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Nonlinear dynamics in infant respiration

MICHAEL SMALL

By using inductance plethysmography it is possible to obtain a non-invasive measurement of the chest and abdominal cross-sectional area. These measurements are "representative" of the instantaneous lung volume. This thesis describes an analysis of the breathing patterns of human infants during quiet sleep using techniques of nonlinear dynamical systems theory [**1**, **6**, **7**]. The purpose of this study is to determine if these techniques may be used to extend our understanding of the human respiratory system and its development during the first few months of life. Ultimately, we wish to use these techniques to detect and diagnose abnormalities and illness (such as apnea and sudden infant death syndrome) from recordings of respiratory effort during natural sleep.

Previous applications of dynamical systems theory to biological systems have been primarily concerned with the estimation of dynamic invariants: correlation dimension, Lyapunov exponents, entropy and algorithmic complexity. However, estimating these numbers has not proven useful in general. The study described in this thesis focuses on building models from time-series recordings and using these models to deduce properties of the underlying dynamical system. We apply a correlation dimension estimation algorithm [**2**, **3**] in conjunction with well known surrogate data techniques [**16**, **17**, **18**] and conclude that the respiratory system is not linear [**10**, **13**]. To elucidate the nature of the nonlinearity within this complex system we apply a new type of radial basis modelling algorithm (*cylindrical* basis modelling) [**4**, **5**, **9**] and generate new nonlinear surrogate data [**10**, **11**].

New nonlinear radial (cylindrical) basis modelling techniques have been developed by the author to model accurately this data [**9**]. This thesis presents new results concerning the use of correlation integral based statistics for surrogate data hypothesis testing. This extends the scope of surrogate data techniques to include hypotheses concerned with broad classes of nonlinear systems [**8**, **11**]. We conclude that the human respiratory system behaves as a periodic oscillator with two or three degrees of freedom [**13**]. This

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system is shown to exhibit cyclic amplitude modulation (CAM) during quiet sleep [**13, 15**].

By examining the eigenvalues of fixed points exhibited by our models, and the qualitative features of the asymptotic behaviour of these models, we find further evidence to support this hypothesis [**14**]. An analysis of Poincaré sections and the stability of the periodic orbits of these models demonstrates that CAM is present in models of almost all data sets. Models which do not exhibit CAM often exhibit chaotic first return maps. Some models are shown to exhibit period doubling bifurcations in the first return map.

To quantify the period and strength of CAM we suggest a new statistic based on an information theoretic reduction of linear models [**12**]. The models we utilise offer substantial simplification of autoregressive models and provide superior results. We show that the period of CAM present before a sigh and the period of subsequent periodic breathing are the same [**13, 15**]. This suggests that CAM is ubiquitous but only evident during periodic breathing [**13**]. Physiologically, CAM may be linked to an autoresucitation mechanism. We observe a significantly increased incidence of CAM in infants at risk of sudden infant death syndrome and a higher incidence of CAM during apneaic episodes of bronchopulmonary dysplasic infants.

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Centre for Applied Dynamics and Optimization
Department of Mathematics and Statistics
University of Western Australia
Nedlands WA 6907
Australia

Current Address:
Department of Physics
Heriot-Watt University
Riccarton, Edinburgh, EH14 4AS
United Kingdom
e-mail: M.A.Small@hw.ac.uk