The Journal of Maternal-Fetal Medicine 9:311–318 (2000)

SisPorto 2.0: A Program for Automated Analysis of Cardiotocograms

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Objective: To describe the latest version of SisPorto, a program for automated analysis of cardiotocograms that closely follows the FIGO guidelines, analyses ante- and intrapartum tracings, performs no signal reduction, and has the possibility of simultaneously recording twins.
Methods: A detailed description of the program's processing algorithms and operation is provided, as well as the main results of the studies performed to-date with this system.
Results: Considering both current and previous versions of the program, SisPorto has been tested in over 6000 pregnancies. The system's FHR baseline was compared with an average of three experts' estimates, and the difference was under 8 bpm in all cases. A fair to good agreement was found with experts' identification of accelerations, decelerations, contractions, and normal/reduced variability (proportions of agreement 0.64–0.89). In a preliminary validity study (n = 85), a sensitivity of 100% and a specificity of 99% were obtained in prediction of poor neonatal outcome. The system is currently undergoing an international multicentre validation study.
Conclusions: Although still at the research level, a considerable experience has now been gathered with this system. Promising results have been achieved in studies comparing SisPorto with experts' analysis and in those evaluating the validity of the system. *J. Matern.-Fetal Med. 2000;9:311–318.* © 2000 Wiley-Liss, Inc.

Key words: fetal heart rate; cardiotocogram; automated analysis; computer analysis; SisPorto

INTRODUCTION

Visual analysis of cardiotocograms has a well-demonstrated poor reproducibility [1,2] and this may have important implications in other aspects of the method's performance. Automated analysis has arisen as a way of overcoming this problem, as it provides users with a quantifiable and consistent report. Computerized systems also allow the evaluation of parameters that cannot reliably be assessed by the human eye, such as short-term variability. Furthermore, they provide a safe, easily accessible, organized, and nondegradable means of tracing storage, review, and transmission, which can lead to considerable economy in cardiotocographic paper. Finally, they enhance the constitution of databases, with important clinical and research applications.

This article describes the processing algorithms and system operation of SisPorto 2.0, the latest version of a program for automated analysis of cardiotocograms developed over the last 13 years at the University of Porto [3,4]. It is the result of a collaboration project between the University's Faculty of Medicine and Institute of Biomedical Engineering.

SYSTEM DESCRIPTION

Hardware and Software Requirements

SisPorto 2.0 runs in any personal computer using the Windows operating systems (Windows 3.1, Windows 95,

Contract grant sponsor: JNICT; Contract grant number: PECS/P/SAU/207/97; Contract grant sponsor: Praxis XXI; Contract grant number: 2/2.1/SAU/1351/95.
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Received 4 August 1999; revised 30 November 1999; accepted 17 January 2000

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Windows NT, or Windows 98). Minimum hardware requirements are a Pentium 166 MHz processor, 16 MB of RAM, and a 3.5-inch floppy disk drive.

Signal Acquisition and Storage

Digital signals are conveyed from the fetal monitor to the computer's serial port via a standard computer cable, using a RS232 or RS485 protocol. SisPorto 2.0 is able to acquire signals from Sonicaid and Hewlett-Packard fetal monitors that have a RS232 or RS485 output (Sonicaid Meridian 800, Sonicaid Team, HP M1350B, HP M1350A with J10 option, and HP M1351-3 with digital connecting interface).

Whether directly provided by the fetal monitor or arrived at by interpolation, instantaneous fetal heart rate (FHR) and simultaneously transmitted uterine contraction signals are the parameters used for subsequent analysis. No averaging or reduction of these signals is performed. Tracings are stored in files as received from the fetal monitor, thus allowing posterior viewing of unprocessed signals, processing by other programs or different upgrades of the same program.

Processing of Signals

Processing of cardiotocographic tracings starts automatically after 10 min of acquisition and is subsequently updated every 5 min. Tracings already stored in the database are processed as a whole. Analysis is based on consensual guidelines for FHR interpretation, such as those proposed by the International Federation of Gynecology and Obstetrics (FIGO) [5] and the National Institutes of Health [6]. It involves the following steps in successive order.

FHR spike removal. Removal of spiky artifacts is performed whenever a difference between adjacent beats exceeding 25 beats per minute (bpm) is detected. In this case, a linear interpolation is made between the first signal and the start of the next stable FHR segment, defined as a group of five adjacent samples with fewer than 10 bpm differences.

Filtering of uterine contraction signals. Each uterine contraction signal is substituted by the average of 17 values centered on it. Thus, most high-frequency noise that impairs contraction detection is eliminated.

Detection of uterine contractions. Uterine contractions are defined as periods lasting 20–240 sec, where an upward shift over the mode of at least three points is detected, reaching a peak in excess of 10 points. If a shift lasting more than 240 sec is detected, the mode for that period is recalculated and the contraction algorithm reapplied, with this principle being employed as many times as necessary. Uterine contractions are identified by green bars on the lower part of the graph and their quantification is displayed underneath the tracing (Fig. 1).

Evaluation of abnormal and mean short-term variability (STV). A point with abnormal STV is identified whenever the difference between two adjacent FHR signals is less than 1 bpm. Vertical red lines on the upper part of the tracing represent these points. Average STV and the percentage of points with abnormal STV are calculated and displayed underneath the tracing (Fig. 1).

Filtering of fhr signals. After STV estimation, each FHR value is substituted by an average of five values centered on it.

Quantification of fetal movements. Fetal movements, as obtained from the fetal monitor (whether by automated detection or as registered by the mother, depending on monitor capabilities), are counted and this result is displayed underneath the tracing (Fig. 1).

Estimation of the FHR baseline. The FHR baseline is calculated using a relatively complex algorithm based on the FHR histogram and STV values, outlined in Figure 2. This aims to represent the mean FHR during episodes of fetal rest and therefore to have a strong physiological background. The baseline algorithm incorporates several physiologically based criteria, and adjustments arrived at mostly by trial and error after analysis of a large number of tracings and selection of several typical FHR patterns [7].

Detection of accelerations and baseline shifts. Accelerations are defined as increases in the FHR above the baseline, lasting 15–120 sec and reaching a peak of at least 15 bpm. They are identified by dark green bars under the baseline and quantified underneath the tracing (Fig. 1). Similar increases in FHR exceeding 120 sec are regarded as baseline shifts, represented by lighter green bars under the baseline shifts. Whenever these are identified, the baseline is recalculated for that period and the algorithm for detecting accelerations is reapplied.

Detection and classification of decelerations. Decelerations are defined as decreases in the FHR under the baseline, lasting at least 15 sec and with amplitude exceeding 15 bpm. They are identified by red bars over the baseline (Fig. 1). Decelerations are classified as mild if they do not exceed 120 sec, prolonged if they last 120–300 sec, and severe if they exceed 300 sec. They are considered repetitive when occurring at a frequency of more than three in 10 min and accompanying more than 80% of contractions, or when their total duration exceeds 50% of the tracing. Quantification of the number and type of decelerations is displayed underneath the tracing (Fig. 1).

Detection of abnormal and mean long-term variability (LTV). LTV is only evaluated in segments that were not considered accelerations or decelerations. A point with abnormal LTV is identified when the difference between maximum and minimum values of a sliding 60-sec window centered on it does not exceed 5 bpm. Vertical red lines on the upper part of the tracing indicate these points. Average LTV and the percentage of points (excluding accelerations and decelerations) with abnormal LTV are calculated and displayed underneath the tracing (Fig. 1).

Evaluation of signal loss and quality. Signal loss is defined as the percentage of FHR signals received from the

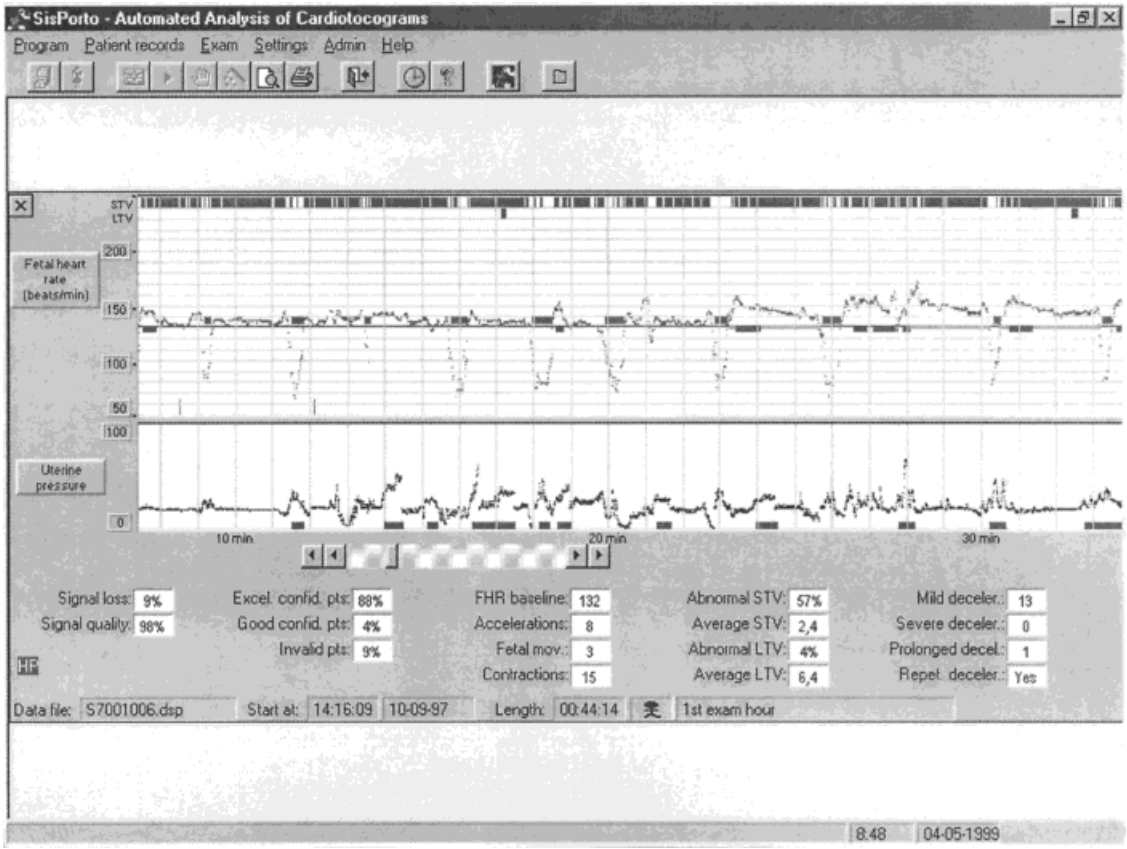


Fig. 1. Cardiotocogram analyzed by SisPorto 2.0. FHR baseline, accelerations, decelerations, baseline shifts, uterine contractions, episodes of abnormal short- and long-term variability are identified on the tracing. Quantification of these and other parameters is displayed underneath the tracing (see text for details).

fetal monitor with values under 50 bpm. Signal quality is defined as the percentage of FHR values that were not interpolated using the previously described spike removal algorithm.

System Operation

System operation follows the usual routines of programs using the Windows environment. From the Main Menu page (Fig. 3), the patients' database, input of a new patient, visualization of stored tracings, and start of tracing acquisition are accessed with a click of the mouse button. Before acquisition of a new tracing, a patient name and hospital number must be inputted, or a patient already in the database selected. The database contains a list of patients in alphabetical order. All tracings acquired for a given patient can be displayed with or without automated analysis, along with the time and date of acquisition. These can be printed on paper, showing up to 60 min of recording (Fig. 4).

The system will automatically detect whether one or two FHR signals are being transmitted from the fetal monitor and open the necessary windows for acquisition of a single fetus or twin's tracing (Fig. 5). The fetal monitor used to acquire tracings should previously be selected in the program settings.

EXPERIENCE WITH THE SYSTEM

Considering both current and previous versions of the system, SisPorto has now been tested in over 6,000 pregnancies; 110 antepartum tracings of twins were also acquired in a preliminary technical study, with a 31-min median duration and an 8% median signal loss [8].

Analysis of 33 tracings by the original system prototype was compared with that of three experts [9]. Sixteen antepartum and 17 intrapartum tracings with signal quality >85% were randomly selected from high-risk third-trimester pregnancies. Mean duration of tracings was 41 min (SD = 14) in the antepartum and 58 min (SD = 27) in the intrapartum. For baseline estimation, the difference between SisPorto's value and an average of experts' estimates was under 8 bpm (2 SD) in all cases. A mean difference of 0.9 bpm and 2.1 bpm was obtained in ante- and intrapartum cases, respectively. A more extensive validation of the SisPorto baseline is currently under way.

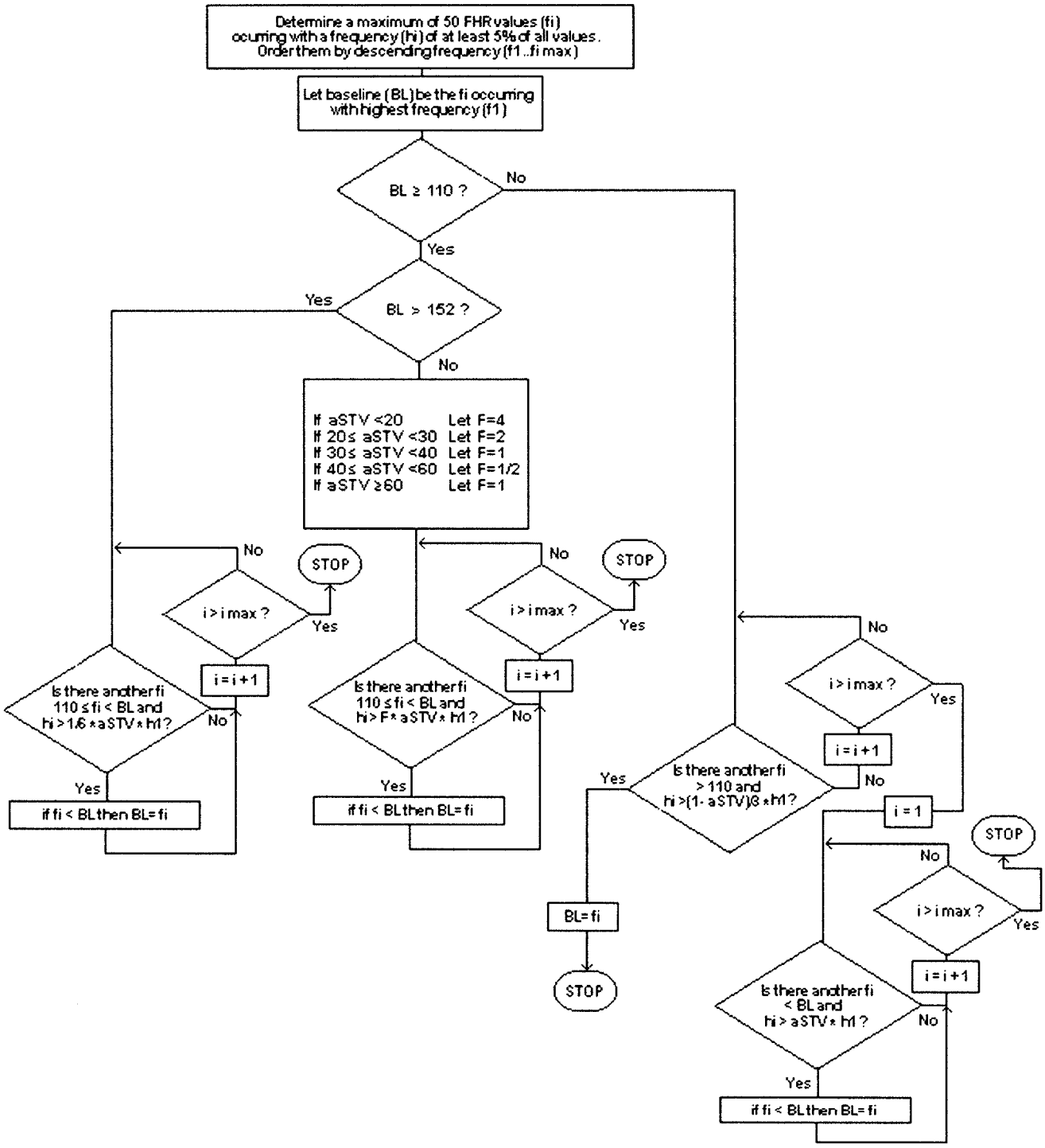


Fig. 2. Flow diagram of SisPorto 2.0's baseline algorithm. Fi = FHR value occuring in at least a 5% frequency; hi = number of fi occurences; F1 = the fi value with most occurences; imax = least frequently occuring fi value; aSTV = abnormal short term variability; BL = varying baseline value.

Using the previously described tracings, the program's identification of accelerations, decelerations, contractions, and normal/reduced variability was compared with that of experts' consensus interpretation by means of the proportions of agreement (pa) and 95% confidence intervals (95% CI) [9]. A fair-to-good agreement was obtained in the identification of accelerations (pa = 0.67, 95% CI 0.60–0.74), decelerations (pa = 0.64, 95% CI 0.53–0.74), uterine contractions (pa = 0.82, 95% CI 0.78–0.86), normal variability (pa = 0.89, 95% CI 0.88–0.90), and reduced

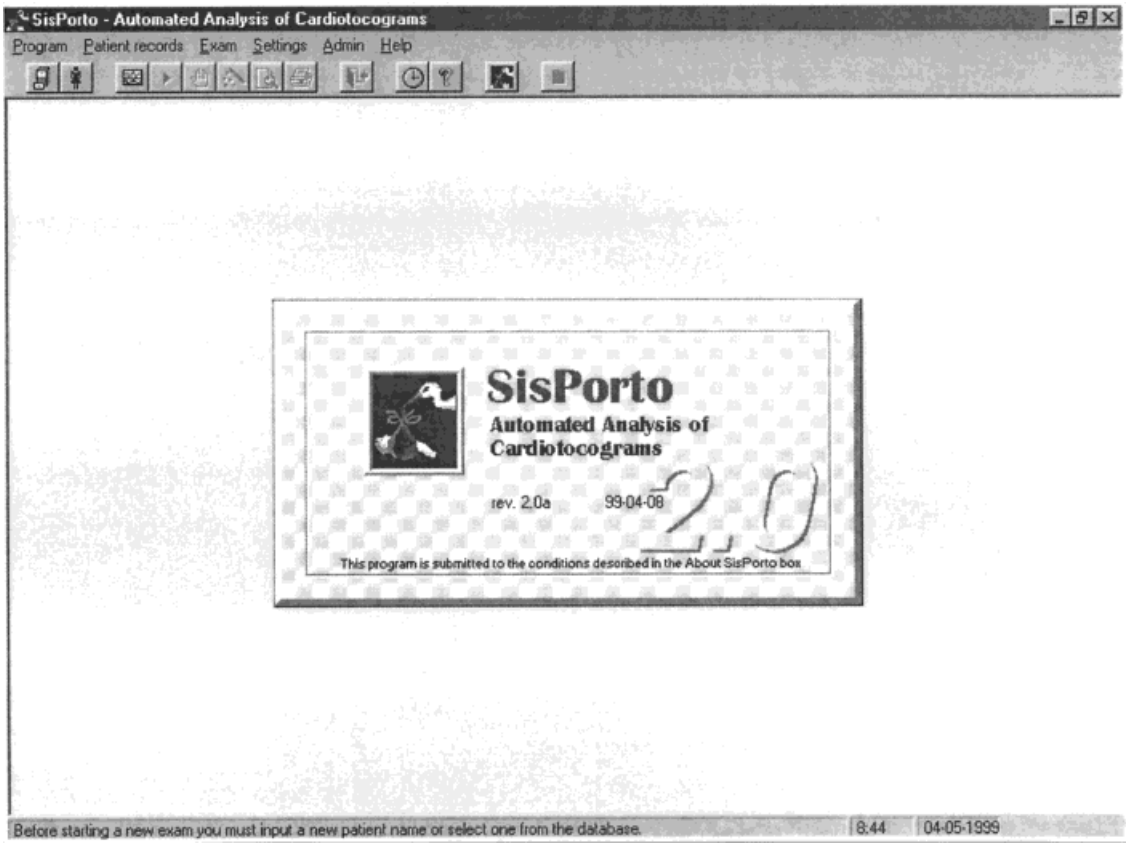


Fig. 3. SisPorto 2.0's Main Menu page. At the top of the page from left to right: patients' database, input of new patient name, visualization of stored tracings, start of new tracing acquisition, end of tracing acquisition, signal processing, print report preview, print report, exit program, date and time settings, help menu, and about SisPorto.

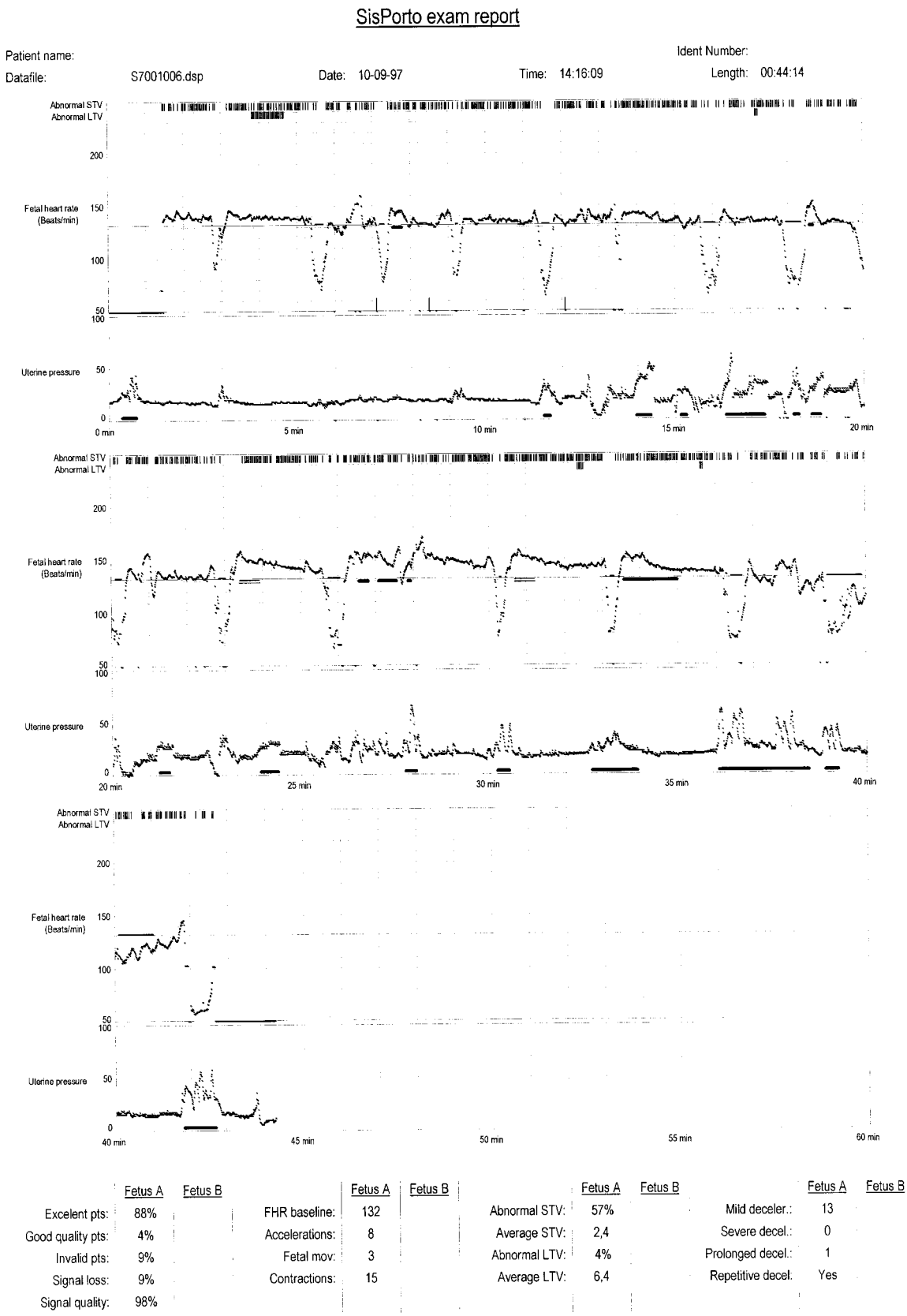
variability (pa = 0.72, 95% CI 0.71–0.74) [9]. Agreement was higher when the comparison was made with the majority, rather than the consensus of experts' analysis [9]. Interobserver agreement among experts was also evaluated in these tracings and a good result was only obtained in baseline estimation [10].

Using the cardiotocographic parameters provided by SisPorto, a quantitative adaptation of the FIGO guidelines' criteria for tracing classification was developed [9,11] and later refined [12]. A preliminary evaluation of this classification system was conducted in 42 antepartum tracings, acquired within 48 h of elective cesarean delivery, and 43 intrapartum tracings, registered until birth or until the 30 min that preceded an emergency cesarean delivery [12]. Poor neonatal outcome was defined as 1-min Apgar score <4, 5-min Apgar score <5, umbilical artery blood pH <7.10, or fetal death within 24 h. Tracings were considered pathological when the following were present: FHR baseline >170 or <100, reduced LTV >40 min, severe or prolonged and repetitive decelerations, bradycardia >10 min, or a sinusoidal pattern. The sensitivity and specificity of pathological tracings in prediction of a poor neonatal outcome were 100% (95% CI 59–100%) and 99% (95% CI 93–100%), respectively.

The quantifiable nature of SisPorto's reports allowed the evaluation of changes in cardiotocographic parameters over time in a study of growth-retarded premature fetuses from hypertensive pregnancies [11]. This study involved only a small number of fetuses, but suggested that the system is capable of monitoring progressive fetal deterioration and that important cardiotocographic changes only appear well after the detection of absent end-diastolic flow in the umbilical artery.

Preliminary studies have also been conducted with SisPorto to evaluate the accuracy of neural networks and fractal models in estimation of the FHR baseline [13], classification of FHR patterns [14], and prediction of neonatal parameters [15]. Using a four-class Apgar score index, an 86% correct and 14% adjacent class prediction was obtained by the neural network in a 35-case test set [15].

SisPorto 2.0 is currently undergoing a multicenter validation study (http://sisporto.med.up.pt) aimed at determining the accuracy of its cardiotocographic parameters in



	Fetus A	Fetus B		Fetus A	Fetus B		Fetus A	Fetus B		Fetus A	Fetus B
Excelent pts:	88%		FHR baseline:	132		Abnormal STV:	57%		Mild deceler.:	13	
Good quality pts:	4%		Accelerations:	8		Average STV:	2,4		Severe decel.:	0	
Invalid pts:	9%		Fetal mov:	3		Abnormal LTV:	4%		Prolonged decel.:	1	
Signal loss:	9%		Contractions:	15		Average LTV:	6,4		Repetitive decel.	Yes	
Signal quality:	98%										

Fig. 4. Printed report of the tracing displayed in Figure 1. The system also allows printing of unprocessed tracings.

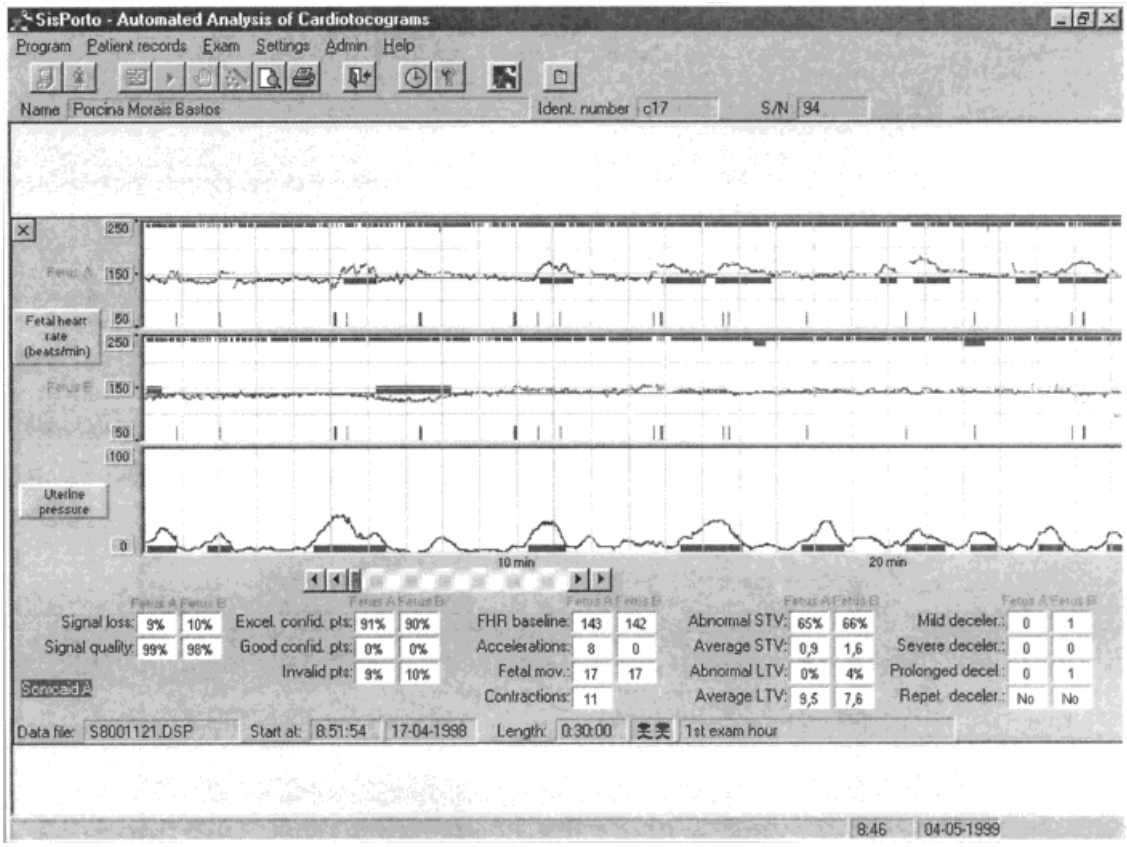


Fig. 5. A twin's tracing analyzed by SisPorto 2.0.

predicting neonatal outcome defined by Apgar scores, umbilical artery blood gas values, and neonatal intensive care unit admissions. The program has been installed in 14 centers in Sweden, Denmark, the United Kingdom, Belgium, Germany, Switzerland, Spain, Portugal, Finland, and Australia, where the study is currently in progress.

Preliminary results are available from the antepartum arm of this study, relating to 135 women with singleton pregnancies of 29–42 weeks' duration, without fetal malformations, where cardiotocographic tracings were acquired within 4 h of cesarean birth and before the onset of labor [16]. A significant correlation was found between SisPorto's parameters LTV, STV, presence of accelerations, and neonatal parameters 1-min Apgar score ($r = 0.55, 0.40, 0.39$, respectively) and 5-min Apgar score ($r = 0.52, 0.41, 0.41$, respectively). No significant correlation was found between cardiotocographic parameters and umbilical artery blood gas values. Receiver operating characteristic (ROC) curves were used to estimate the sensitivity and specificity of various cutoff points for LTV, STV, and number of accelerations in prediction of neonatal Apgar scores. The largest areas under the ROC curves were obtained when abnormal LTV (0.98; SE = 0.4) and abnormal STV (0.93; SE = 0.38) were used to predict 5-min Apgar scores <7.

DISCUSSION

Other systems for automated analysis of cardiotocograms have been described [17–19] and some are commercially available. While many aspects are shared by all systems, important differences can also be found. Perhaps the most important step in any program for automated analysis of cardiotocograms is the determination of the FHR baseline. Indeed, after this all other calculations are relatively easy to perform. Systems 8000/8002 and 2CTG have adopted the concept of a "wandering" FHR baseline, based mainly on digital filtering of FHR signals. SisPorto 2.0 has maintained the traditional "straight-line" baseline, using a relatively complex algorithm to estimate the mean FHR during periods of fetal rest. We believe that this has the advantage of providing a more correct interpretation of FHR pattern D and most second-stage of labor tracings (http://sisporto.med.up.pt/homediss.html). The latter is especially important in that, contrary to some systems, SisPorto can be used throughout both the first and second stages of labor.

Another important difference is the fact that SisPorto 2.0 performs no signal reduction. This contrasts with System 8000/8002, where signals are averaged every 3.7 sec [17], the 2CTG system, where averaging is performed every 2.5 sec [18], and the Toitu fetal monitoring system, where

this occurs every 2 sec [19]. Analysis of all incoming signals allows the closest possible evaluation of beat-to-beat variability [20,21]. It may be argued that with external FHR monitoring this is an underestimated parameter because autocorrelation is almost universally employed with Doppler probes. However, this does not occur with intrapartum scalp electrode ECG signals. Of course, it remains to be determined whether beat-to-beat variability, which can now be objectively quantified by the computer, will prove to have the value attributed to it by early investigators using visual analysis of cardiotocograms.

SisPorto 2.0's analysis criteria follow the FIGO [5] and National Institutes of Health [6] guidelines for FHR interpretation, which probably represent the widest consensus yet obtained in this field. The option to develop a system based on widely used criteria for visual analysis has the advantage of incorporating many years of previous experience with cardiotocography, and of providing CTG interpretations that are familiar to clinicians. While we believe that, in the long run, the computer should be able to tell us more than what has been learned with visual analysis; this requires the conduction of large and carefully designed studies, many of which have yet to be performed.

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