A Nonlinear Artificial Model For Generating Realistic Correlated ECG, BP And Respiration

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Abstract. An artificial ECG, BP and respiration signal generator, based upon three ordinary differential equations, and a stochastic RR interval generator. The signals are shown to accurately reproduce many of the intra- and inter-beat variations in each signal, together with the expected inter-signal interactions, such as pulse transmission time, pulsus paradoxus, respiratory sinus arrhythmia, QRS and QT dispersion, ECG peak height modulation, ST changes and baseline wander. Open source code is available from Physionet.

1 Introduction

Extensions are presented to a previously published nonlinear model for generating realistic artificial electrocardiograms (ECGs) [1], which accurately reproduces many of the important clinical qualities of ECG signals such as QRS and QT dispersion and realistic beat-to-beat variability in timing and morphology. As well as including a method for generating realistic blood pressure (BP) and respiratory signals, modifications to the original ECG model are proposed to improve the realistic nature of the ECG.

2 Methods

The ECG is generated by resolving the vertical (z) component of a perturbed limit cycle in three dimensions. Figure 1 illustrates how resolving the z-axis of an evolving trajectory through the 3D (x,y,z) space leads to a realistic ECG. The trajectory is derived by integrating three ordinary differential equations (ODEs);

$$\dot{x} = \alpha x - \omega y$$
$$\dot{y} = \alpha y + \omega x$$
$$\dot{z} = -\sum_{i\in\{P,Q,R,S,T\}} a_i \Delta\theta_i \exp\left(-\frac{\Delta\theta_i^2}{2b_i^2}\right) - (z - z_0) \quad (1)$$

over a suitable set of parameters. Here, $\alpha = \sqrt{(x^2-y^2)}$, $\Delta\theta = (\theta - \theta_i) \bmod 2\pi$, $\theta = \mathrm{atan2}(x,y)$ and ω is the angular frequency around the limit cycle. The θ_i are the angles of the extrema (P, Q, R, S and T) around the limit cycle, the a_i are the repulsive strength of the extrema and the b_i define the Gaussian region of influence that each of the extrema have. θ_i, a_i and b_i therefore define the morphology of the ECG. Realistic values of these parameters are given in [1].

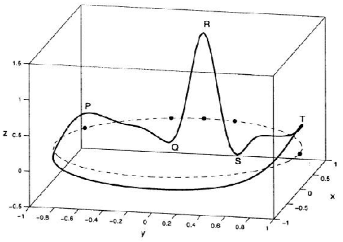

Fig 1. A limit cycle in the x-y plane is perturbed by fixed-point extrema P,Q,R,S & T, to produce a three-dimensional limit cycle.

	P	Q	R	S	T
a_i	0	0	0.45	0.25	0.45
b_i	0.25	0.1	0.3	0.5	0.3
θ_i	$-75\pi/180$	$-5\pi/180$	0	$10\pi/180$	$80\pi/180$

Table 1. Values of the P,Q,R,S & T, system parameters for generating artificial BP. Note that the P and Q extrema set the baseline.

The beat-to-beat variations in morphology and timing occur as a result of varying ω in a realistic manner (such as driving with a bimodal Gaussian spectrum – see [1] and [2]). The upper plot in Fig. 2 illustrates an example of an ECG derived from this model. The respiratory signal is simply the high frequency ($0.3\pi \leq \omega \leq 0.8\pi$) driving component. The BP is then generated by choosing appropriate values for θ_i , a_i and b_i (see table1), adding a positive offset $\delta\theta$ in order to simulate the PTT (pulse transmission time; the time from depolarisation to the measured pulse wave) then integrating over time with an appropriate time step. Experiments have shown that this time step must be at least as high as the sampling frequency to avoid serious differences in the input/output characteristics. Furthermore, to avoid having to anti-alias filter, the integration step (which can be thought of as an *internal* sampling frequency) must be an integer multiple of the desired output sampling frequency. The PTT is modelled as a heart rate dependent offset $\delta\theta = (1-\sqrt{RR_j}/2)/2\pi$, added to θ_i , where RR_j is the j^{th} precession (RR interval) around the limit cycle. PTT therefore changes realistically from beat-to-beat (see [3] for experimental values). Open source code in Matlab, C and Java is available from Physionet (http://www.physionet.org/physiotools/ecgsyn/).

3 Results

The lower three plots of Fig.2 represent the respiration, RR interval and BP signals derived from this method, with corresponding power spectral densities. Note that the respiratory signal has a PSD with very similar properties to the higher frequency peak for the RR intervals (which exhibits both low and high frequency peaks). The PSD of the peak-trough variations of the BP signal exhibits strong low frequency peaks as expected, with some component in the higher respiratory segment due to inspiratory BP drops (*pulsus paradoxus*).

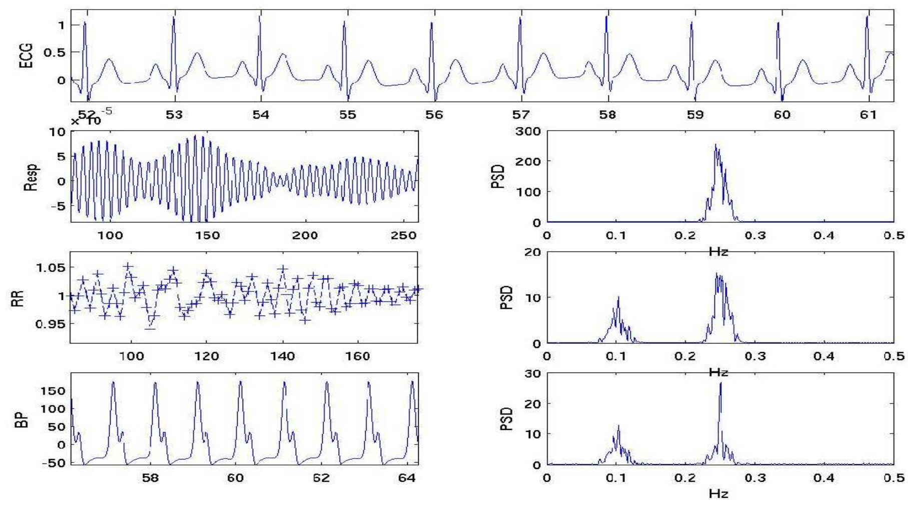

Fig. 2. ECG, Respiration, RR interval and BP generated with the model given in (1), with PSDs. BP PSD is derived from peak-peak oscillations.

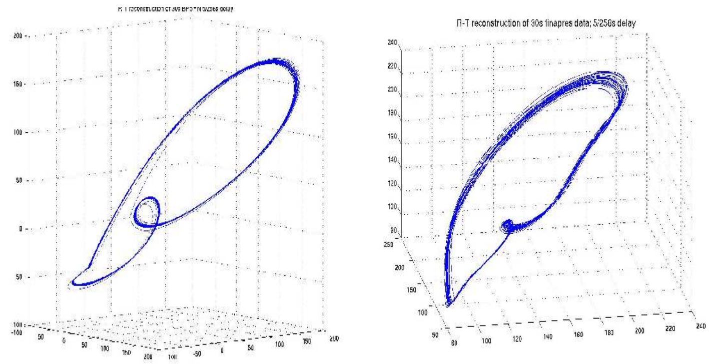

Fig. 3. Ruelle-Takens [4] reconstructions of artificial (left) and real (right) BP signal for an embedding dimension of 3 and a step delay of 5/256 seconds.

It should be noted however, that although the model produces a nonstationary respiration signal, the sinusoidal variation is not asymmetric, as in nature. This problem can, in part, be mitigated by adding correlated noise to the respiratory signal. The same minor departure from reality can also be seen in the lack of asymmetry in the (Gaussian) T-waves.

Together with a realistic reproduction of most of the important linear statistical, spectral and time domain features of a real set of ECG, BP and respiration signals, the model can be shown to produce realistic nonlinear behaviour as well. Figure 3 illustrates the phase space trajectories of a realistic (left) and artificial (right) BP waveforms. As well as a qualitative correspondence between the two signals, they also exhibit quantitative similarities with Correlation Dimension ($D_2 \approx 1.1$) and Approximate Entropy (ApEn ≈ 2.3) similar to those previously reported [4].

4 Conclusions

The described model produces realistic coupled linear and nonlinear physiological variations for heart rate, ECG, respiration and BP with completely known properties. The model may therefore prove useful in testing conventional and emerging signal processing techniques in cases where realistic expert annotated test data may not be available. Extensions to the nonlinear model could include 24hr realsitic RR interval variations [2] and multiple ECG lead modelling (by taking angluar slices through the embedding space).

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