Virtual simulator for the generation of patho-physiological foetal ECGs during the prenatal period

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The design, implementation, and verification of a signal simulator for the generation of patho-physiological records of foetal electrocardiograms (fECGs) during the prenatal period are briefly reported. The simulator enables users to model the patho-physiological changes that occur within the foetus' myocardium under hypoxic conditions (hypoxemia, hypoxia, asphyxia, etc.) during the 20th to 42nd week of pregnancy. The simulator deploys a dynamic fECG model including an actual fECG record taken from clinical practice, patho-physiological cardiotocography (CTG), and ST-analysis (STAN) records along with the ratio of T waves to the QRS complex; as well as clinical recommendations by FIGO (International Federation of Gynecology and Obstetrics) for classifying these records. By comparing synthesised and real patho-physiological CTG and STAN records, the functionality of the simulator, which effectively captured significant indicators of the foetus' condition during the prenatal period including fECG morphology, dynamic fECG characteristics, and others is evaluated and validated. The simulator enables users to test both current and emerging approaches in a very challenging area of gynaecology, namely the identification/classification of hypoxic conditions in the foetus during labour. Obstetricians can also use the simulator as a reference tool during the evaluation of suspect fECG abnormalities.

Introduction: The unavailability of a database for physiological and pathological foetal electrocardiogram (fECG) records limits the current research focused on identifying and classifying hypoxic conditions in the foetus [1–5]. Pathological cardiotocography (CTG) and fECG records are the key source of information used to develop a system that automatically classifies the vitality of the foetal heart. However, obtaining fECG records from the clinical practice (CP) is still very difficult [5]. This is particularly true in threatening foetal conditions such as asphyxia during which the obstetrician has to intervene and perform an operative pregnancy termination [1, 2, 5].

This Letter focuses on the modern methods used to model hypoxic conditions that threaten the proper development of a foetus and reduce the chance of having an easy birth without any complications. It builds upon a fundamental knowledge of the anatomy, physiology, and pathology of the foetal heart during the perinatal period [3–5].

Using this knowledge, the simulator models and reconstructs fECG signals that allow the user to define characteristics such as amplitudes and duration of P and T waves as well as the QRS complex; the foetal heart rate (FHR); ratio of T waves to the QRS complex (T/QRS); and to choose settings such as tachycardia, bradycardia, acceleration, and deceleration. Furthermore, following the CRC (FIGO (International Federation of Gynecology and Obstetrics)) [5] for classifying CTG and ST-analysis (STAN) [6] and based on FHR and T/QRS, the constructed fECG signal allows the user to model symptoms of hypoxic conditions, which could include the selection of the following: ST interval pathology, a biphasic ST segment (a negative ST segment with a predominance over the basal line, a negative ST segment partially crossing the basal line, depression of the ST segment under the basal ECG line) or the tendency or the ST segment.

Dynamic fECG model: The fECG dynamic model captures many important electrocardiographic characteristics of the foetal heart. Changes in the underlying anatomical structures are manifested as morphological changes in the observed fECGs. Model parameters can be changed to generate different wave shapes of the fECG signals. Various types of artefacts and noise can also be incorporated into the signals. The model is suitable for testing techniques detecting ST depressions or elevations by decreasing or increasing the position of the T wave on the Z axis over time.

Equation (1) represents a generalised dynamic model of the foetal heart dipole $\boldsymbol{d}(t)$ vector, which was prepared for possible incorporation into software based on the McSharry's approach [7, 8]

$$\boldsymbol{d}(t) = x(t)\cdot\boldsymbol{e}_x + y(t)\cdot\boldsymbol{e}_y + z(t)\cdot\boldsymbol{e}_z \quad (1)$$

This is a valid cardiac vector representation in the Cartesian coordinate system [7], where $\boldsymbol{e}_x$, $\boldsymbol{e}_y$, and $\boldsymbol{e}_z$ show dimensionless unit direction vectors in a three-dimensional space, respectively, in parallel with the three axes of the relevant vector cardiogram (Fig. 1). Different ECG leads can be considered to be the projections of the heart dipole vector $\boldsymbol{d}(t)$, (2), onto the recording electrode axes in the Cartesian coordinate system.

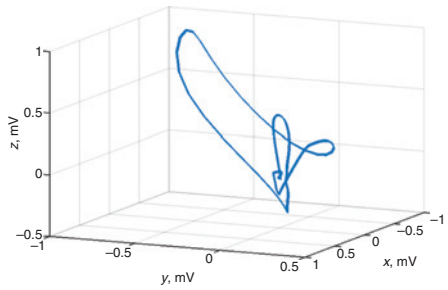

Fig. 1 *Dynamic fECG model*

These leads are therefore synchronised with each other and they have a quasi-periodic shape. The corresponding dynamical model of the synthetic fECG is as follows (in SI units):

$$\frac{\dot{x}_\mathrm{f}(t)}{f_\mathrm{s}} = -\frac{\omega_\mathrm{f}}{f_\mathrm{s}}\cdot\sum_{i=1}^{N}\frac{(\alpha_{\mathrm{f},x})_i}{(\beta_{\mathrm{f},x})_i^2}\cdot\left[\Delta(\theta_{\mathrm{f},x})_i\right]\cdot\exp\left\{-\frac{\left[\Delta(\theta_{\mathrm{f},x})\right]_i^2}{2\cdot(\beta_{\mathrm{f},x})_i^2}\right\} - x_\mathrm{f}(t) - A_{\mathrm{f},x}\cdot\sin(\omega_\mathrm{f}\cdot t) \quad (\mathrm{V})$$

$$\frac{\dot{y}_\mathrm{f}(t)}{f_\mathrm{s}} = -\frac{\omega_\mathrm{f}}{f_\mathrm{s}}\cdot\sum_{i=1}^{N}\frac{(\alpha_{\mathrm{f},y})_i}{(\beta_{\mathrm{f},y})_i^2}\cdot\left[\Delta(\theta_{\mathrm{f},y})_i\right]\cdot\exp\left\{-\frac{\left[\Delta(\theta_{\mathrm{f},y})\right]_i^2}{2\cdot(\beta_{\mathrm{f},y})_i^2}\right\} - x_\mathrm{f}(t) - A_{\mathrm{f},y}\cdot\sin(\omega_\mathrm{f}\cdot t) \quad (\mathrm{V})$$

$$\frac{\dot{z}_\mathrm{f}(t)}{f_\mathrm{s}} = -\frac{\omega_\mathrm{f}}{f_\mathrm{s}}\cdot\sum_{i=1}^{N}\frac{(\alpha_{\mathrm{f},z})_i}{(\beta_{\mathrm{f},z})_i^2}\cdot\left[\Delta(\theta_{\mathrm{f},z})_i\right]\cdot\exp\left\{-\frac{\left[\Delta(\theta_{\mathrm{f},z})\right]_i^2}{2\cdot(\beta_{\mathrm{f},z})_i^2}\right\} - x_\mathrm{f}(t) - A_{\mathrm{f},z}\cdot\sin(\omega_\mathrm{f}\cdot t) \quad (\mathrm{V})$$

Where $\Delta(\theta_{\mathrm{f},x})_i = [\theta_\mathrm{f} - (\theta_{\mathrm{f},x})_i]\cdot\mathrm{mod}(2\cdot\pi)$ (rad), $\Delta(\theta_{\mathrm{f},y})_i = [\theta_\mathrm{f} - (\theta_{\mathrm{f},y})_i]\cdot\mathrm{mod}(2\cdot\pi)$ (rad), $\Delta(\theta_{\mathrm{f},z})_i = [\theta_\mathrm{f} - (\theta_{\mathrm{f},z})_i]\cdot\mathrm{mod}(2\cdot\pi)$ (rad), $\omega_\mathrm{f} = \dot{\theta}_\mathrm{f} \equiv 2\cdot\pi\cdot f_{\mathrm{f,bb}}$ (rad s^{-1}), and $f_\mathrm{s} = 1/T_\mathrm{s}$ (Hz). Accordingly, (2) generates a circular trajectory rotating with the frequency of foetus's beat-to-beat heart rate (in bpm, dimensionally in s^{-1}). Each of the three coordinates of the dipole vector $\boldsymbol{d}(t)$ (see (1)) are modelled by a summation of Gaussian functions [7], including the foetus' voltage amplitudes of $(\alpha_{\mathrm{f},x})_i$, $(\alpha_{\mathrm{f},y})_i$, and $(\alpha_{\mathrm{f},z})_i$ (all in V); the foetus' angular widths of $(\beta_{\mathrm{f},x})_i$, $(\beta_{\mathrm{f},y})_i$, and $(\beta_{\mathrm{f},z})_i$ (all in rad) located at foetus' rotational angles of $(\theta_{\mathrm{f},x})_i$, $(\theta_{\mathrm{f},y})_i$, and $(\theta_{\mathrm{f},z})_i$ (all in rad).

The above equations (see (2)) apply for non-zero values of the signals $x(t)$, $y(t)$, and $z(t)$, while in [8] a primary definition of the dynamic foetal ECG system is mentioned when it is true that $x_\mathrm{f}(t) = y_\mathrm{f}(t) = z_\mathrm{f}(t) \equiv 0$ (all in V) and $x_{(\mathrm{f},0)}(t) = y_{(\mathrm{f},0)}(t) = z_{(\mathrm{f},0)}(t) \equiv 0$ (all in V).

Virtual simulator of fECG: The virtual simulator for the generation of non-invasive physiological and pathological records of a fECG is shown in Fig. 2, where dMMfECG represents a dynamic mathematical fECG model and VP mtx stands for the view point matrix.

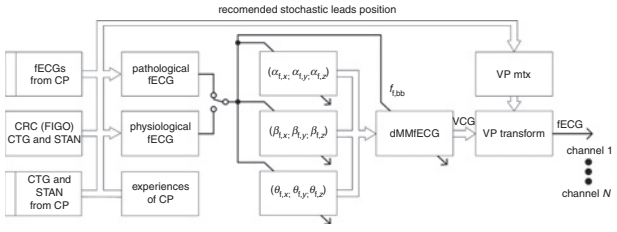

Fig. 2 *Simplified block diagram of fECG simulator*

Fig. 3 shows an actual physiological record of CTG and T/QRS from CP [6] for a 34-year-old G2 P1, gest. week 41 + 5, normal pregnancy. Fig. 4 shows an actual pathological record of CTG and T/QRS from CP [6] for a 26-year-old G1 P0, gest. week 41 + 3, normal pregnancy – 15:31 second biphasic in the event log. Intervention was required. By physician assessment, decision was made to perform a caesarean section – emergency caesarean section. Baby girl was born. AS 9,10,10. Birth weight 4410 g.

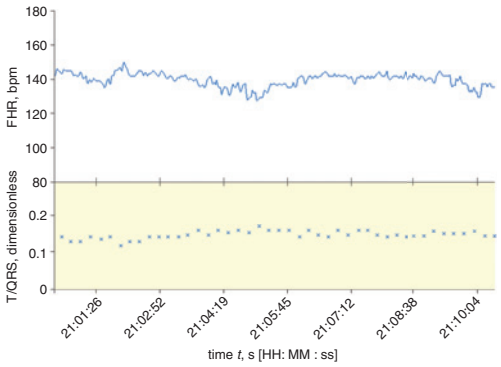

Fig. 3 *Real physiological records of CTG and T/QRS from CP*

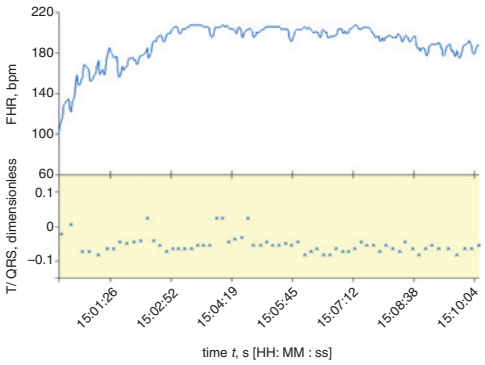

Fig. 4 *Real pathological records of CTG and T/QRS from CP*

Fig. 5 shows a physiological record of CTG and T/QRS modelled by the simulator. Fig. 6 shows a modelled pathological CTG and T/QRS records. These records demonstrate the possibilities of flexible simulation by merging fECG dynamics with actual CP records.

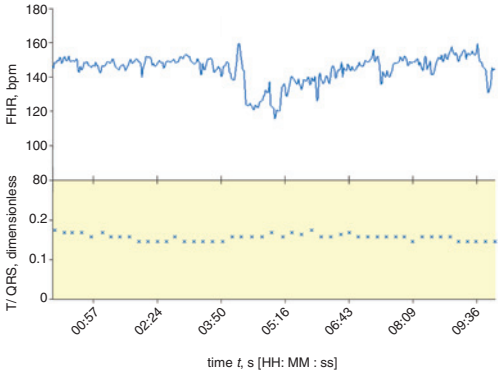

Fig. 5 *Modelled physiological CTG and T/QRS records*

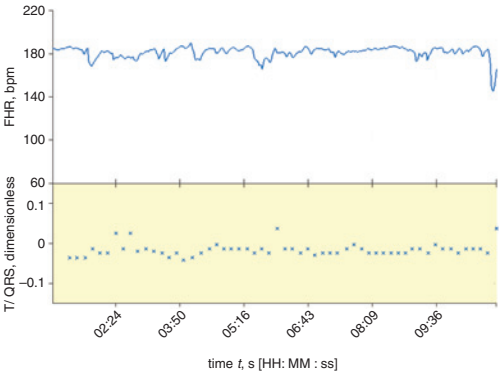

Fig. 6 *Modelled pathological CTG and T/QRS records*

Conclusion: The developed virtual simulator enables users to reliably model the significant electrocardiographical pathophysiology of changes within a foetus's myocardium during the prenatal period (the 20th to 42nd week of pregnancy). This simulator has the potential to significantly improve future research focused on the automatic identification and classification of CTG and STAN.

The simulator allows clinicians as well as technicians and obstetricians to model dangerous hypoxic conditions that may occur during the prenatal period without jeopardising the life of the foetus. Such tools can help practitioners in the field to develop the ability to timely diagnose hypoxic conditions and take effective measures in an efficient manner to safe the foetus' life.

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One or more of the Figures in this Letter are available in colour online.

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