERVALS

Employing the technique described in Section II - 4.3, 11 intrapartum beat-to-beat recordings were made. The HRMIC device detected faithfully even the abrupt frequency changes. However, all records showed an artifical-type regularity to a greater or lesser extent (Figure 5-29, 5-31).

During the test measurements the HRMIC device could be categorically excluded as a source of any artificial signal. It was therefore eventually concluded that the Meridian 800 fetal monitor should detect the ECG QRS complexes using a threshold technique. This means that if the input signal level rises above the threshold, the hardware identifies it as a QRS complex. However, because the waveform is not really regular the triggering point can sometimes vary and produce the observed artificial regularity in the data.

II - 5.4 HIGH PRECISION FHR MEASUREMENT FROM DIRECT FECG RECORDS

Six direct intrapartum FECG records were made according to the method described in Section II - 4.4., none of which showed artificial-type regularity in the data (see Figure 5-30, 5-32).

II - 5.5 SURVEY OF THE HEART RATE DETECTION METHOD OF THE MERIDIAN 800 IN ECG MODE

According to the method presented in Section II - 4.5, 50 parallel values were compared to each other (Table 5-6.).

Overall the results of the comparison suggest that the QRS complex detection method of the Meridian 800 actually does not provide the exact R-R interval value. Furthermore, the electronic circuitry which produces the bleeping sounds in the trials seems to produce some additional inaccuracy.

	Group I	Group II	Group I-II
WITHOUT MOVEMENT			
Fetus A	1.2	1.2	1.2
Fetus B	0.8	0.3	0.7
AB synchronous	1.4	0.4	1.0
Total	3.4	1.9	2.9
WITH MOVEMENT			
Fetus A	2.6	2.4	2.5
Fetus B	0.9	1.2	1.0
AB synchronous	3.4	1.9	2.9
Total	6.9	5.5	6.4
TOTAL			
Fetus A	3.8	3.6	3.7
Fetus B	1.7	1.5	1.7
AB synchronous	4.8	2.3	3.9
Total	10.3	7.4	9.3
The ratio of accelerations with and without FM	**1 : 2**	**1 : 3**	
Group II in the percentage of Group I			
without movement		55.9	
with movement		79.7	
Total		71.8	

Table 5-1
The number of accelerations per record

	Fetus A	Fetus B	AB synchronous
WITHOUT MOVEMENT			
Group I	36.0	24.5	39.5
Group II	59.8	19.5	20.7
Total	41.2	23.5	35.3
WITH MOVEMENT			
Group I	37.5	12.7	49.8
Group II	42.5	22.1	35.4
Total	38.9	15.2	45.9
TOTAL			
Group I	37.0	16.6	46.4
Group II	47.2	21.4	31.4
Total	39.6	17.8	42.6

Table 5-2 The percentage of accelerations (A+B+AB = 100%)

A	B	C
598	2	14.0
556	2	14.0
549	2	15.0
546	2	16.5
608	2	15.5
618	2	15.0
2 beats missed!?		17.5
308	2	17.5
5 beats missed!?		20.0
273	2	20.0
3 beats missed!?		21.0
262	2	21.0
2 beats missed!?		21.5
240	2	21.5
3 beats missed!?		22.5
238	2	22.5
2 beats missed!?		24.0
240	2	24.0
3 beats missed!?		23.0
236	2	23.0
3 beats missed!?		25.0

Table 5-5
Beat-to-beat data values of an intrapartum CTG record
(A: FHR/ms [!? = a data of 95% accuracy], B: signal quality [2 = excellent, C: tocometer value [%])

	Equal	Different
Meridian 800	10	40
HRMIC	2	48

Table 5-6 Digital ECG heart beat interval values compared to values measured simultaneously by the Meridian 800 and HRMIC [n=50]

	Screen resolution		Box count	
	640 x 480	320 x 200	640 x 480	320 x 200
Box size 2	1.156005	1.167786	1444	674
Box size 4	1.245935	1.178981	648	300
Box size 6	1.198163	1.218530	391	186
Average	1.200034	1.188433		

Function lineto (x, y)

	Screen resolution		Box count	
	640 x 480	320 x 200	640 x 480	320 x 200
Box size 2	0.345616	0.345616	568	568
Box size 4	0.682077	0.682077	447	447
Box size 6	0.882384	0.882384	339	339
Average	0.636692	0.636692		

Function setpixel (x, y)

Table 5-3 Estimated fractal dimension values of the box-counting method using different screen resolutions

	Signal loss %		Longest unfragmanted segment
	System 8000	Beat-to-beat	
Record 18	0.0	2.6	3 min 45.326 sec
Record 14	0.0	5.5	3 min 15.116 sec
Record 3	0.0	5.4	3 min 11.709 sec
Record 15	0.2	9.2	2 min 47.492 sec
Record 10	0.0	9.7	1 min 48.698 sec
Record 13	1.3	9.5	1 min 39.890 sec
Record 6	0.5	14.6	1 min 38.424 sec
Record 8	0.0	10.4	1 min 35.278 sec
Record 16	0.6	8.6	1 min 32.564 sec
Record 2	0.5	9.4	1 min 31.067 sec
Record 5	0.6	16.3	1 min 23.246 sec
Record 1	0.0	7.1	1 min 23.006 sec
Record 7	1.8	5.2	0 min 59.337 sec
Record 19	1.0	13.9	0 min 58.120 sec
Record 9	3.6	11.3	0 min 53.865 sec
Record 4	0.1	15.2	0 min 53.134 sec
Record 12	8.7	31.5	0 min 50.979 sec
Record 11	0.6	13.3	0 min 41.476 sec
Record 20	9.1	29.1	0 min 32.332 sec
Record 17	17.2	37.6	0 min 29.536 sec

Table 5-4 The longest unfragmented segment of 20 beat-to-beat FHR records

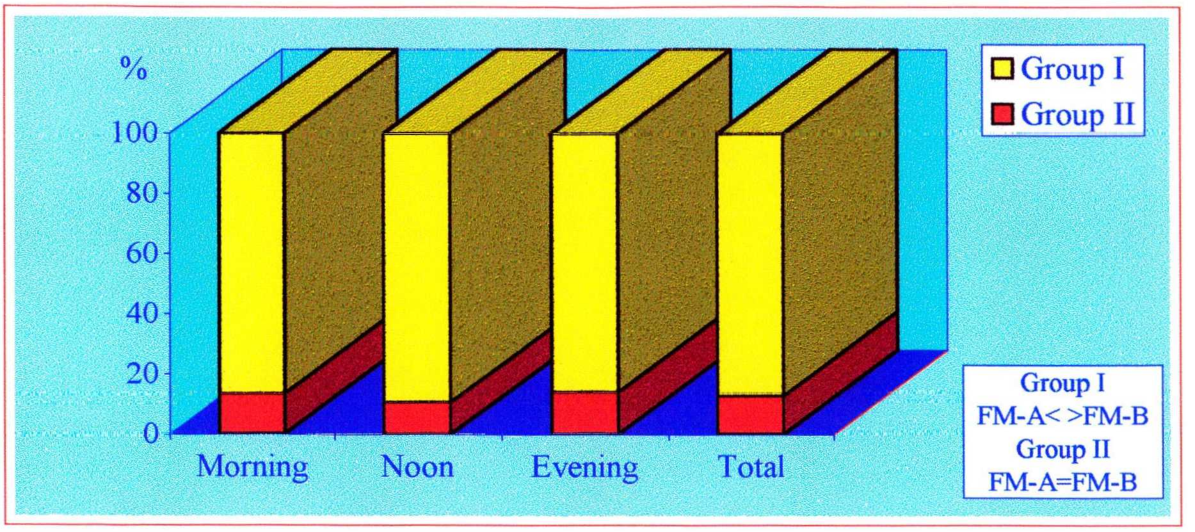


Figure 5-1 The percentage of 10-minute periods in the Group I and Group II in the morning, at noon, and in the evening (n=1299)

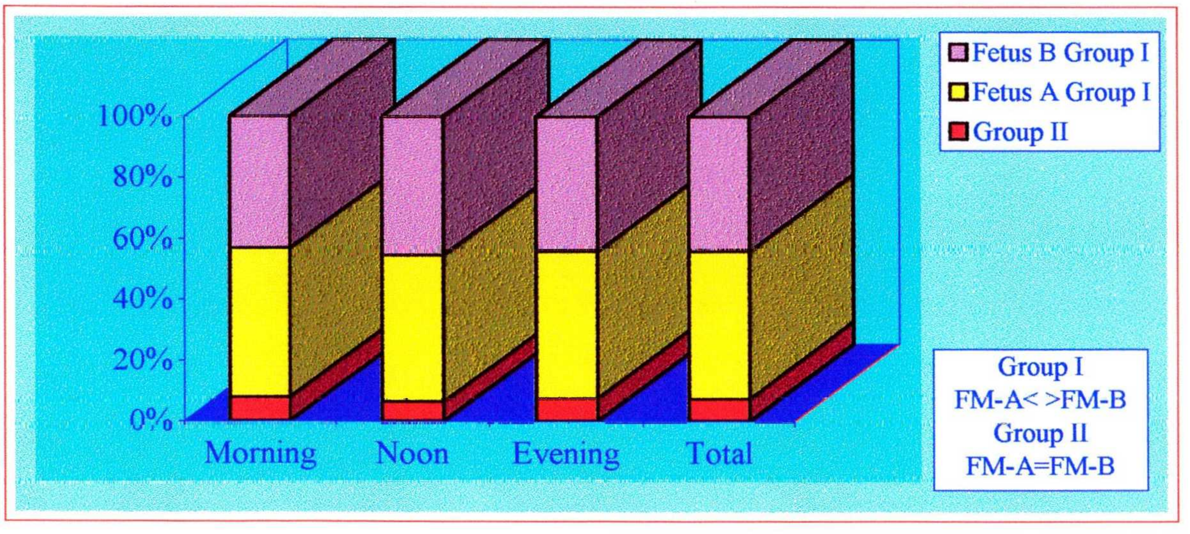


Figure 5-2

The percentage of fetal movements (n=10726) in the Group I and Group II

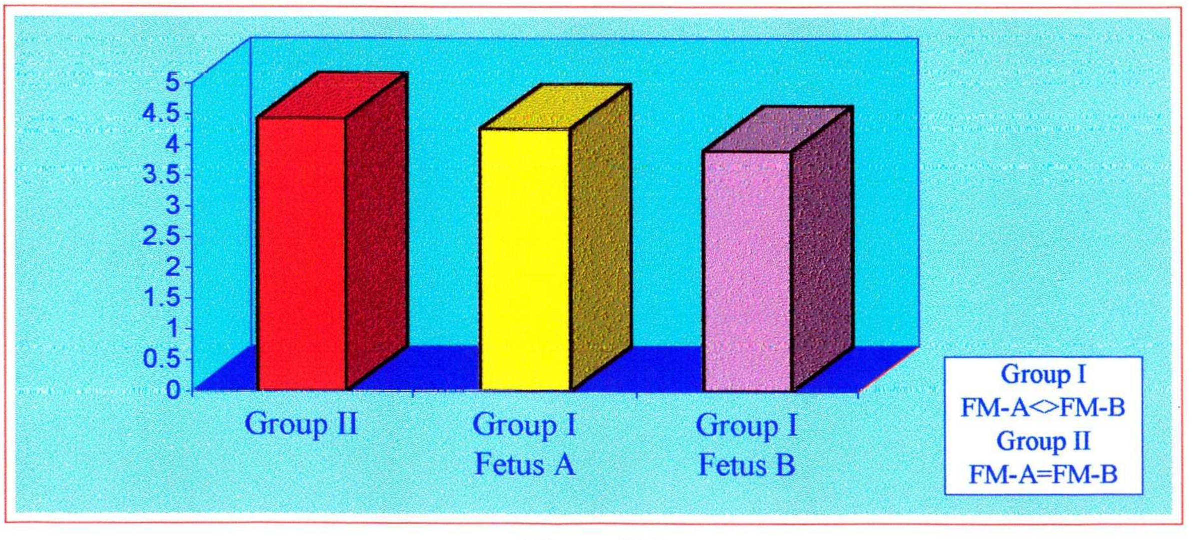


Figure 5-3

The average fetal movement number obtained during a 10-minute period

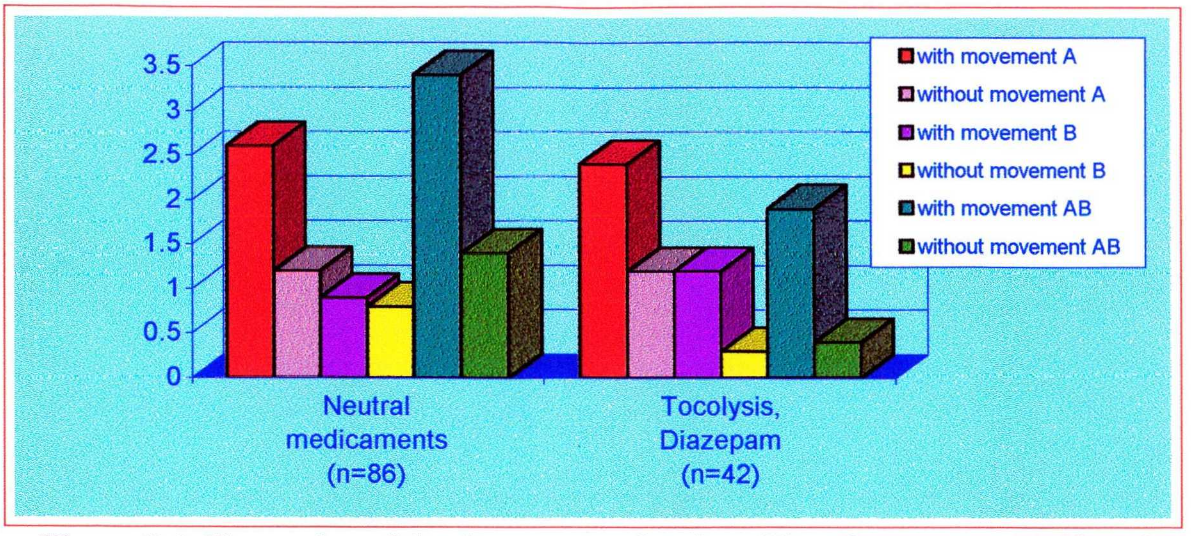


Figure 5-4 The number of simultaneous accelerations (No. of pregnants: 50. No. of recordings [n] 128. Accelerations: 1190. Acceleration/recording ratio: 9.3)

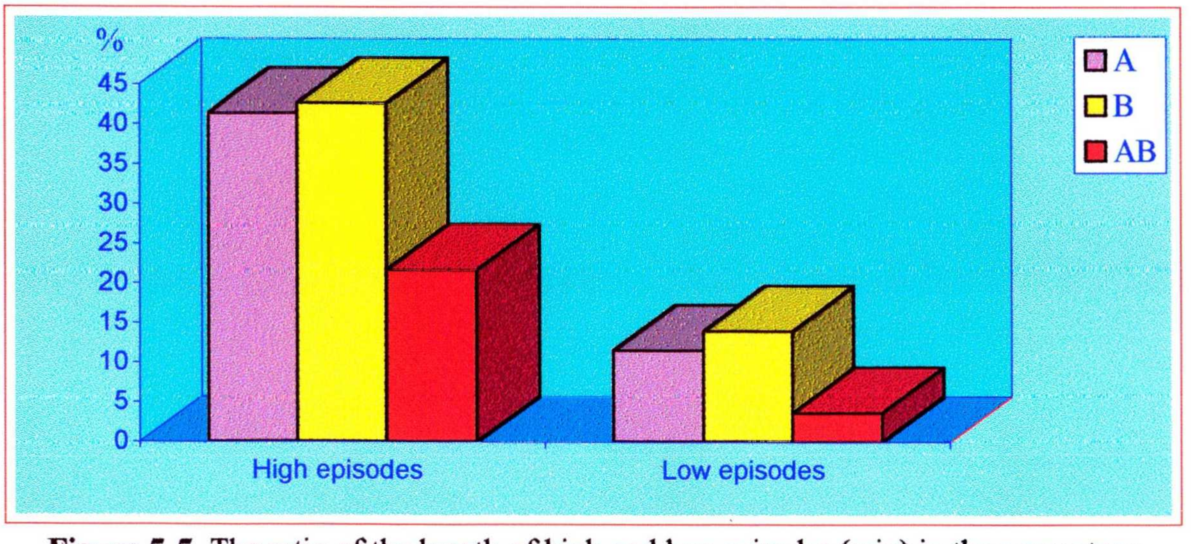


Figure 5-5 The ratio of the length of high and low episodes (min) in the percentage of the total recording time [n=1798 min]

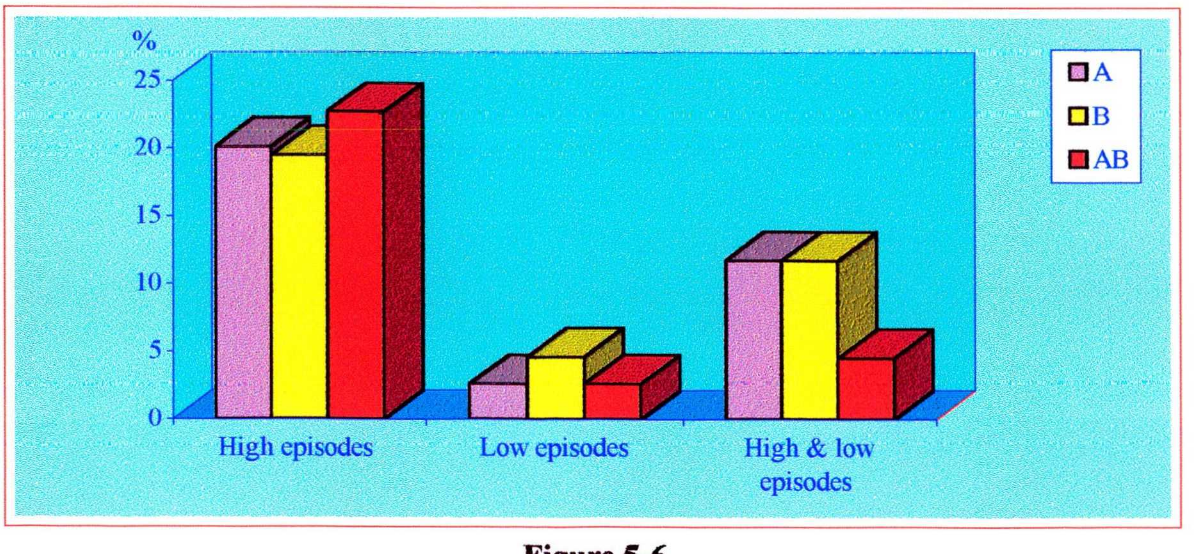


Figure 5-6

The ratio of records with high and low episodes in the percentage of all records [n=116]

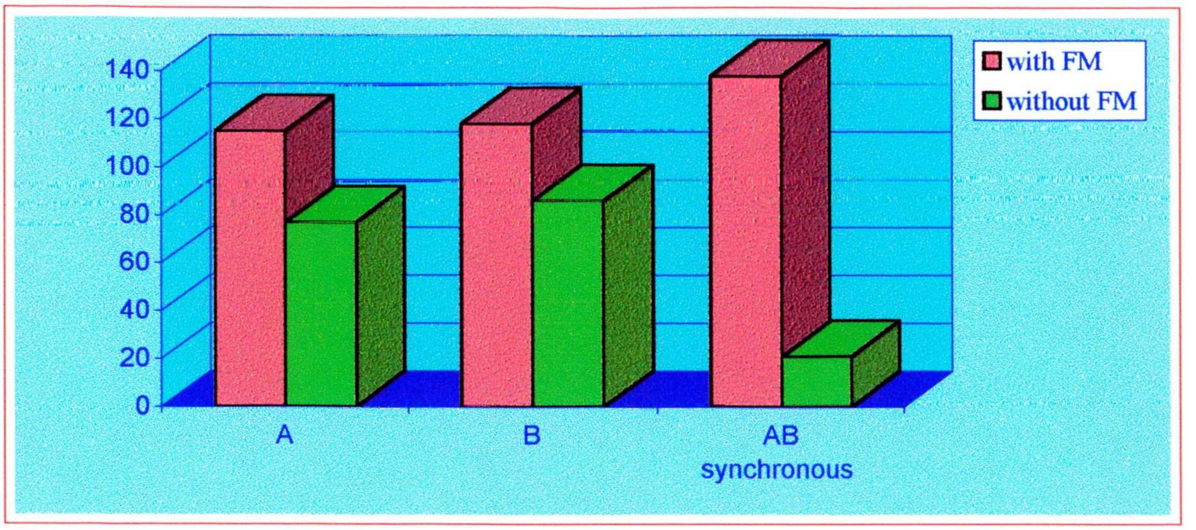


Figure 5-7
The number of accelerations with and without FM [n=714]

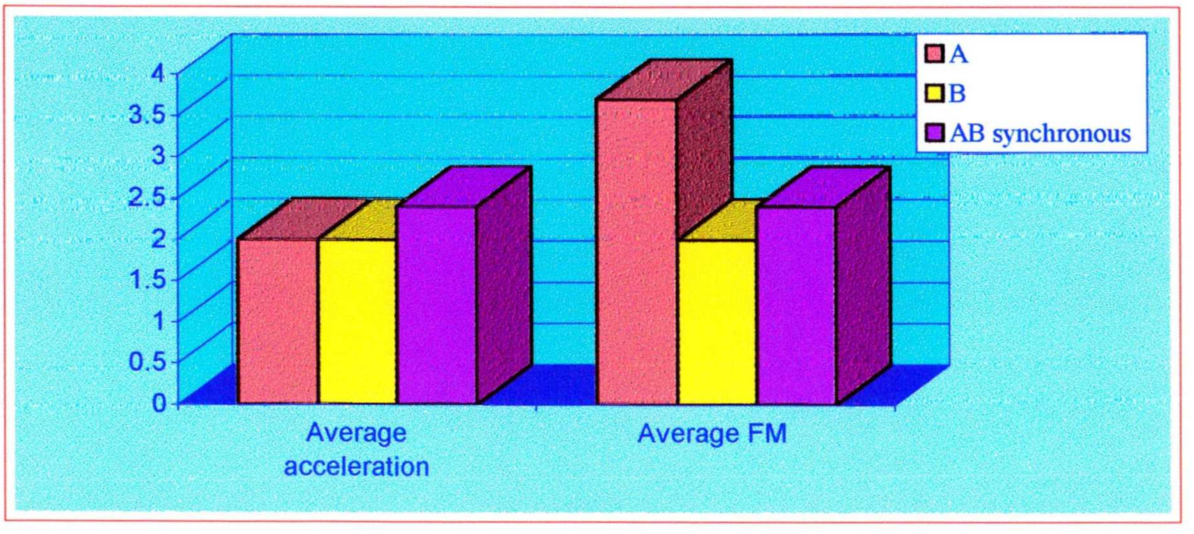


Figure 5-8
The average number of accelerations and FM

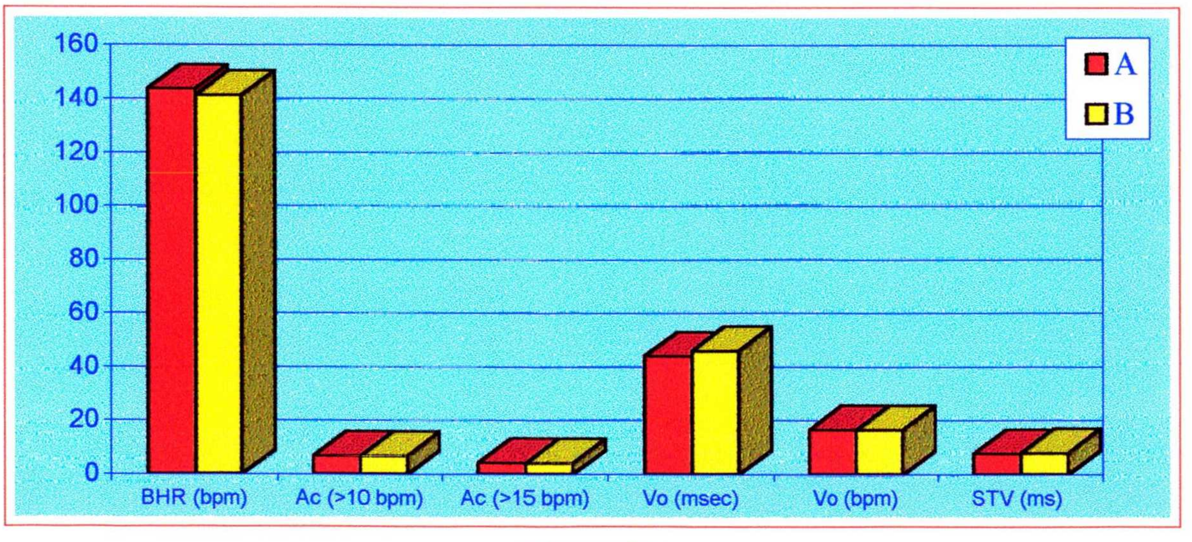


Figure 5-9
The average value of System 8000 analysis parameters

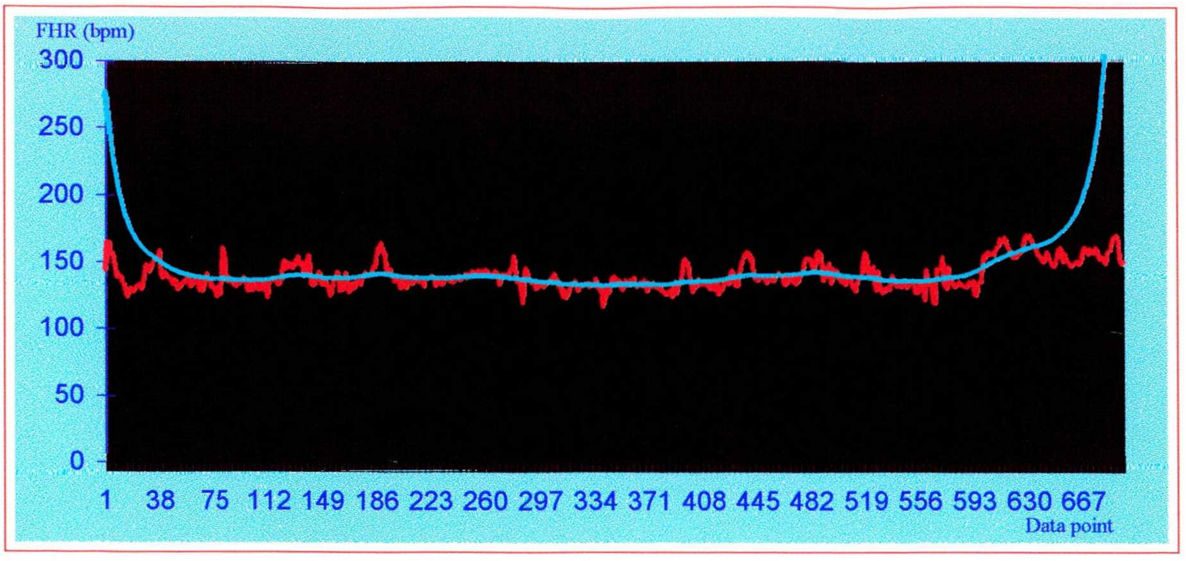


Figure 5-10

Dawes algorithm with $B_{n-1} = C_{n+1} = 0$

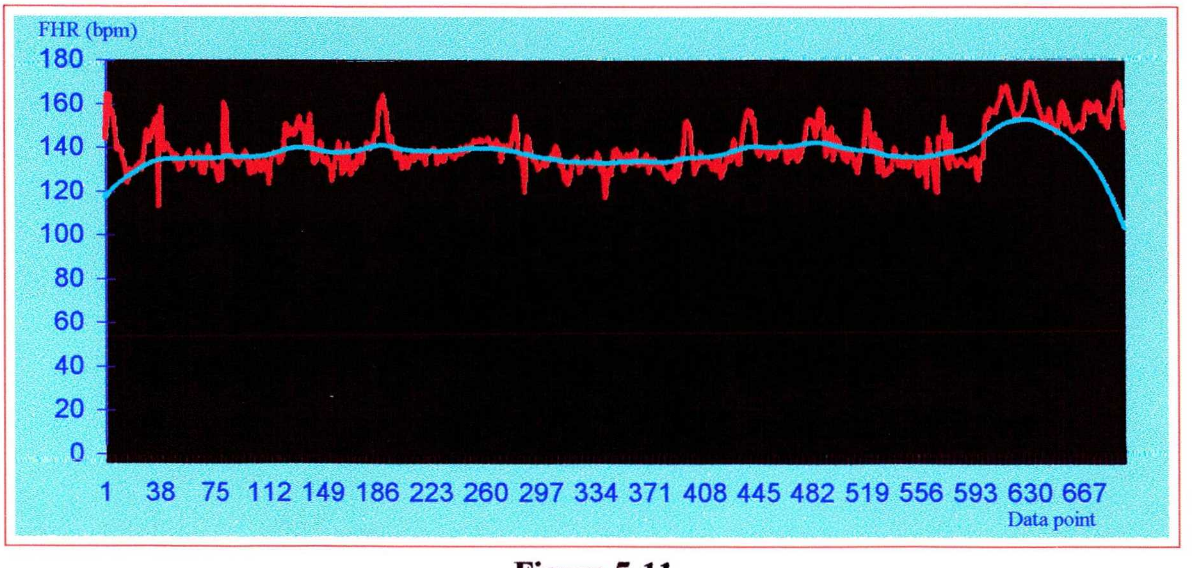


Figure 5-11

Dawes algorithm with $B_{n-1} = C_{n+1} =$ the minimum of FHR values (bpm)

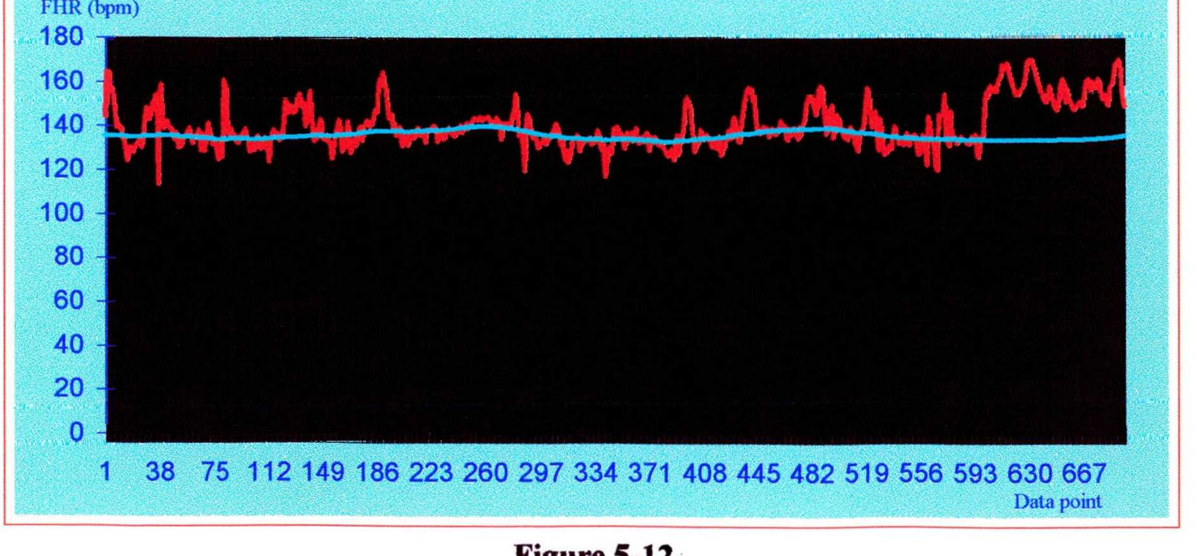


Figure 5-12

Modified Dawes algorithm with $B_{n-1} = C_{n+1} =$ optimal

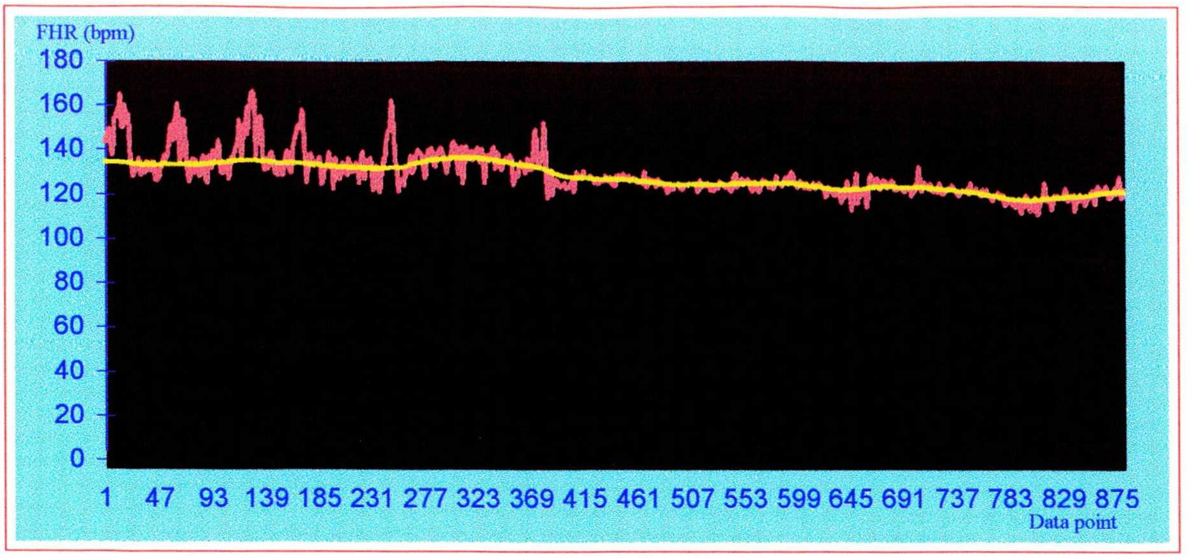


Figure 5-13

Baseline fitting using the modified Dawes algorithm

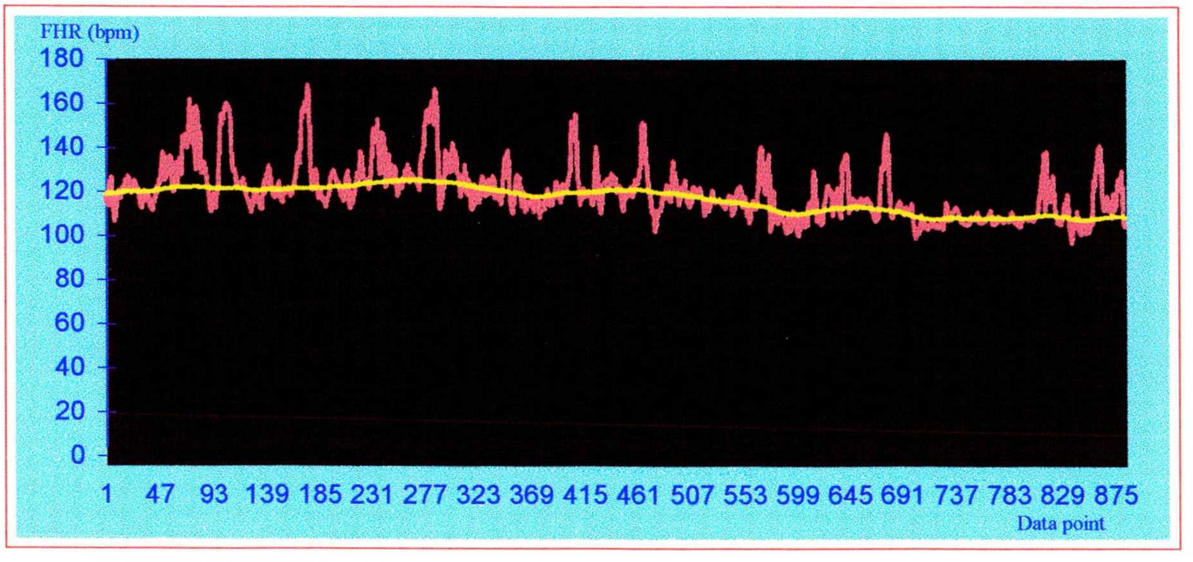


Figure 5-14

Baseline fitting using the modified Dawes algorithm

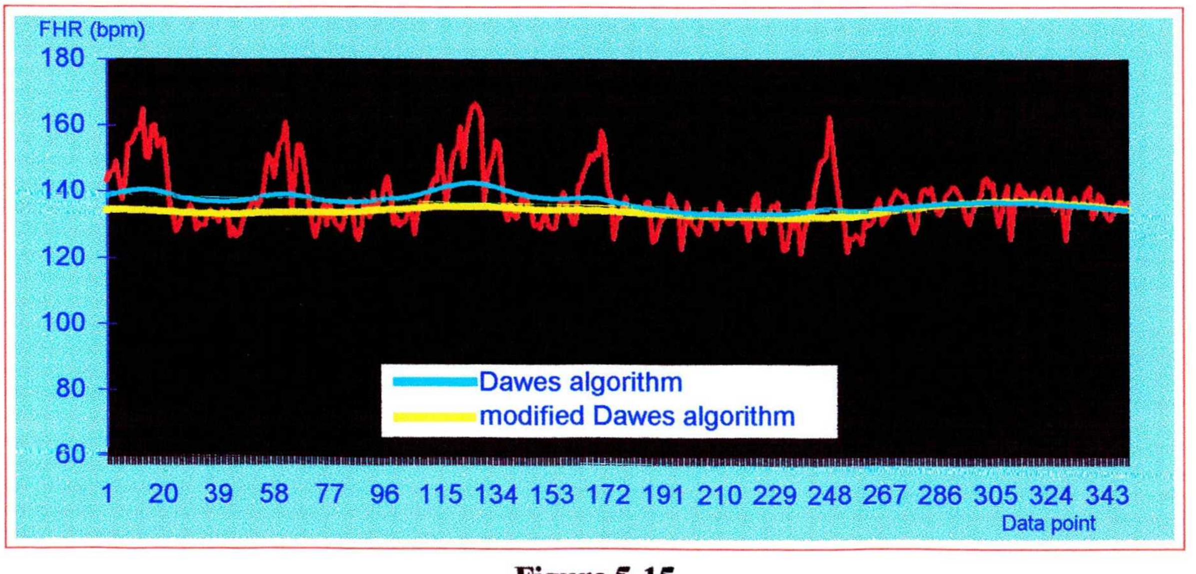


Figure 5-15

Comparison of the BL fitted by the Dawes and the modified Dawes algorithm

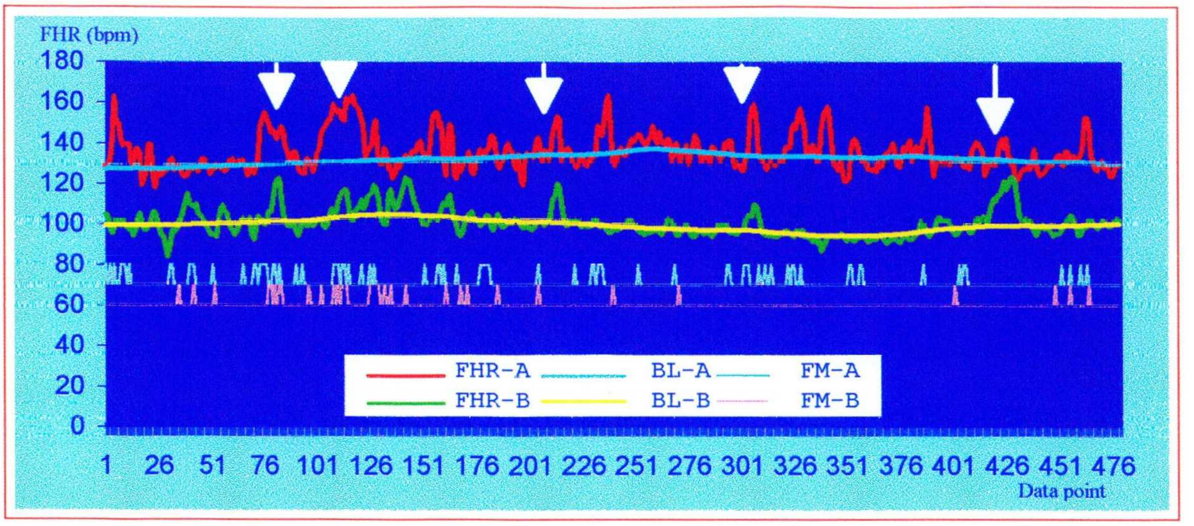


Figure 5-16 A real simultaneous antepartum objective CTG twin record (white arrow = synchronous AB acceleration)

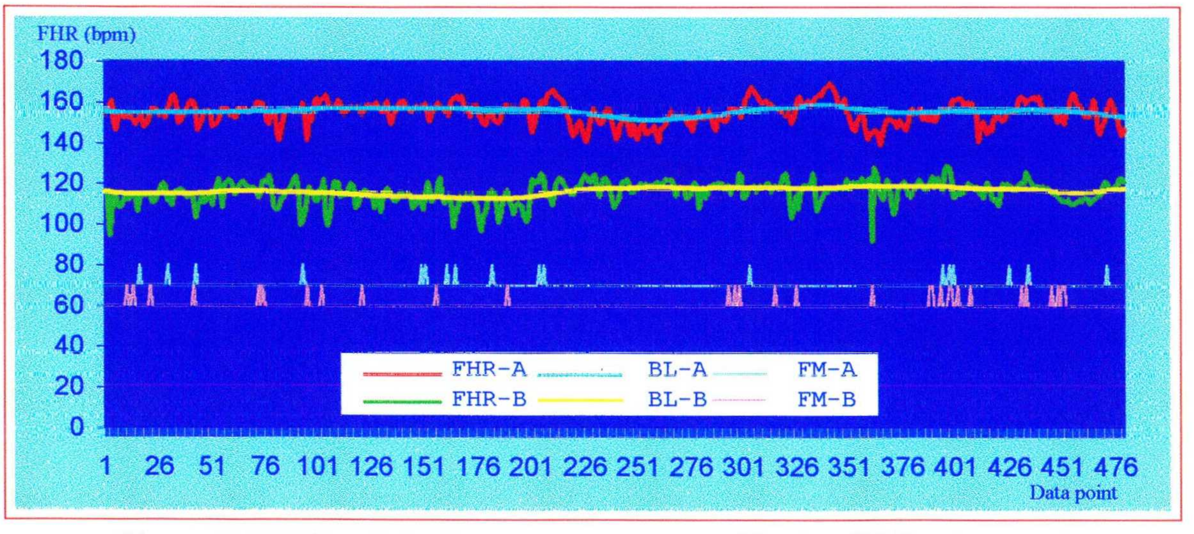


Figure 5-17 A real simultaneous antepartum objective CTG twin record

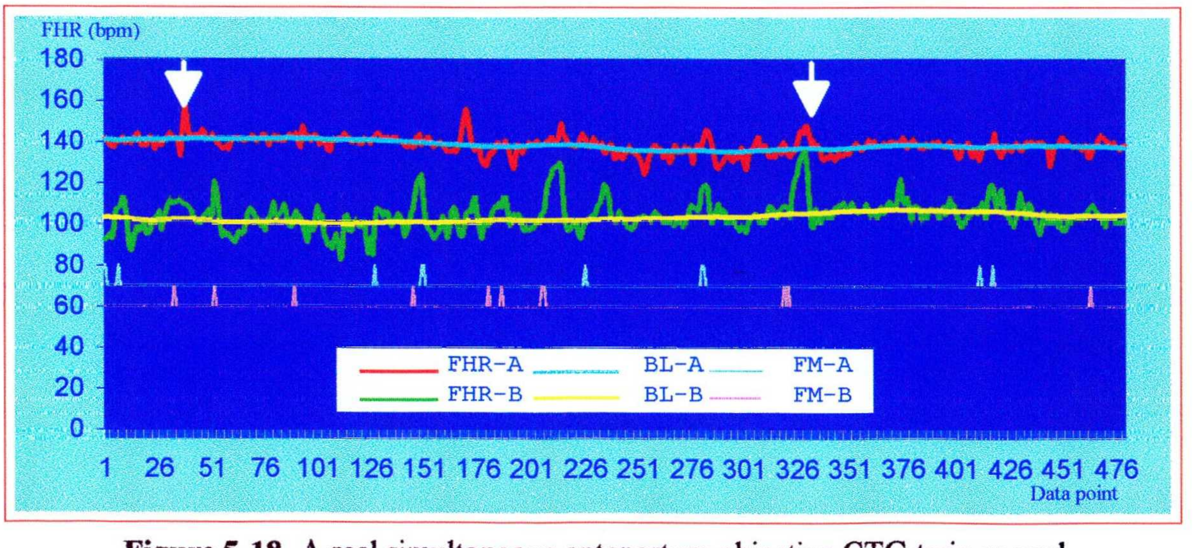


Figure 5-18 A real simultaneous antepartum objective CTG twin record (white arrow = synchronous AB acceleration)

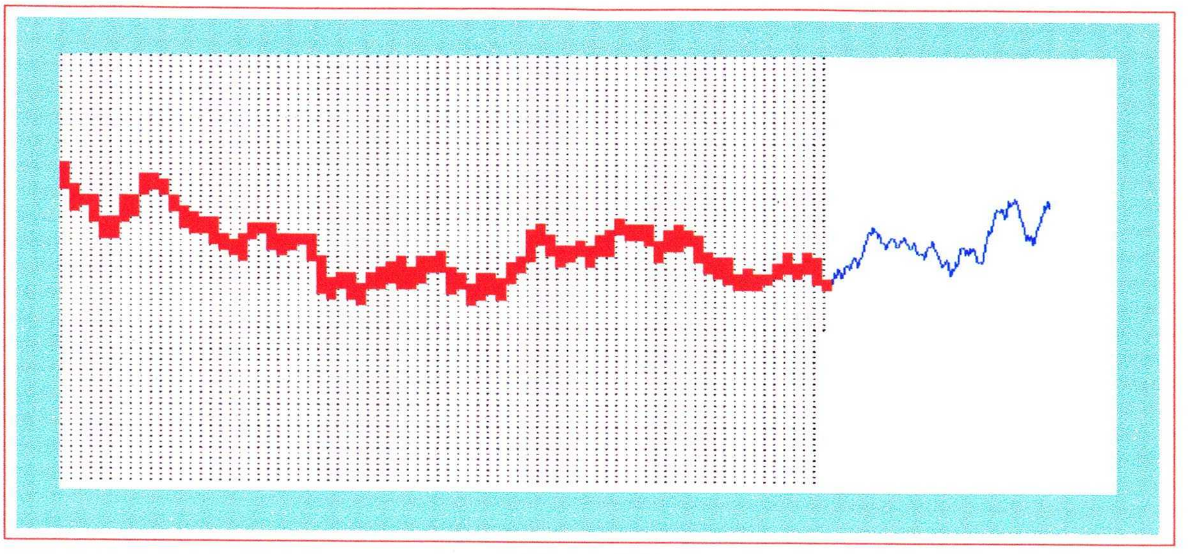


Figure 5-19
The box-counting method in action using the function lineto (x,y)

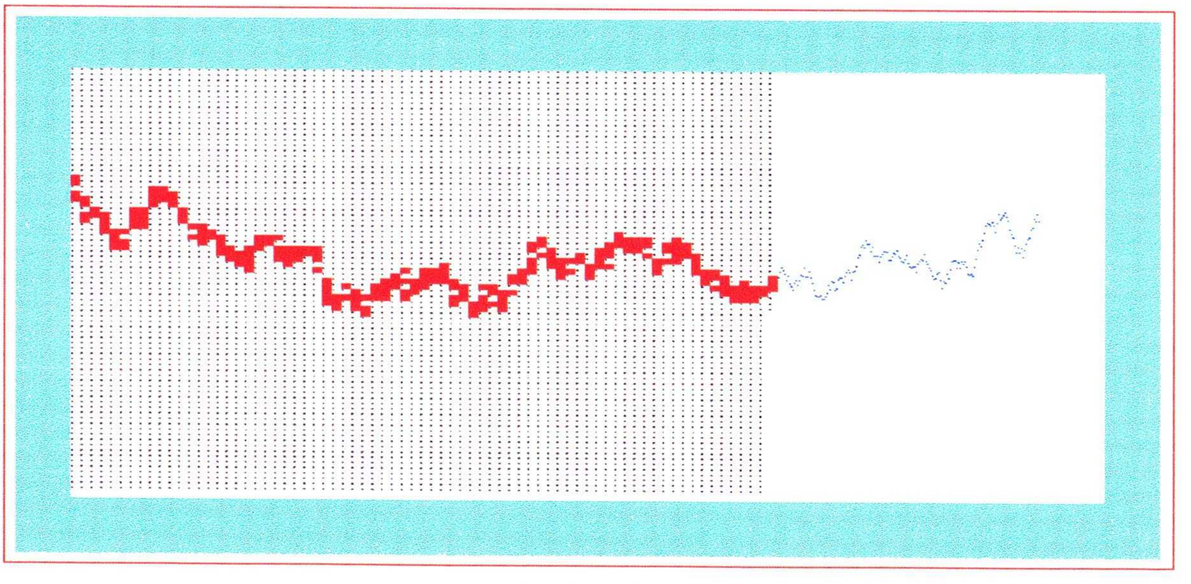


Figure 5-20
The box-counting method in action using the function setpixel (x,y)

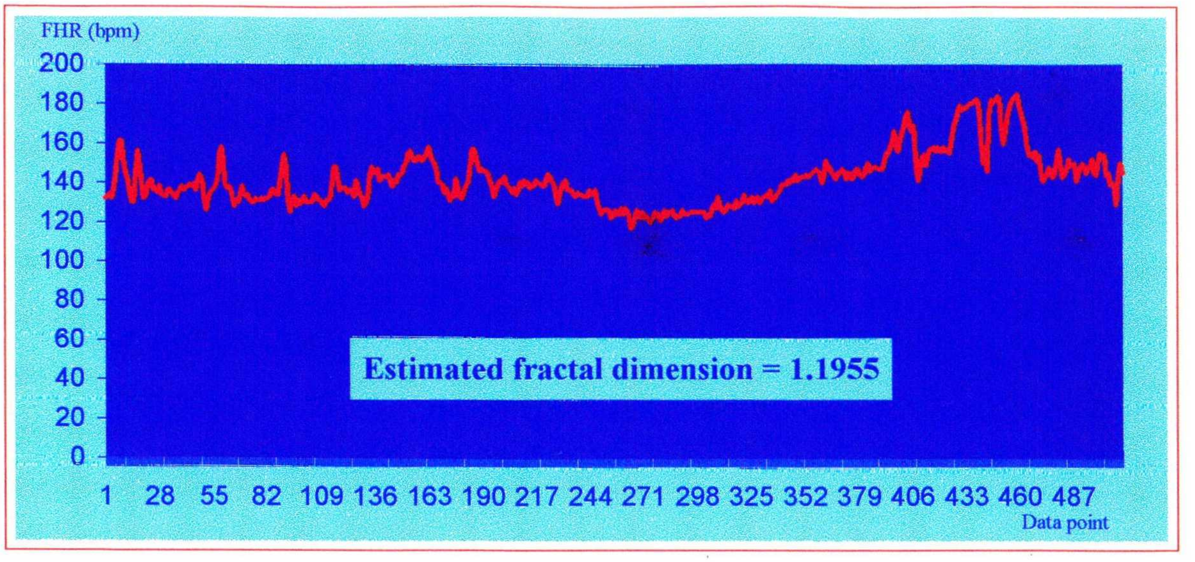


Figure 5-21
The estimated fractal dimension of a FHR record (STV=9.2)

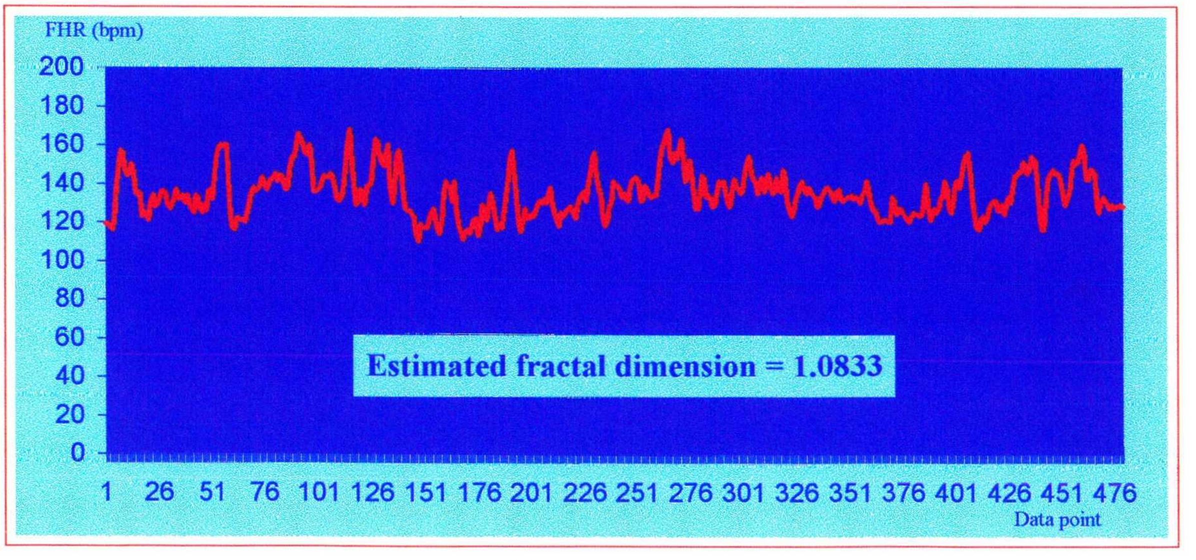


Figure 5-22
The estimated fractal dimension of a FHR record (STV=14.2)

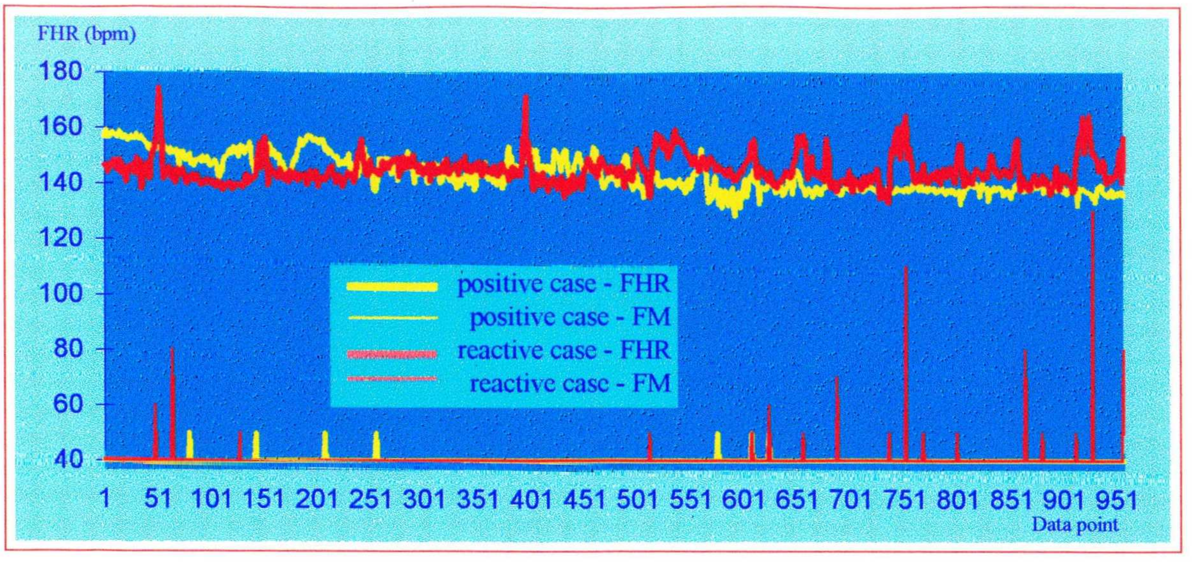


Figure 5-23

A reactive and a positive FHR record of 60 min length with corresponding FM

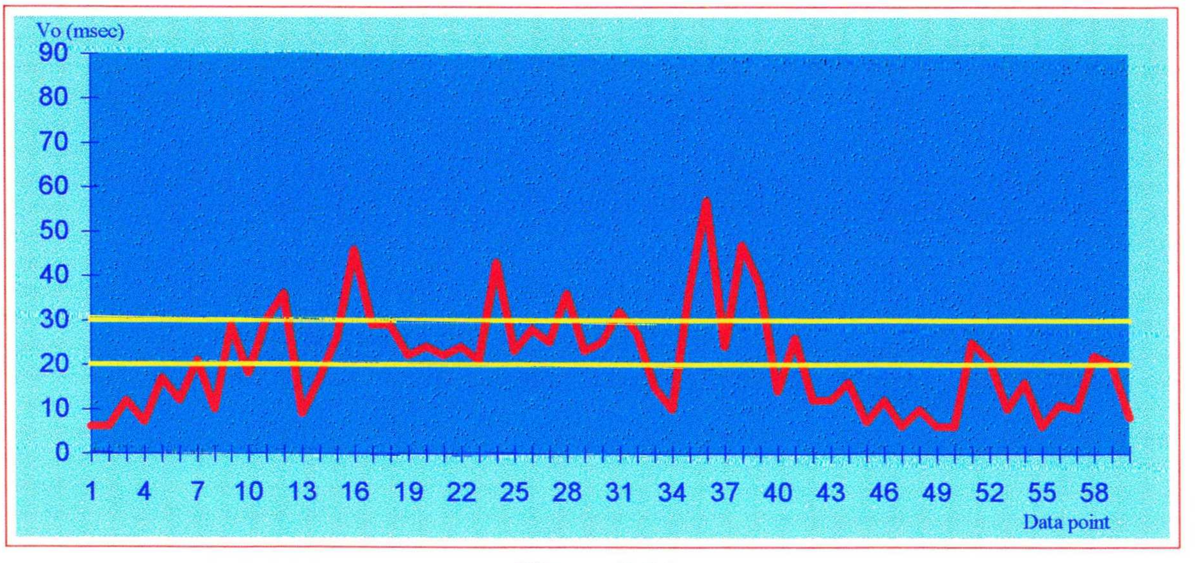


Figure 5-24

The variability (mean minute range) of the positive case

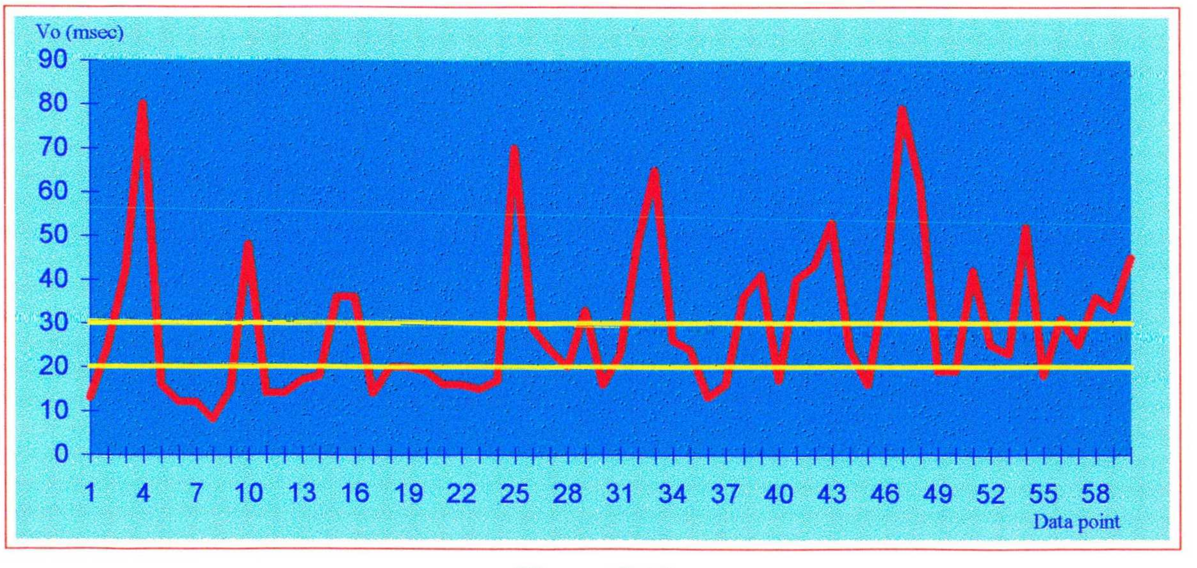


Figure 5-25

The variability (mean minute range) of the reactive case

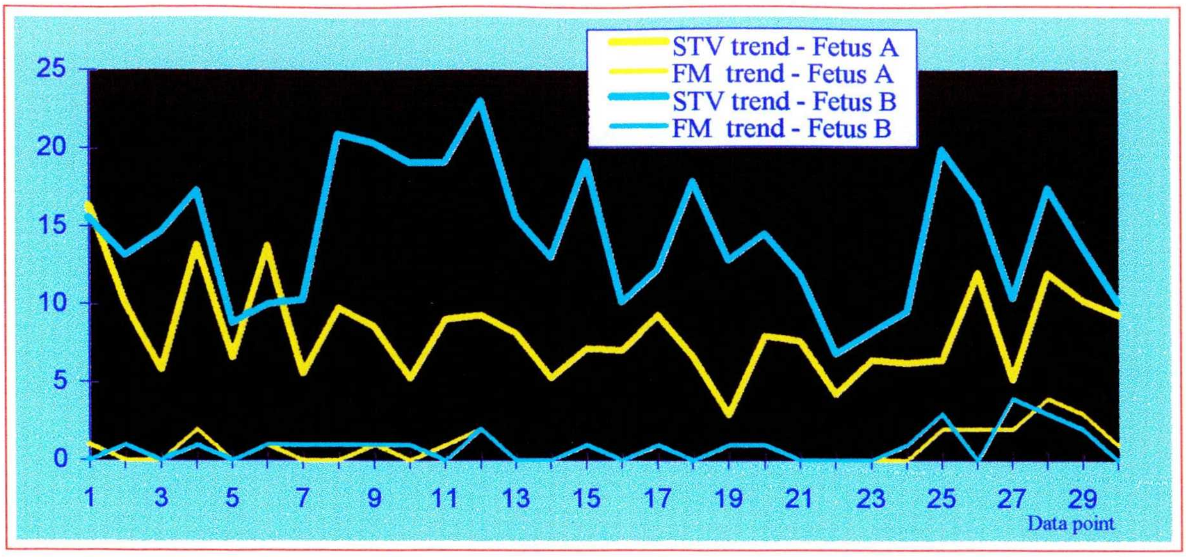


Figure 5-26 The STV and FM trend of a real simultaneous twin CTG record, averaging data values over 1 minute

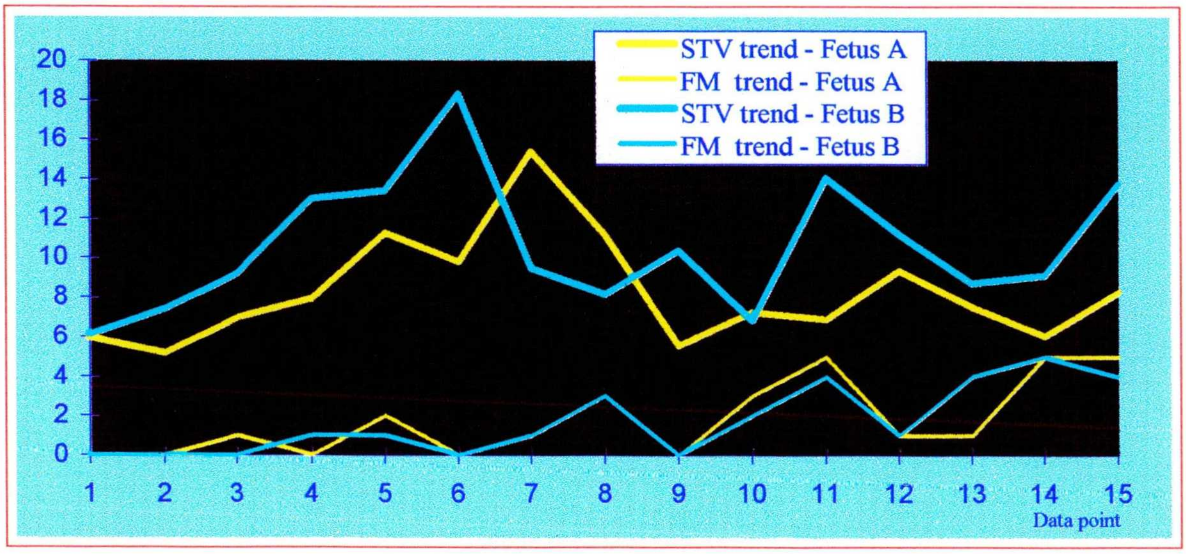


Figure 5-27 The STV and FM trend of a real simultaneous twin CTG record, averaging data values over 2 minutes

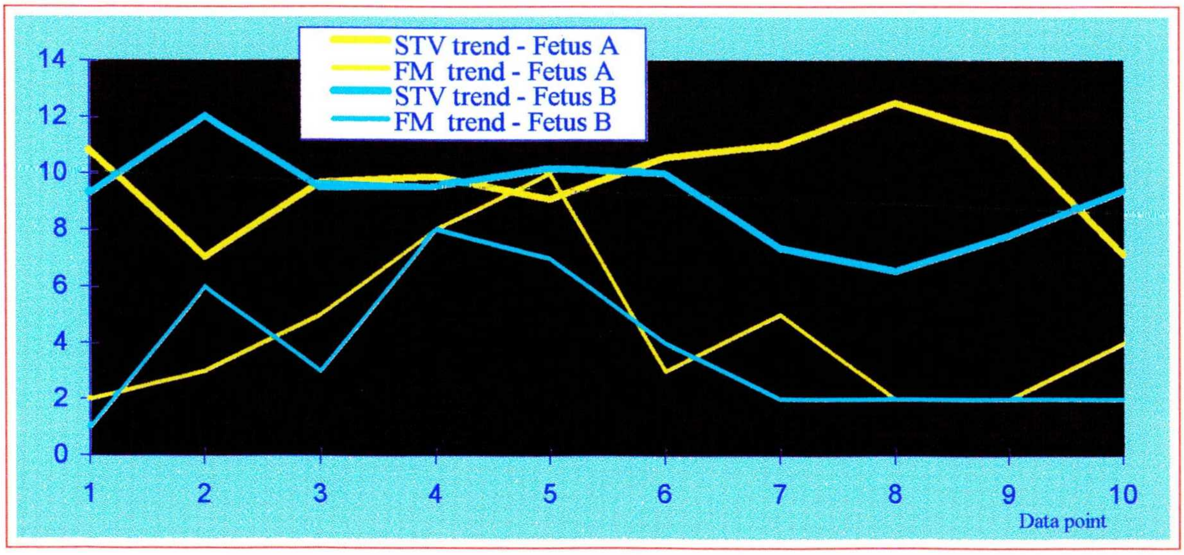


Figure 5-28 The STV and FM trend of a real simultaneous twin CTG record, averaging data values over 3 minutes

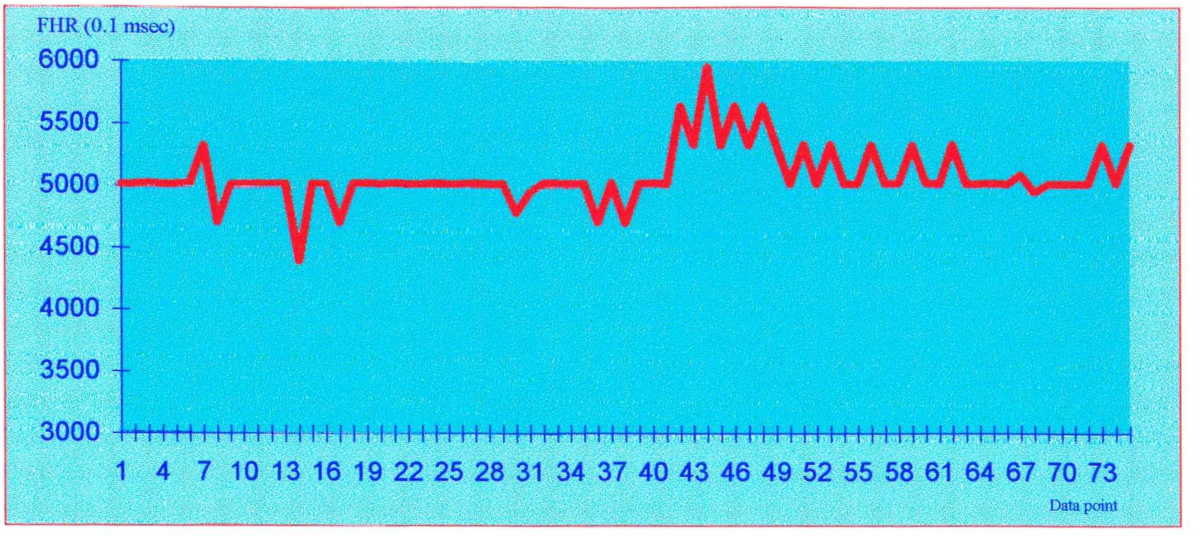


Figure 5-29
Heart-beat interval values obtained using the HRMIC equipment

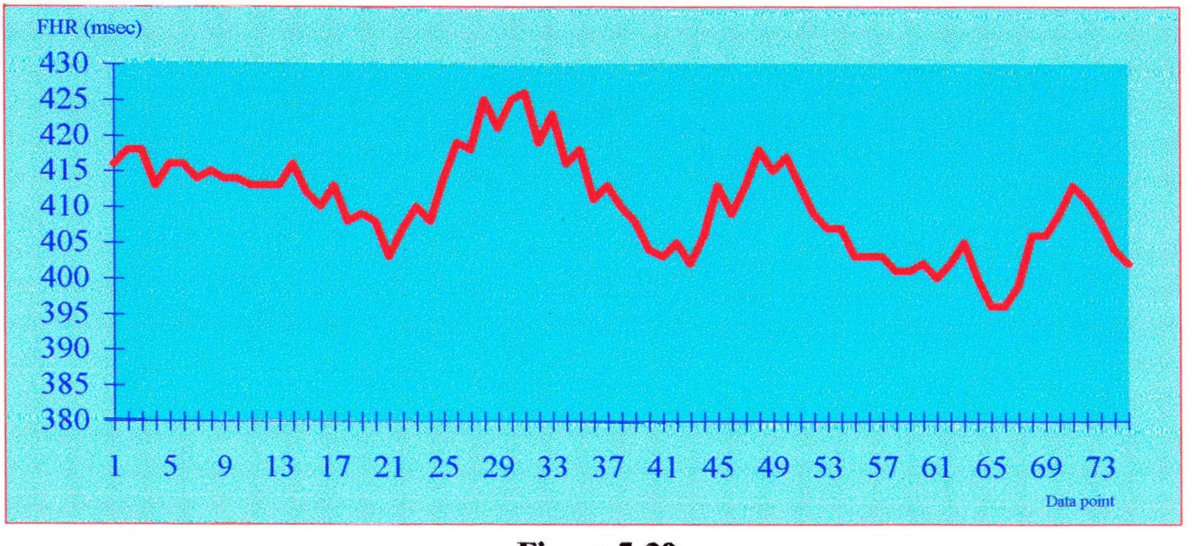


Figure 5-30
Heart-beat interval values obtained using direct digital FECG technique

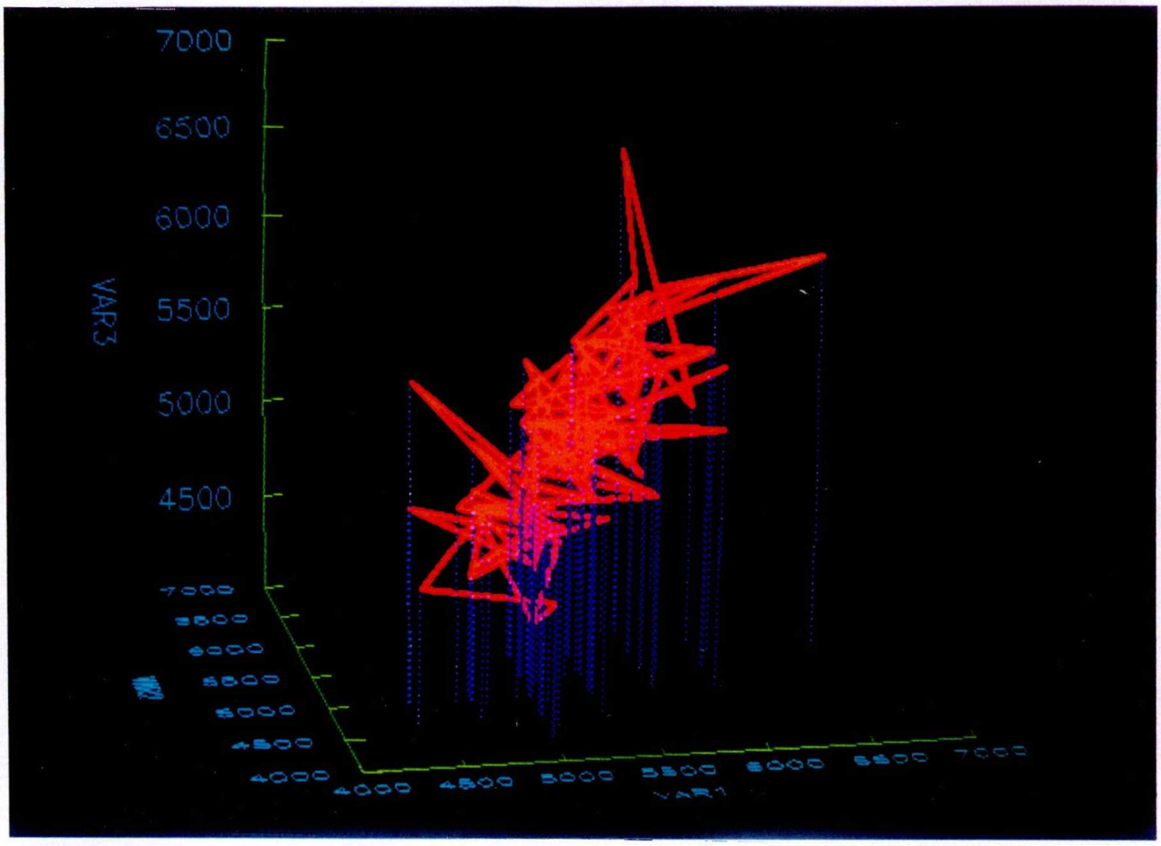


Figure 5-31
The phase-space reconstruction of Figure 5-29

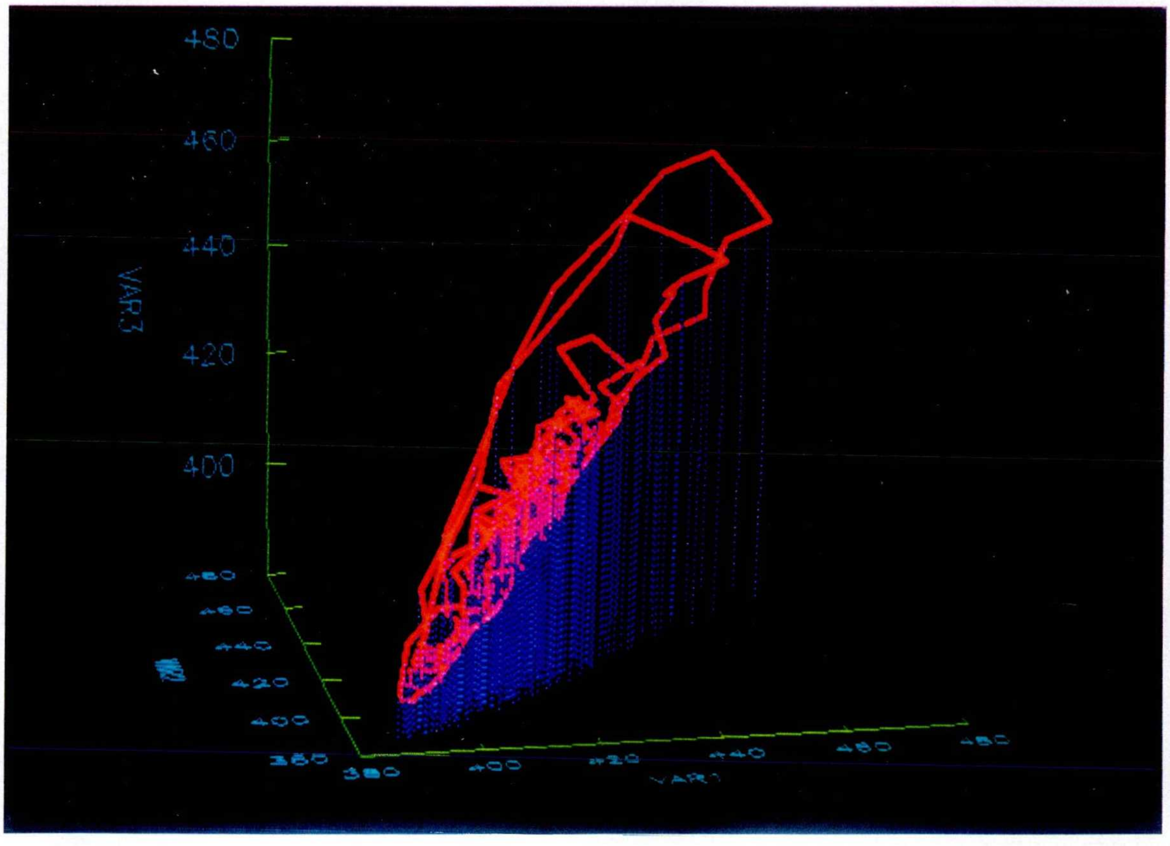


Figure 5-32
The phase-space reconstruction of Figure 5-30

6 CONCLUSIONS AND DISCUSSION

The work presented here had two main topics for investigation. These were:

I The method of the prenatal computer CTG monitoring of twin pregnancies.

II The method of obtaining strictly continuous and highly precise beat-to-beat FHR data suitable for spectral and chaos theory analysis.

Topic I

As twin pregnancies are at high risk, special surveillance is really an absolute requirement. To assess fetal well-being cardiotocography is one of the most widely-used methods currently employed. The introduction of computer CTG analysis into clinical practice has reduced the inter- and intraobserver error of the visual evaluation. In recent years manufacturers have made available cardiotocographs that provide the possibility of simultaneous FHR monitoring of twin fetuses. But computer systems have not quite kept abreast of these changes, so the only way to overcome this and perform computer-based simultaneous twin recordings was to purchase two systems. Considering the exorbitant price of one system this solution cannot be considered a reasonable choice. In the CTG literature of single pregnancies fetal movements proved to have an important diagnostic value, but there was no corresponding data available on twin fetuses. The pilot study done here suggested different, but highly interdependent, movement and behaviour patterns. The conclusion was that the movements of twins must be registered separately, which proved to be possible using the clinical event marker of the Meridian 800 cardiotocograph. Until the appearance of Oxford Sonicaid TEAM monitors only the pseudo-simultaneous computer monitoring of twins could be employed as a solution to the problem. The six-hour memory capacity of this new generation of fetal monitors enabled one to store simultaneously received Fetus B data and to transfer them to the System 8000 CTG Computer Analysis program at the end of the recording. In this way the problem of the real objective simultaneous CTG monitoring of twin fetuses with separately registered FM was solved. As it is shown in the studies and results section various parameters can be analysed by comparing corresponding values with each other. It seems evident as a conclusion that the ratio of synchronous accelerations with or without FM carries clinically significant information for medical staff. There is no doubt that only a large double-blind multicentre study can decide the practical value of the other corresponding parameters. This is also true for the technique of the internal trend analysis, but it certainly gives more reliable and comparable information than the original method employed by the System 8000. Synchronous accelerations can be detected manually using a ruler with exact precision, but it is eye-straining and slow for clinical purposes. It is also unnecessary when it can be entirely automated by fitting a baseline to the FHR trace. On the basis of the corresponding studies it is concluded that with the employed baseline fitting algorithm slightly different values may result. While this difference can hardly have any significant influence on the clinical decision, it does emphasize however the importance of independent variables involved here. In the present work STV was found appropriate to characterize the irregularity of FHR tracings, which explains its unique high predictive value.

On the basis of these results the development of a versatile twin monitoring computer program could be developed for future research and clinical purposes.

Topic II

Most phenomena of nature proved to be nonlinear explaining satisfactorily the failure of the statistical description of the world at the precision the end of the 20th century requires. The successful prediction of the behaviour of the environment has been crucial ever since the birth of the humankind. The development of the perinatology has recently allowed us to consider the fetus as a patient. The number of tools of diagnostics and therapy increases from day to day. Intrauterine hypoxia is the primary cause of the fetal distress, so its reliable and early detection, and the ability to recognize its different degrees from the point of view of consequences is today the most important question of fetal surveillance. A statistical approach to computer analysis of CTG tracings has brought noticable improvements, but it has its own drawbacks too. The nonlinear nature of FHR requires new study methods. The introduction of the spectral and chaos theory analysis to cardiotocography cannot occur without the development of a formal methodology. Using appropriate input data is cardinal, otherwise results will be misleading. After solving the problem of the serial communication with Oxford Sonicaid fetal monitors the data structure of FHR records could be analysed from the viewpoint of data continuity and precision. The result of these studies, that only digitally registered intrapartum direct FECG records really provide the required data continuity and precision, does not deny the validity of present computer systems within their own frameworks. However, it is firmly concluded that statements derived from studies of spectral and chaos theory analysis using inappropriate input data must definitely be considered questionable.

Choosing the right technique for trials is only one side of the coin. The other side is to find analytical methods which are able to recognize an early, but reliably predictive sign of disorder of a complex materno-placental-fetal system. We need to be able to decide whether the system has enough in reserve to eliminate this disorder and maintain the balance in further stress cases, or the risk of the collapse or unacceptable harm will be higher than that of extrauterine life. Future plans should therefore include not only the monitoring of the pregnancy and labour period, but the neonatal period as well.

7 NEW FINDINGS AND RESULTS

Topic I

I - 1. It was found that CTG monitoring of twin pregnancies requires real objective simultaneous computer analysis including separately registered fetal movements.

I - 2. The problem of real objective simultaneous CTG computer monitoring of twins with separately registered fetal movements was solved.

I - 3. It was shown that the ratio of synchronous accelerations with or without movement carries relevant information for the assessment of fetal well-being in twin pregnancies.

I - 4. A modified algorithm of baseline fitting to FHR tracings was developed that eliminated the disadvantages of the method of Dawes et al. but keeps the advantages.

I - 5. The problem of detecting synchronous accelerations with or without FM by impartial numerical analysis in twin pregnancies was solved.

I - 6. A method of internal CTG trend-analysis at optional zoom-rate was worked out, providing a new research tool for studies of the behaviour of single and twin gestations.

I - 7. On the basis of the studies involving baseline fitting it was shown that independent variables are needed to describe FHR tracings.

I - 8. A fast algorithm was written that estimates the fractal dimension according to the graphical box-counting method, but it is not restricted by the screen size or resolution.

I - 9. It was found that the original box-counting method is unsuitable for estimating the irregularity of FHR tracings with an independent parameter.

Topic II

II - 1. The problem of serial data communication with Oxford Sonicaid fetal monitors was solved, allowing the acquisition of beat-to-beat FHR values and other data in real-time.

II - 2. It was proved that beat-to-beat antepartum CTG records made using abdominal transducers do not meet the necessary requirement of data continuity for spectral and chaos theory analysis.

II - 3. It was proved that beat-to-beat FHR values read via the serial port of the Oxford Meridian 800 fetal monitor during direct intrapartum FECG recordings meet the data continuity requirement. However, at acute intrapartum fetal distress the signal loss becomes unacceptably high.

II - 4. It was demonstrated that time intervals between bleeps given by the Oxford Meridian 800 in FECG/MECG mode can be measured to high precision.

II - 5. It was found that the bleeps given by the Oxford Meridian 800 in FECG/MECG mode do not match the QRS complexes to the required degree of accuracy.

II - 6. The problem of the digital recording of even long-term direct fetal ECG records at optional sampling rates was solved and successfully employed in the practice.

II - 7. It was shown that the determination of heart beat intervals between successive R peaks using the digital FECG recording technique developed here provides strictly continuous and highly precise data sets that are suitable for spectral and chaos theory analysis.

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