

Multi-Channel ECG and Noise Modeling: Application to Maternal and Fetal ECG Signals

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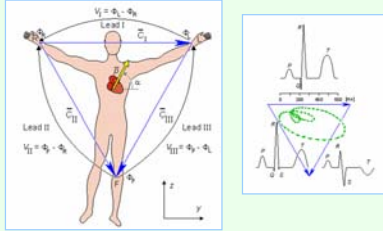
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Dipole Model of the Heart

The cardiac potentials may be modeled by a single rotating dipole located at the heart. This model is known as the **Single Dipole Model (SDM)**.



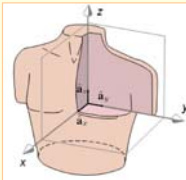
The ECGs can be considered as projections of the cardiac dipole onto the electrode axes.

A Dynamic Model for Multi-Channel ECG Generation

The cardiac dipole vector: $\mathbf{s}(t)_{3 \times 1} = [x(t), y(t), z(t)]^T$

A dynamic model for the dipole vector:

$$\begin{aligned} \dot{\theta} &= \omega \\ \dot{x} &= -\sum_i \frac{\alpha_i^x \omega}{(b_i^x)^2} \Delta \theta_i^x \exp\left[-\frac{(\Delta \theta_i^x)^2}{2(b_i^x)^2}\right] \\ \dot{y} &= -\sum_i \frac{\alpha_i^y \omega}{(b_i^y)^2} \Delta \theta_i^y \exp\left[-\frac{(\Delta \theta_i^y)^2}{2(b_i^y)^2}\right] \\ \dot{z} &= -\sum_i \frac{\alpha_i^z \omega}{(b_i^z)^2} \Delta \theta_i^z \exp\left[-\frac{(\Delta \theta_i^z)^2}{2(b_i^z)^2}\right] \end{aligned}$$



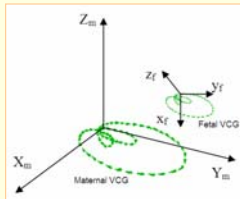
Synthetic adult ECG signals:

$$\mathbf{ECG}(t) = \mathbf{H} \cdot \mathbf{s}(t) + \mathbf{v}(t)$$

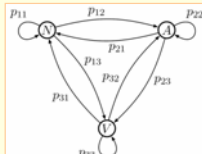
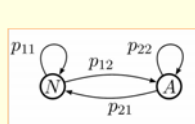
Synthetic maternal and fetal ECG mixtures:

$$\mathbf{X}(t) = \mathbf{H}_m \cdot \mathbf{R}_m \cdot \mathbf{A}_m \cdot \mathbf{s}_m(t) + \mathbf{H}_f \cdot \mathbf{R}_f \cdot \mathbf{A}_f \cdot \mathbf{s}_f(t) + \mathbf{W}(t)$$

These models are based on the single dipole model of the heart and a linear instantaneous body volume conductor medium. In these models \mathbf{H} corresponds to the body volume conductor transfer matrix, \mathbf{R} to the rotation of the dipole with respect to the body axes, and \mathbf{A} to the scaling of the dipole vector. $\mathbf{v}(t)$ and $\mathbf{W}(t)$ are synthetic nonstationary ECG noises.



Extension to abnormal beats using Hidden Markov Chains: Transition from normal to abnormal beats is modeled with a probabilistic model



Abstract

In this work, a three dimensional dynamic model of the electrical activity of the heart is presented. The model is based on the single dipole model of the heart and is later related to the body surface potentials through a linear model which accounts for the temporal movements and rotations of the cardiac dipole, together with a realistic ECG noise model. The proposed model is also generalized to maternal and fetal ECG mixtures recorded from the abdomen of pregnant women in single and multiple pregnancies. The applicability of the model for the evaluation of signal processing algorithms is illustrated using Independent Component Analysis (ICA). Considering the difficulties and limitations of recording long-term ECG data, especially from pregnant women, the model described in this work may serve as an effective means of simulation and analysis of a wide range of ECGs, including adults and fetuses.

Synthetic ECG Noise Generation

Typical high-amplitude ECG noises:

- Baseline Wander (BW)
- Muscle Artifact (MA)
- Electrode Movement (EM)

For the fetal ECG recorded from the maternal abdomen there are additional noises:

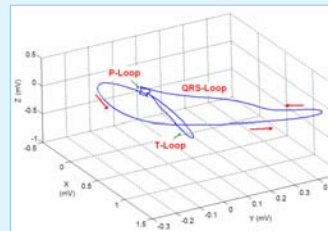
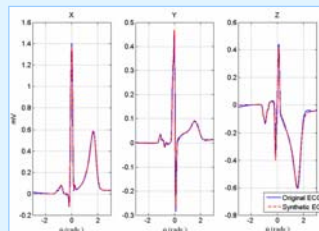
- Maternal ECG
- Fetal movements
- Maternal uterus contractions
- Changes in the conductivity of the maternal volume conductor due to the development of the *vernix caseosa* layer around the fetus

A time-varying **Autoregressive (AR)** model is used for generating synthetic ECG noises. The time-varying AR coefficients are estimated from typical samples of real ECG noise (such as the **MIT-BIH Non-Stress Test Database**), by using a **Kalman Filter**:

$$\begin{aligned} y_n &= -a_{n1}y_{n-1} - a_{n2}y_{n-2} - \dots - a_{np}y_{n-p} + v_n \\ &= -[y_{n-1}, y_{n-2}, \dots, y_{n-p}] \begin{bmatrix} a_{n1} \\ a_{n2} \\ \vdots \\ a_{np} \end{bmatrix} + v_n, \\ \mathbf{x}_n &= [a_{n1}, a_{n2}, \dots, a_{np}]^T \\ \mathbf{h}_n &= -[y_{n-1}, y_{n-2}, \dots, y_{n-p}]^T \\ \begin{cases} \mathbf{x}_{n+1} = \mathbf{x}_n + \mathbf{w}_n \\ y_n = \mathbf{h}_n^T \mathbf{x}_n + v_n \end{cases} \end{aligned}$$

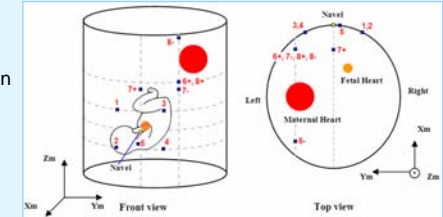
Where the \mathbf{y}_n are the real ECG noise samples used for training, \mathbf{x}_n is a vector of the AR coefficients which are assumed to follow a **Random Walk Process** with an input white noise of \mathbf{w}_n , and \mathbf{v}_n is the measurement noise.

Example 1: Noise-Free Adult ECG and VCG

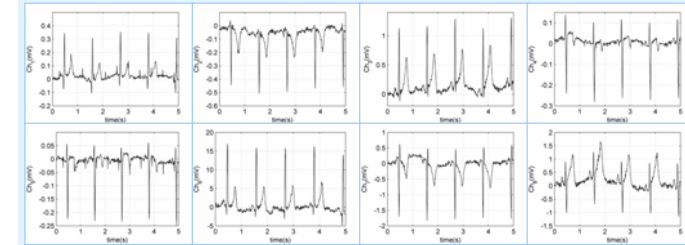


Example 2: Synthetic Noisy Maternal Abdominal Signals

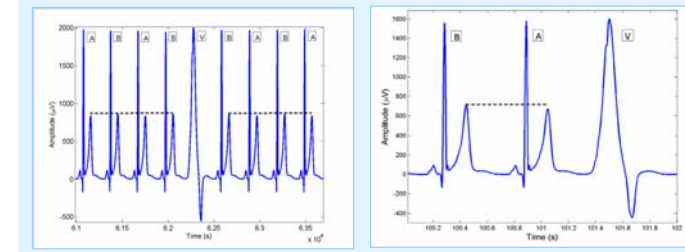
Electrode configuration



Synthetic noisy multi-channel abdominal ECGs



Abnormal Beat Generation using Hidden Markov Chains



Conclusions

The proposed model can be effectively used for the modeling of normal and abnormal ECG of adults and fetuses with variable SNRs. The model is specifically useful for the evaluation of single and multi-channel ECG filtering techniques.

References

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