Determination of pain intensity in newborns by time series analysis

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Abstract

We present interesting experimental results obtained from an observational study of the cries of several newborns aged between 24 and 48 hours, recorded during the phase of blood sampling. Analysis performed put in evidence that the emitted vocalization becomes more irregular and aperiodic with the increase of the pain suffered by the newborn. We think that this phenomenon can be explained by taking into account some behaviors observed in the model by Ishizaka and Flanagan of the vocal folds [1]. Chaotic behaviors have been found in the cries of healthy infants as well as infants with several perinatal complications [2]. We show that these phenomena also appear in healthy infants and are related to the newborn's pain intensity. Under the point of view of the dissipative systems, pain acts as a bifurcation parameter for the motion of the vocal folds. These hypothesis are supported by the recurrence plot [3, 4] analysis performed on the cries and, in particular the shape and the patterns observed in the plots are typical of chaotic transitions observed in dissipative systems.

1 Introduction

In this work we perform a time series analysis on the vocalizations in order to find a relation between the pain suffered and the arise in the signal of irregular and chaotic dynamics. It would be very important to understand the health status of the newborn by an analysis of the cry. Chandre *et al.* [5] shows that it is possible to describe and individuate chaotic and irregular dynamics by an inspection of the spectrogram of irregular signals and, in literature, Herzel *et al.* observed several irregular behaviors inspecting spectrograms of newborns cries [2]: Subharmonics and chaotic behaviors have been found in cries of healthy infants as well as infants

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 ISBN 1-85312-721-3

with several perinatal complications. However frequency and the duration of the episodes are dependent on the health status of the newborn. This may indicate that brain control on the vocal apparatus is poor or not completely developed [2].

In this study we perform a Time Series Analysis based on Recurrence Plots (RPs) [6, 3] and will show that the arise of chaotic dynamics is also related to the pain suffered by newborns and we think that the arise of nonlinear phenomena in painful cries may be correlated to the muscolar contraction typical of sufference. The contraction causes strong variations in the elastic constants of the tissues and determinates different oscillating behaviors of the vocal folds [7, 8].

2 Materials

In this observational study, newborns were evaluated during heel-pricks performed with different analgesic techniques [9, 10]. Each baby was recorded by a Sony video camera, and a pain score on the DAN scale Douleur Aiguë du Nouveau Né) [11] was assigned to each baby after the sampling. The DAN score is obtained by scoring three items according with the extent they are present during the painful event: crying, arms and legs movements, grimacing. The DAN scale is reported in table 1: the total score ranges from 0 (minimum pain) to 10 (maximum pain).

The acoustic signals were collected by an analog recorder and digitized at a sampling frequency of 44100 Hz. From each record several series of 500-800 msec, corresponding to the first cry, were extracted. To avoid influence of the movements of the child a normalization on the maximum value was performed.

The recording are divided in three groups:

1. Low pain: DAN=1-4.
2. Medium pain: DAN=5-7.
3. High pain: DAN=8-10.

3 Time series analysis based on recurrence plots

Recurrent behaviors are typical of natural systems and, the recurrence of states, in the meaning that states are arbitrarily close in time with other is a classic behavior of dynamical systems. In 1987 Eckmann *et al.* [6] developed a visual tool to identify spatiotemporal recurrences in multidimensional phase spaces. Since a dimensional phase space can be only visualized in 3 dimensions by a projection, it is hard to investigate stuctures in high dimensional attractors. The *Recurrence Plot* (RP) is a tool able to investigate higher dimensional dynamics through a two dimensional binary plot of its recurrences. Any recurrence of state i with state j is pictured on a boolean matrix and marked by a black dot in the position (i, j) in the diagram and can be mathematically expressed by [4]:

$$\mathbf{R}_{i,j}^{m,\varepsilon_i}\Theta(\varepsilon_i - ||\vec{x}_i - \vec{x}_j||) \tag{1}$$

Where $\vec{x}_{i,j} \in \mathbb{R}^m$ and $i, j \in \mathbb{N}$, ε_i is an arbitrary threshold. Since any state is recurrent with itself, the RP has a $\pi/4$ diagonal, said *Line of Identity* (LOI).

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Table 1: DAN: behavioral acute pain-rating scale for neonates.

Measure	Score
Facial Expressions	
Calm	0
Snivels and alternates gentle eye opening and closing	1
Determine intensity of one or more of eye squeeze, brow bugle nasolabial furrow	
Mild, intermittent with return to calm	2
Moderate	3
Very pronounced, continuous	4
Limb movements	
Calm or gentle movements	0
Determine intensity of one or more of the following signs: pedals, toes spread legs tensed and pulled up, agitation of arms, withdrawal reaction	
Mild intermittent with return to calm	1
Moderate	2
Very pronounced, continuous	3
Vocal expressions	
No complaints	0
Moans briefly; for intubated child, looks anxsious or uneasy	1
Intermittent crying; for intubated child, gesticulations of intermittent crying	2
Long-lasting crying, continuous howl; for intubated child gesticulation of continuous crying	3

To compute a RP, a norm must be defined, and the most known are the L_1, L_2, L_∞ norm, the last is largely used because is independent from the phase space dimension, and no rescaling is requested. Furthermore special attention must be turned to the choice of the threshold ε. For this estimation, the noise level of the time series must be taken in account and suggested values in literature are some percentage of the maximum diameter of the attractor (in any case, not more than 10%).

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3.1 Structures in recurrence plots

The initial purpose of the RP is the visual inspection of high dimensional phase space trajectories. The RP are characterized by patterns of two kinds [6], *Typology* and *Textures*.

Typology offers a global impression and can be characterized as:

- *Homogeneous*: This kind of RP is typical of stationary processes, and usually is associated with white noise.
- *Periodic*: Diagonal lines parallel to the LOI are typical of periodic systems.
- *Drift* behaviors are caused by slow varying parameters in the system.

Changes in dynamics are identified by white areas or bands.

The textures are the local structures that can be observed in RP, they are: *single dots, diagonal lines, vertical and horizontal lines*.

- *Single Points*: The state does not persist for many time, usually a RP made only of single points is related to white noise.
- *Diagonal lines*: This kind of texture can be expressed by:

$$\mathbf{R}_{i+k,j+k} = 1 \,\Big|_{k=1}^{L}$$

  where L is the length of the line. The Trajectory visit the same region of phase space at different times.
- *Vertical and Horizontal lines* of length L can be expressed by:

$$\mathbf{R}_{i,j+k} = 1 \,\Big|_{k=1}^{L}$$

  the state does not changes or changes slowly in time.

RPs are useful in the analysis of non stationary time series. In this case, the traditional methods of nonlinear time series analysis are not adequate for the computation of the characteristic parameters that identify chaos dynamics such as Lyapunov exponents, correlation dimension, and embedding dimension. Since voice is a strongly nonstationary process, and RP in the last years were used to analyze large time series of human and animal vocalizations [12].

4 Results

The first part of the cries collected are reported in Fig. 2, where 9 signals are divided in three groups:

1. Column (a): Low DAN cries.
2. Column (b): Medium DAN cries.
3. Column (c): High DAN cries.

Form the figure we can observe that there is a difference between column (a) and (c). The signals in column (a) are periodic and those in column (b) have some periodicities and aperiodicities. The signals in column (c) are completely irregular.

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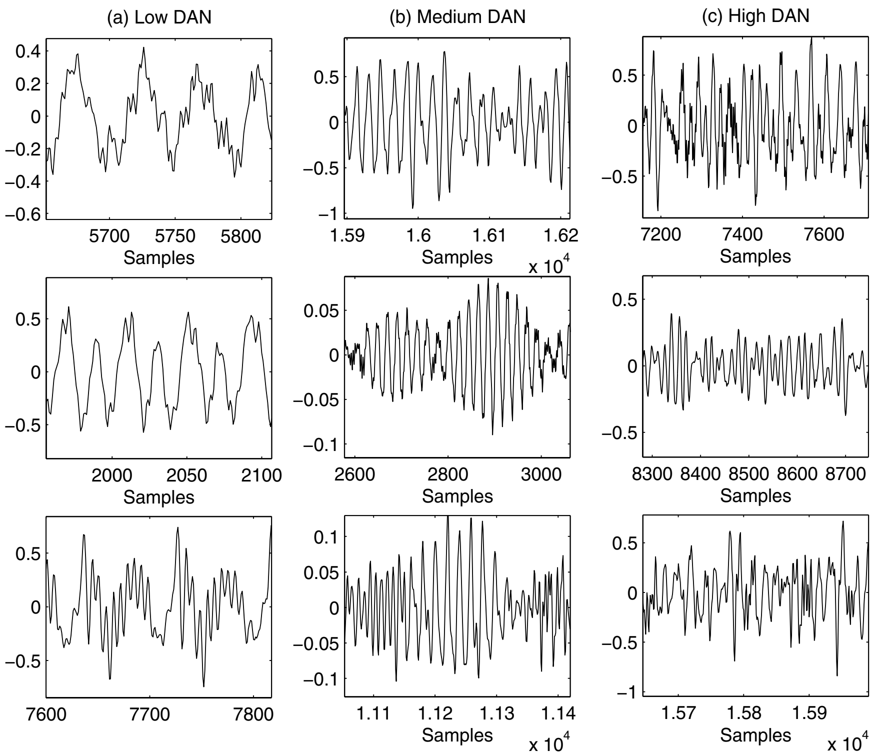

Figure 1: Some portions of the analyzed signals:(a) Periodic motion characterizing painless cries. (b) Intermittency arise when the pain increases. (c) Full irregular motion is the characteristic of cries with high DAN values.

4.1 Recurrence Plot analysis results

In order to compute the RPs, the underlying attractor must be reconstucted using the method of delays by Takens and Mañe [13] and embedding dimension D_E and delay time T_d must be computed. For the computation of the delay time was used the *mutual information* and the value $T_d = 7$ was found. Since the model of the vocal folds is a four dimensional one the value $D_E = 4$ would be good, but the time series are non stationary and corrupted by noise. Using the overembedding [14] technique the reconstruction dimension for all the signal is $D_E = 8$. For the computation of the threshold ε the L_∞ norm is used and the plot are renormalized using the maximum value. In table 2 are reported the values of the ε for the time series showed.

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Table 2: Values of the threshold ε for the analyzed time series.

	ε		ε		ε
$(a)_1$	12	$(b)_1$	15	$(c)_1$	12
$(a)_2$	16	$(b)_2$	10	$(c)_2$	15
$(a)_3$	18	$(b)_3$	8	$(c)_3$	14

In the following subsection will be reported the discussion of the RPs for the three groups of DAN score.

4.2 Low DAN

In figure 2(a) the RPs relative to low DAN cries are reported. The plots are characterized by long lines parallel to the LOI, indicating that the signal are almost periodic and that the phase space trajectories visit the same regions at different times.

4.3 Medium DAN

In figure 2(b) cries associated to a DAN score of 5,6,7 are reported. The main feature of the plot is the alternance of regular bands and white bands. This indicates that the vocal folds oscillates with intermittencies in their regular oscillations, typical of toroidal oscillations [15].

4.4 High DAN

RPs from highly painful cries are those typical of chaotic dynamics. In figure 2(c) a distribution of short parallel lines can be observed. As stated in cited literature this configuration is typical in systems where chaos is fully developed.

5 Discussion of results

The three columns of figure 2 show a transition of a dynamical system toward chaos by a cascade bifurcation. According to [7] the elastic constants of the two mass model are bifurcation parameters and, in this case, the bifurcation parameter is the pain suffered. Since the vocal folds can be modelled by two viscoelastic coupled oscillators, pain causes an higher rigidity of the tissues and, of course, of the vocal folds too. Furthermore, the chaotic nature of animal and human vocalization has been analyzed by consolidated and well accepted techniques [16, 8].

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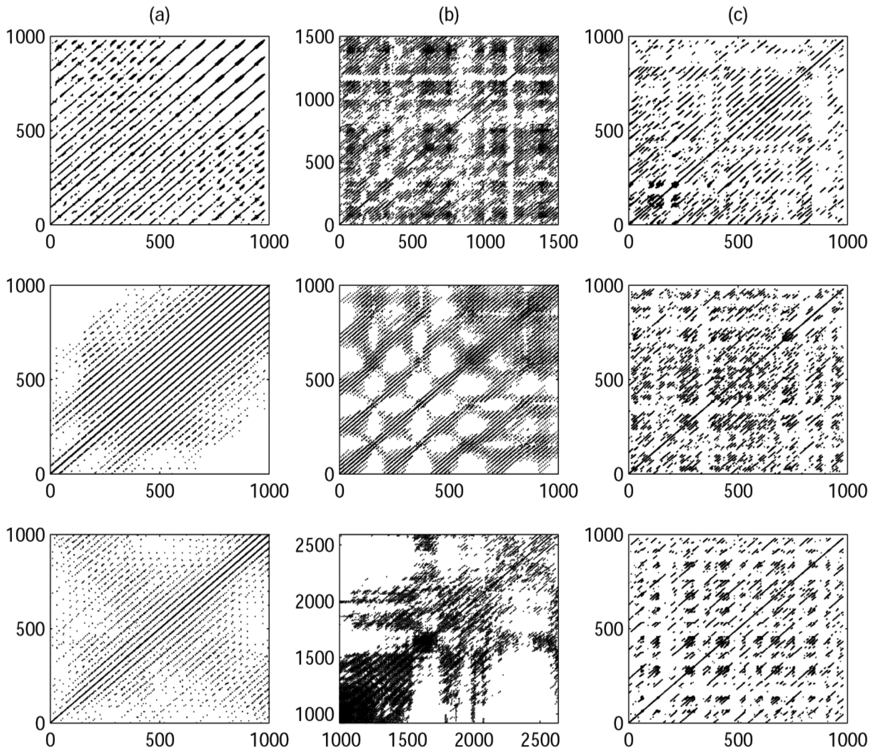

Figure 2: Recurrence Plots of the analyzed signals. (a) Low DAN: The presence of periodic lines parallel to the LOI indicates the periodic nature of the signal. (b) Medium DAN cries: White band in RPs appears when the periodicity of the signals is interrupted by irregularities. (c) High DAN cries: The distribution on the plot of short parallel lines is an indication of chaotic behavior in the time series.

6 Conclusions

In this paper we have presented the results obtained by an observational study of several newborns cries. On the basis of the above discussions we may think that pain acts as bifurcation parameter for the oscillations of the vocal folds. This assumption is supported by the inspection of RPs and this result may be very important to understand the causes of newborn cries, a poorly investigated field.

References

[1] Ishizaka, J.L. & Flanagan, K., Synthesis of voiced sounds from a two-mass model of the vocal cords. *Bell Syst Tech J*, **51**, pp. 1233–1268, 1972.

[2] Herzel, H., Mende, W. & Wermke, K. Bifurcations and chaos in newborn infant cries. *Physics lett A*, **145(8,9)**, pp. 418–424, 1990.
[3] Casgadli, M., Recurrence plot revisited. *Physica D*, **108**, pp. 12–44, 1997.
[4] Marwan, N., *Encounters with Neighbours: Current development of concepts based on recurrence plots and their applications*. Ph.D. thesis, Institut für Physik, Universität Potsdam, 2003.
[5] C.Chandre, S.Wiggins & T.Uzer, Time-frequency analysis of chaotic systems. *Physica D*, **181(3-4)**, pp. 171–196, 2003.
[6] Eckmann, J., Kamphorst, S. & Ruelle, D., Recurrence plot of dynamical systems. *Europhysics Letters*, **5**, pp. 973–977, 1987.
[7] H.Herzel, Bifurcations and chaos in voice signals. *Appl Mech Rev*, **46(7)**, pp. 399–413, 1993.
[8] H.Herzel, D.Berry, I.Titze & I.Steincke, Nonlinear dynamics of the voice: Signal analysis and biomechanical modeling. *CHAOS*, **5(1)**, pp. 30–34, 1995.
[9] C.V.Bellieni, R.Sisto, D.M.Cordelli & G.Buonocore, Cry features reflect pain intensity in term newborns: an alarm threshold. *Pediatric Research*, **55(1)**, pp. 142–146, 2004.
[10] Bellieni, C., Bagnoli, F., Perrone, S., Nenci, A., Cordelli, D., Ceccarelli, M.F.S. & Buonocore, G., Effect of multisensory stimulation on analgesia in term neonates: a randomized control trial. *Pediatric Researh*, **51(4)**, pp. 460–463, 2002.
[11] R.Carbajal, A.Paupe, E.Hoenn, R.Lenclen & M.O.Martin, Dans 1997 une échelle comportamentale d'èvaluation de la doleur aigue du nouveau-nè. *Arch Pediatr*, **4**, pp. 623–628, 1997.
[12] Matassini, L., Kantz, H., Yst, J. & Hegger, R., Optimizing of recurrence plots for noise reduction. *Phys Rev E*, **65(2)**, 2002.
[13] H.D.I.Abarbanel, *Analysis of observed chaotic data*. Springer-Verlag, 1996.
[14] Hegger, R., Kantz, H., Matassini, L. & Schreiber, T., Coping with nonstationarity by overembedding. *Phys Rev Lett*, **84(18)**, pp. 4092–4095, 2000.
[15] Strogatz, S., *Nonlinear Dynamics and Chaos: With Applications to Physics, Biology, Chemistry and Engineering*. Perseus Books, 2001.
[16] A.Facchini, S.Bastianoni, N.Marchettini & M.Rustici, Characterization of chaotic dynamics in the vocalization of the cervus elaphus corsicanus. *J Acoust Soc Am*, **114(6)**, pp. 3040–3043, 2003.

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