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Open-access software for analysis of fetal heart rate signals

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ABSTRACT

Cardiotocography (CTG) comprises fetal heart rate (FHR) and uterine contraction (UC) signals that are simultaneously recorded. In clinical practice, a visual examination is subjectively performed by observers depending on the guidelines to evaluate CTG traces. Owing to this visual assessment, the variability in the interpretation of CTG between inter- and even intra-observers is considerably high. In addition, traditional clinical practice involves different human factors that distort the quantitative quality of the evaluation. Automated CTG analysis is the most promising way to tackle the main shortcomings of CTG by providing reproducibility of the evaluation as well as the quantitative results. In this study, open-access software (CTG-OAS) developed with MATLAB® is introduced for the analysis of FHR signals. The software contains important processes of the automated CTG analysis, from accessing the database to conducting model evaluations. In addition to traditionally used morphological, linear, nonlinear, and time–frequency features, the developed software introduces an innovative approach called image-based time–frequency features to characterize FHR signals. All functions of the software are well documented, and it is distributed freely for research purposes. In addition, an experimental study on the publicly accessible CTU-UHB database was performed using CTG-OAS to test the reliability of the software. The experimental study obtained results that included an accuracy of 77.81%, sensitivity of 76.83%, specificity of 78.27%, and geometric mean of 77.29%. These fairly promising results indicate that the software can be a valuable tool for the analysis of CTG signals. In addition, the results obtained using CTG-OAS can be easily compared to different algorithms. Moreover, different experimental setups can be designed using the tools provided by the software. Thus, the software can contribute to the development of new algorithms.

1. Introduction

Cardiotocography (CTG) is the most widely used monitoring technique for determining the fetal state during the antenatal period. CTG is composed of fetal heart rate (FHR) and uterine contraction (UC) signals that are simultaneously recorded by electronic fetal monitoring (EFM) devices [1]. In clinical practice, the EFM device produces a paper strip (sometimes called a CTG trace or CTG strip) during the test. After the test is completed, observers interpret the paper strip with the naked eye depending on guidelines such as those laid down by the International Federation of Gynecology and Obstetrics (FIGO) [2].

In the context of these guidelines, the routinely judged FHR components, often called FIGO-based or morphological features, are the baseline heart rate, variability, accelerations, and decelerations. These components are the most robust indicators to ascertain fetal well-being [3]. For this reason, in almost all studies that address automated CTG analysis, these basic morphological features are confirmed as an indispensable part of the analyses. The reproducibility of the visual assessment of CTG strips has poor value because this is associated with the expertise level of the observers [4]. Therefore, disagreement regarding the interpretation of CTG has been reported as considerably high in various studies [5,6]. In other words, there are numerous factors influencing the fetal heart rhythm that are based on complex physical mechanisms and maturational changes, and the interpretation of these factors using only a paper strip is not an easy task. Thus, the major drawbacks of FHR monitoring stem from the reading and interpretation of CTG traces rather than technical aspects [7].

The initial studies on automated CTG analysis focused on the detection of morphological features that clinicians examine with the naked eye [8,9]. Nevertheless, this is not a simple task owing to a lack of standards on how computers estimate the diagnos-

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tic indices. In general, the morphological features are enlarged with other diagnostic indices obtained from linear [10,11], nonlinear [12–14], discrete wavelet transform (DWT) [15–17], empirical mode decomposition (EMD) [18,19], time–frequency [20,21] and image-based time–frequency (IBTF) [22,23] domains to identify FHR signals.

In summary, automated CTG analysis is the most promising way to overcome CTG's drawbacks. This approach aims to reduce the subjective nature of fetal state evaluation and to ensure a more objective and quantitative assessment [24]. Furthermore, computerized systems can be beneficial means for achieving, storing, transmitting, and assessing the signals [24]. Numerous algorithms and software have tried to develop a model that enables a more quantitative, objective, and consistent implementation of CTG analysis, and some of these attempts resulted in commercial products.

SYSTEM 8000 was developed for antenatal FHR analysis [25], and the improved version of this system, *sonicadFetalCare*, is commercially available nowadays. In addition, 2CTG2 was developed to analyze antepartum recordings using a set of standard parameters obtained from different domains [26]. A graphical tool for the automatic and objective analysis of CTG tracings, CTG Analyzer was generated using MATLAB® [27]. In addition, a medical expert system, NST-EXPERT, was designed to evaluate the fetal condition [28]. The Computer Aided Foetal Evaluator (CAFE) is a successor to this system [29].

SisPorto, which closely followed the FIGO guidelines, was introduced in 1990. Today, the fourth version of the SisPorto program has been distributed [30]. In addition, *K2 Medical Systems* presented an intelligent system consisting of central and local units to collect information such as CTG and results of blood sample analyses from a patient's bed [31]. Nowadays, the commercial version of this system is known as INFANT® [32]. This topic is still under discussion since automated CTG systems have not yet gained enough clinical acceptance.

In this study, we introduce a prototype of an open-access software for CTG analysis (CTG-OAS). This software contains important processes such as accessing the database, preprocessing, feature transform, and classification in terms of an automated CTG analysis. In addition, the applicability of texture features such as contrast, correlation, energy, and homogeneity is explored for detecting fetal hypoxia. A comparison of the three different classifier performances is also examined for this particular purpose. An experimental study is performed on the publicly accessible CTU-UHB database using only CTG-OAS, and fairly promising results are achieved. This software, which was developed mainly for research purposes, has great potential for the automated analysis of antenatal CTG. In addition, while the software cannot be used directly as a diagnostic tool, it can be used to ensure technical support for observers.

The rest of this paper is organized as follows: The database and the components of the software are summarized in Section 2. Experimental results and a discussion are presented in Section 3. Finally, concluding remarks are given in Section 4.

2. Material and methods

2.1. CTU-UHB intrapartum CTG database

A publicly accessible intrapartum CTG database called CTU-UHB [33] was used in this study to test the performance of the developed software. A total of 9164 intrapartum recordings were collected between 2010 and 2012 through STAN S21/S31 and Avalon FM40/FM50 EFM devices in the obstetrics ward of the University Hospital in Brno, Czech Republic. Then, 552 instances were carefully selected from these recordings, considering several technical and clinical criteria. All signals sampled at 4 Hz were stored in electronic form in the OB TraceVue® system. Each recording was divided into four parts, and each part was interpreted by nine experienced obstetricians. Furthermore, an annotated file providing biochemical markers, clinical features, and details of the evaluation was presented. Please refer to [33] for more detailed information about the database.

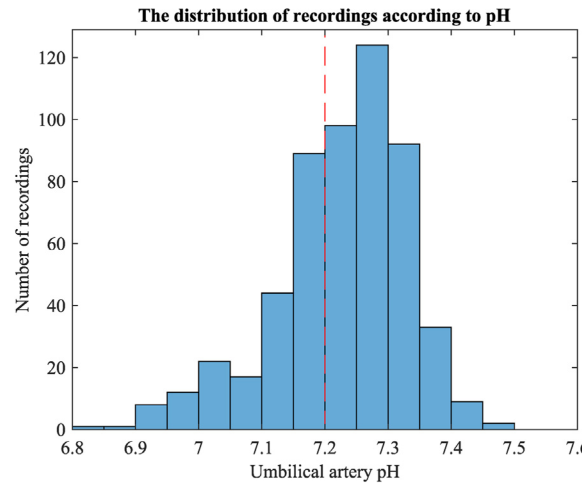

Fig. 1. Histogram of total number of CTG recordings used in the study, ordered by umbilical artery pH. There is a total of 552 recordings ranging from 6.85 to 7.47.

In a supervised learning approach, labeling of the data is a mandatory step that provides the network training to be performed. Either the views of clinicians [34] or fetal outcomes [35] can be chosen to label the signals. The fetal outcomes (pH values, the base deficit of newborn umbilical artery blood measured, etc.) are admitted as the objective annotation, whereas expert annotations (visual inspection) or evaluations of newborns (Apgar score) in the delivery room are agreed to be subjective in perinatal terminology [35]. In experimental studies, we prefer to use pH values to provide an objective evaluation of fetal hypoxia [36]. However, no specific umbilical artery pH value has been determined for separating the FHR signals as normal and abnormal. Furthermore, different values were used in previously reported studies [37,38]. These various works demonstrate that a cord artery pH of less than 7.20 points to fetal distress; otherwise, the pH value refers to fetal well-being [39].

The adjusted umbilical artery pH value emphasized with a red dashed line in Fig. 1 is used as a borderline for separating the recordings. A total of 552 recordings are taken into consideration, and the numbers of normal and hypoxic recordings are 375 and 177, respectively. In addition, we focus on the last 15 min of the signals, representing the second stage of labor in this study.

2.2. Basic components of CTG-OAS

CTG-OAS equipped with advanced signal processing and machine learning tools is an open-access software package developed for FHR signal analysis. The software is freely distributed for research purposes [40]. CTG-OAS was developed with the MATLAB® graphical user interface development environment (GUIDE). A block diagram of CTG-OAS is illustrated in Fig. 2. The software ensures the necessary processing steps are carried out: data preparation, feature transform, and classification regarding automated CTG analysis. CTG-OAS ensures a basic preprocessing scheme and also has the ability to provide a comprehensive feature set extracted from morphological, linear, nonlinear, time–frequency, DWT, and statistical domains to represent FHR signals.