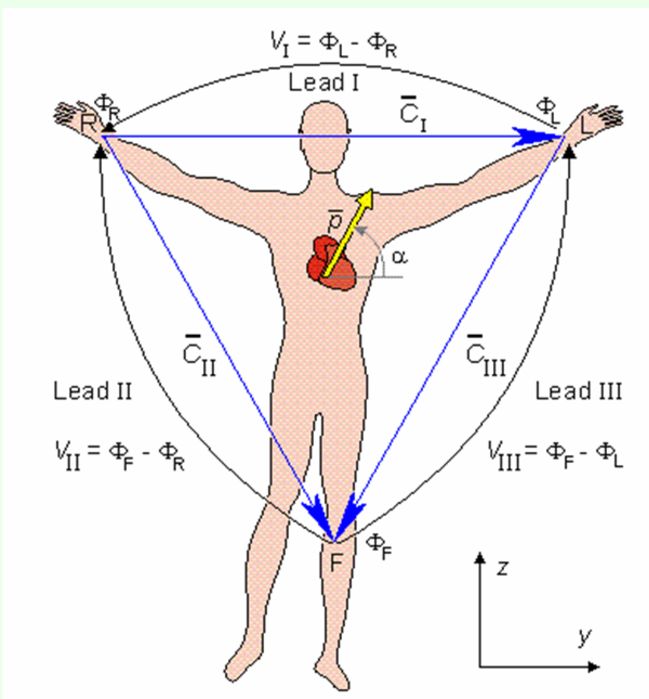
Multi-Channel ECG and Noise Modeling: Application to Maternal and Fetal ECG Signals

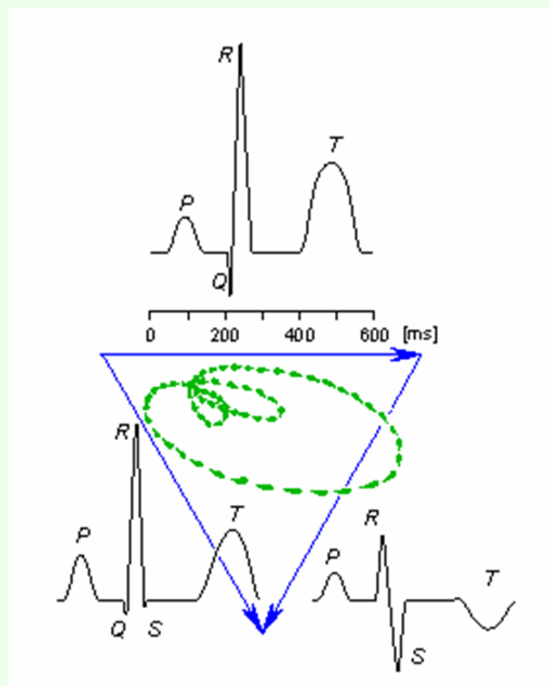
Reza Sameni, Gari D. Clifford , Christian Jutten , and Mohammad B. Shamsollahi

Biomedical Signal and Image Processing Laboratory (BiSIPL), School of Electrical Engineering, Sharif University of Technology, Tehran, Iran
Laboratoire des Images et des Signaux (LIS) – CNRS UMR 5083, INPG, UJF, Grenoble, France
Laboratory for Computational Physiology, Harvard-MIT Division of Health Sciences and Technology (HST), Cambridge MA, USA
Emails: reza.sameni@gmail.com, gari@mit.edu, christian.jutten@inpg.fr, mbshams@sharif.ir

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).





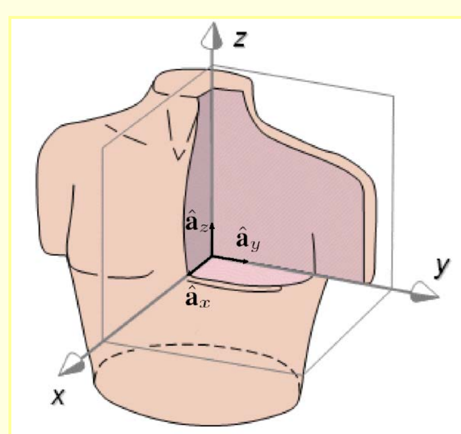
The ECGs can be considered as projections of the cardiac dipole onto the electrode axes.

A Dynamic Model for Multi-Channel ECG Generation

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

A dynamic model for the dipole vector:

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

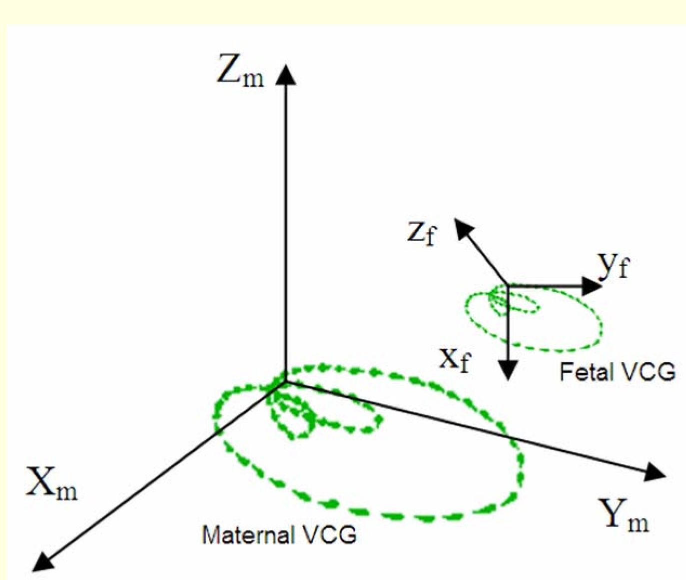


Synthetic adult ECG signals: $\mathbf{ECG}(t) = H\cdot\mathbf{s}(t) + \mathbf{v}(t)$

Synthetic maternal and fetal ECG mixtures:

$$X(t) = H_m \cdot R_m \cdot \Lambda_m \cdot s_m(t) + H_f \cdot R_f \cdot \Lambda_f \cdot s_f(t) + W(t)$$

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



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*:

$$
\begin{aligned}
y_n &= -a_{n1}y_{n-1} - a_{n2}y_{n-2} - \dots - a_{np}y_{n-p} + v_n \\
&= -[y_{n-1}, y_{n-2}, \dots, y_{n-p}]\begin{bmatrix} a_{n1} \\ a_{n2} \\ \vdots \\ a_{np}\end{bmatrix} + v_n,
\end{aligned}
$$

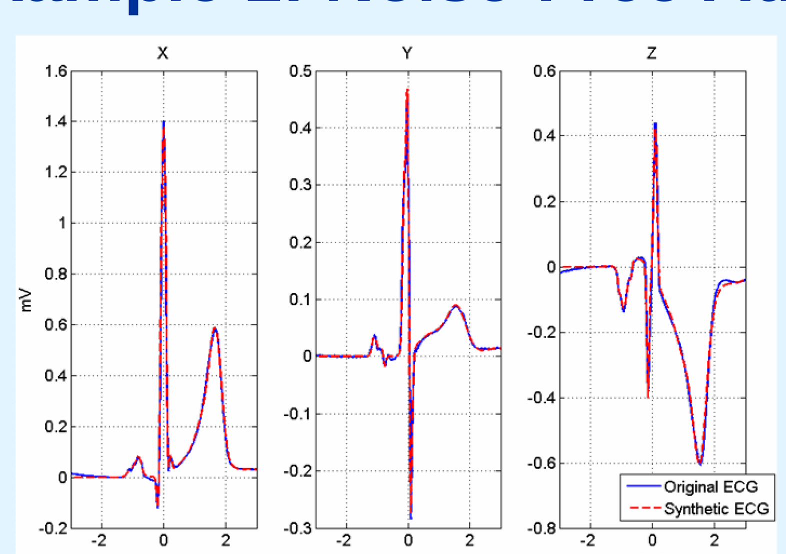
$$\mathbf{x}_n = [a_{n1}, a_{n2}, \dots, a_{np}]^T$$

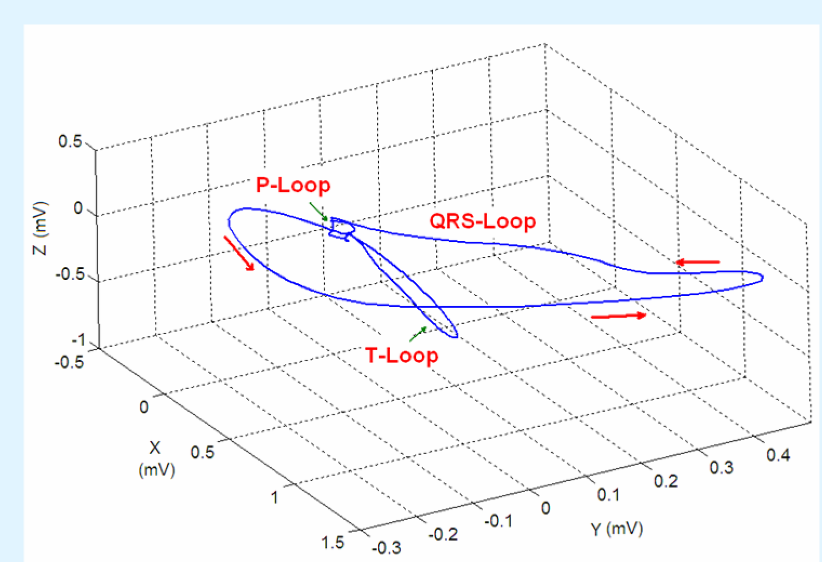
$$\mathbf{h}_n = -[y_{n-1}, y_{n-2}, \dots, y_{n-p}]^T$$

$$\begin{cases} \mathbf{x}_{n+1} = \mathbf{x}_n + \mathbf{w}_n \\ y_n = \mathbf{h}_n^T\mathbf{x}_n + v_n \end{cases}$$

Where the y_n are the real ECG noise samples used for training, x_n is a vector of the AR coefficients which are assumed to follow a *Random Walk Process* with an input white noise of w_n, and v_n is the measurement noise.

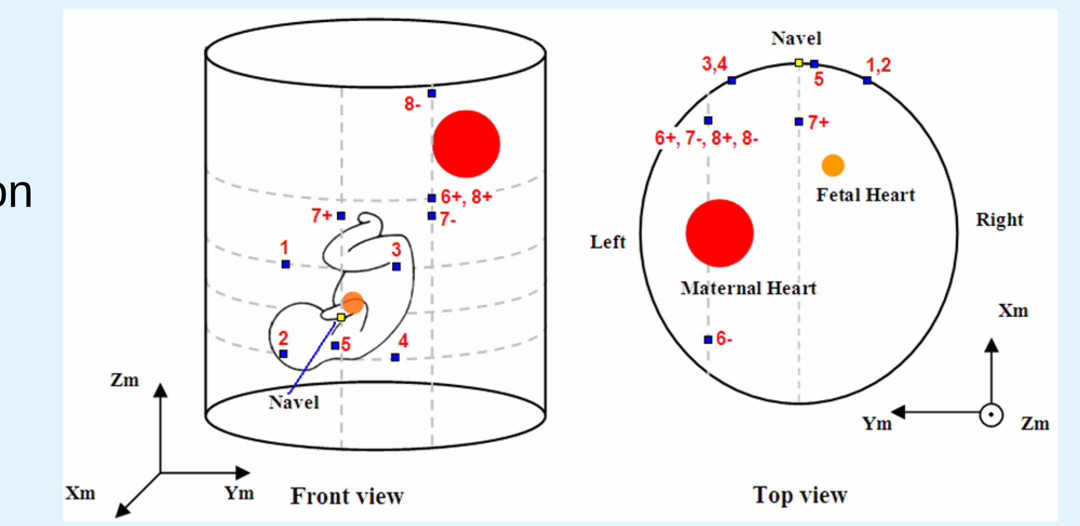
Example 1: Noise-Free Adult ECG and VCG



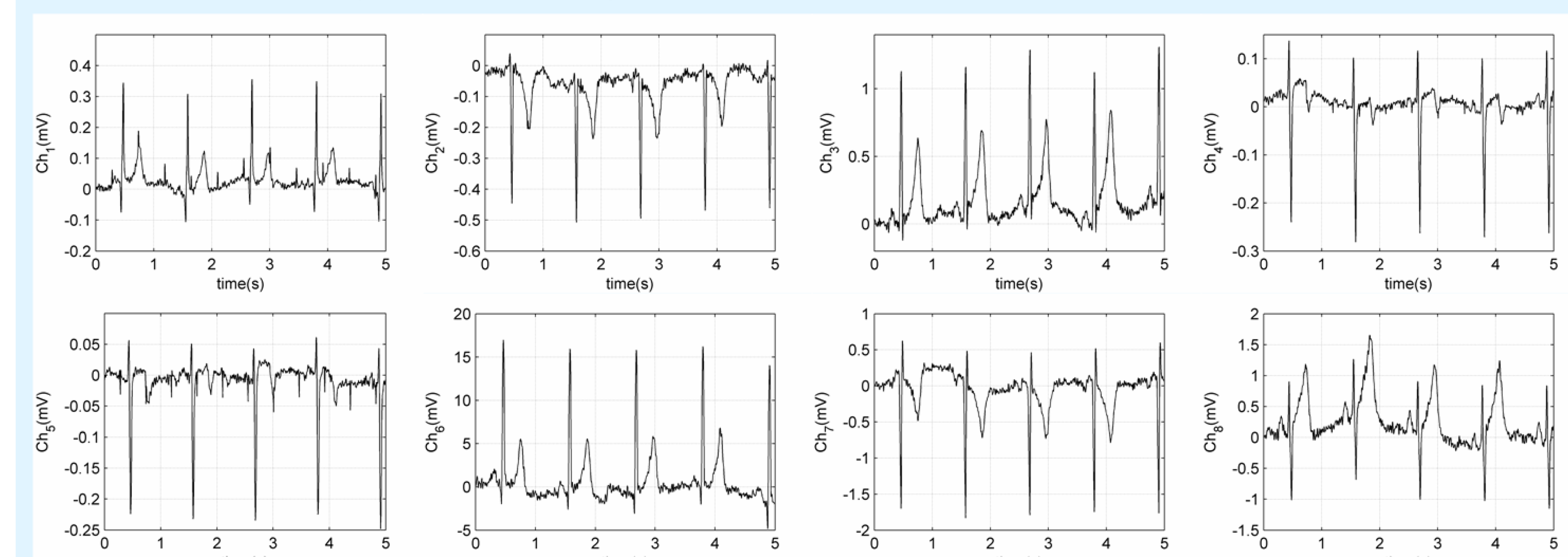


Example 2: Synthetic Noisy Maternal Abdominal Signals

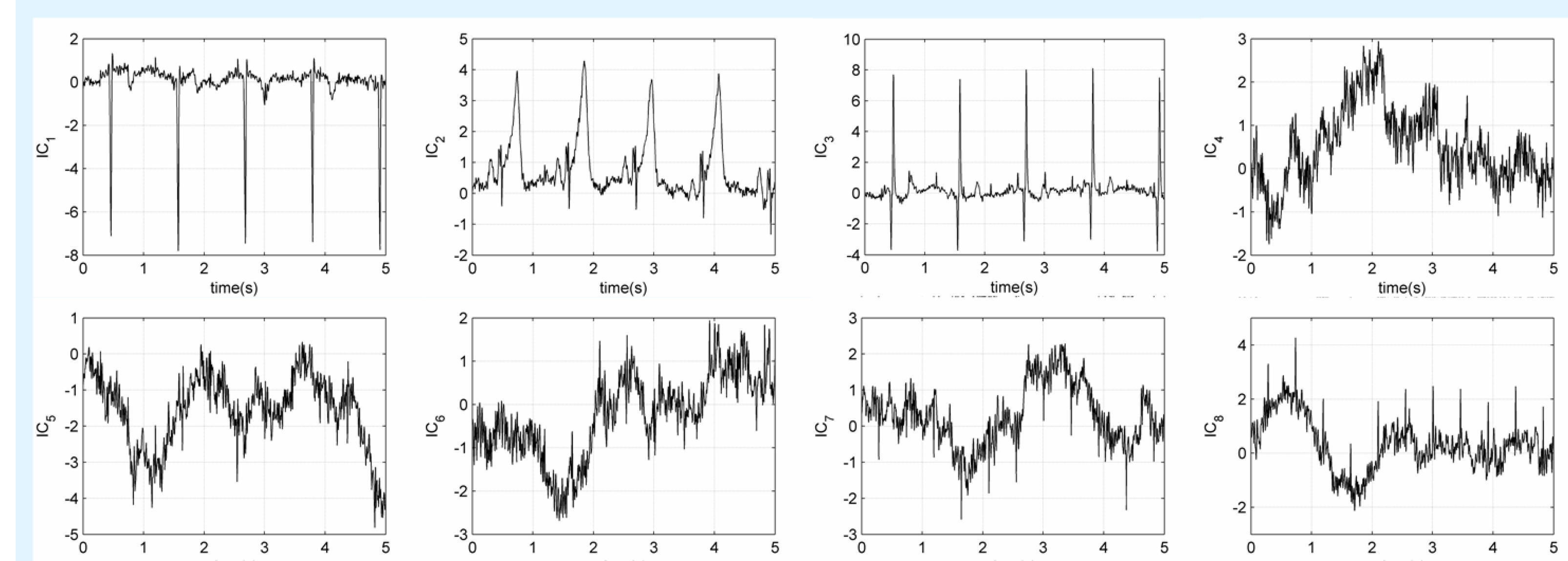
Electrode configuration



Synthetic noisy multi-channel abdominal ECGs



Independent components extracted from multi-channel abdominal ECGs



Conclusions

The proposed model can be effectively used for the modeling of realistic adult and fetal ECG with variable SNRs. The model is specifically useful for the evaluation of multi-channel signal decomposition techniques such as ICA.

References

R. Sameni, G. D. Clifford, C. Jutten, and M. B. Shamsollahi. **Multi-Channel ECG and Noise Modeling: Application to Maternal and Fetal ECG Signals**. *EURASIP Journal of Applied Signal Processing*, 2007. [In Press]

P. E. McSharry, G. D. Clifford, L. Tarassenko, and L. A. Smith. **A Dynamic Model for Generating Synthetic Electrocardiogram Signals**. *IEEE Trans. Biomed. Eng.*, 50:289-294, march 2003.

Contact Information

Address: Biomedical Signal and Image Processing Laboratory (BiSIPL), School of Electrical Engineering, Sharif University of Technology, Tehran, Iran.

Email: reza.sameni@gmail.com Web: http://ecg.sharif.ir