ELSEVIER

Brain Research 787 (1998) 351–357

BRAIN RESEARCH

Interactive report

The development of nuchal atonia associated with active (REM) sleep in fetal sheep: presence of recurrent fractal organization [1]

Carl M. Anderson [a,*], Arnold J. Mandell [b], Karen A. Selz [b], Leslie M. Terry [c], Chi H. Wong [d], Scott R. Robinson [e], Steven S. Robertson [f], William P. Smotherman [d]

[a] *Consolidated Department of Psychiatry, Harvard Medical School, and the Developmental Biopsychiatry Research Program, McLean Hospital, Belmont, MA 02178, USA*

[b] *Department of Psychiatry and Behavioral Sciences, Emory University School of Medicine, Atlanta, GA, USA*

[c] *Department of Psychology, College of Liberal Arts, Florida Atlantic University, Davie, FL, USA*

[d] *Laboratory of Perinatal Neuroethology and Center for Developmental Psychobiology, Binghamton University, Binghamton, NY, USA*

[e] *Department of Psychology, University of Iowa, Iowa, IA, USA*

[f] *Department of Human Development, Cornell University, Ithaca, NY, USA*

Accepted 7 November 1997

Abstract

The behavioral state of active or rapid eye movement sleep (REMS) is dominant during fetal life and may play an important role in brain development. One marker of this state in fetal sheep is neck nuchal muscle atonia (NA). We observed burst within burst NA patterns suggestive of recurrent fractal organization in continuous 13 day in utero recordings of NA during the third trimester. Consistent with fractal renewal processes, the cumulative mean and standard deviation (SD) diverged over this time and the tail of NA distributions fit a stable Lévy law with exponents that remained invariant over the periods of development examined. The Hurst exponent, a measure of self-affine fractals, indicated that long-range correlations among NA intervals were present throughout development. A conserved complex fractal structure is apparent in NA which may help elucidate ambiguities in defining fetal states as well as some unique properties of fetal REMS. © 1998 Elsevier Science B.V.

1. Introduction

According to some estimates, the mammalian fetus spends 50 to 70% of the time in the state of active sleep also known as REMS or paradoxical sleep [1–5]. Many have hypothesized that this state is fundamental in brain development and that it provides an internal source of stimulation which helps to organize the developing brain [3]. How REMS may accomplish this role is for the most part unclear. Activity associated with REMS could incorporate a particular temporal organization that may enable phasic events to structure many aspects of brain development [6]. We sought to test the hypothesis that REMS associated behavior in the fetus is organized in a fashion similar to other biological processes which have recently been shown to have fractal organization in time [7–13]. Though fetal REMS is homologous to adult REMS, events used to define this state in adults such as long periods of activated EEG or loss of muscle tone occur more phasically in the fetus [3,14]. NA associated with REMS [15] is considered a reliable indicator of this state in many birds [16] and mammals [17] and so it provides an external marker of multiple state-dependent processes in the reticular formation, such as single unit activity, that are strongly associated with REMS in adults.

We observed that neck nuchal muscle electromyography (EMG) recordings during gestational days E121–E133 appeared to have a repetitive burst-within-burst pattern over 3 to 4 orders of magnitude of time (see Fig. 1). This pattern appears to be a form of statistical self-affinity and has been described as fractal in time in other biological data [6,8,10–13] in contrast to well defined self-similar fractal time processes [18,19]. We have hypothesized that ambiguities in the definition of behavioral states in the fetus may be due to the fractal nature of markers used to define active sleep [6,17]. We also hypothesized, based on the unique informational characteristics of fractals (i.e., the repetition of statistically similar patterns or distributions on

* Corresponding author. Fax: +1 (617) 855 3712; E-mail: remfract@warren.med.harvard.edu

[1] Published on the World Wide Web: 27 January 1998.

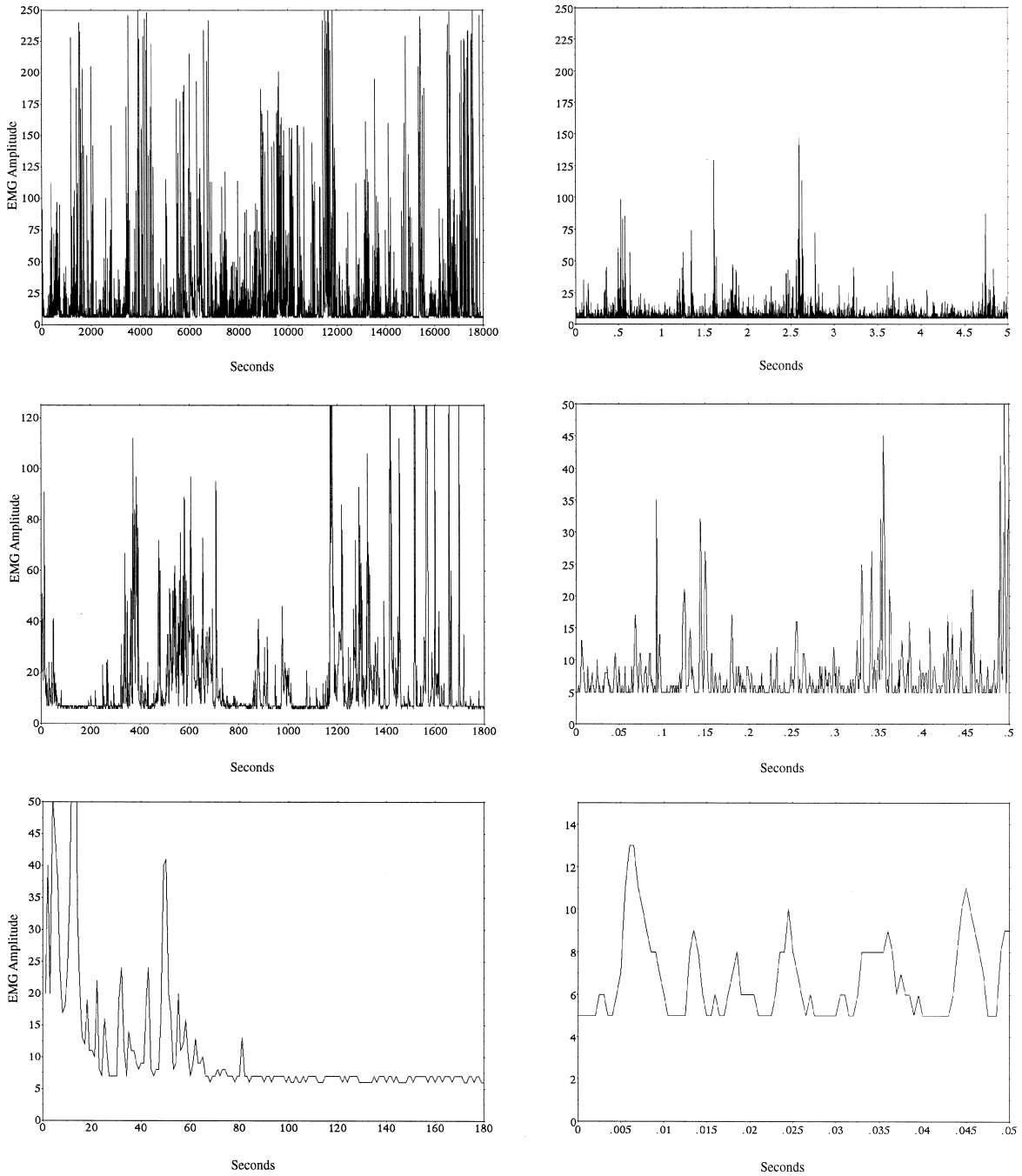

Fig. 1. Fractal bursting is apparent in nuchal activity with intervening periods of atonia on E122 (Left Column) and E134 of gestation (Right Column). Left column: Nuchal EMG activity sampled at 1 Hz along the vertical axis (2 volt range normalized to 250 standard units), plotted over 18 000 s (5 h) on the horizontal axis (top trace). Rescaling the amplitude, vertical axis and time, the horizontal axis, over an 1800 and a 180 second subset of the original series (middle and bottom traces) reveals smaller clusters within larger clusters of both muscle discharges and atonia. Right column: Nuchal EMG activity sampled at 200 Hz along the vertical axis plotted over 5 s on the horizontal axis (top trace). Rescaling time, the horizontal axis, over a 0.5 and 0.05 second subsets of the original series (middle and bottom traces) reveals smaller bursts within larger bursts of muscle discharges. Notice the similarity between columns suggesting that bursting in muscle unit activity over fractions of a second is statistically self-affine to bursting in EMG activity over hours

different time scales), that REMS associated behaviors, if fractal, could serve as a unique form of level independent patterned stimulation to a variety of developing neuronal and organ systems [6,17]. We undertook analysis of NA periods to examine support for these hypotheses.

Burst within burst behavior in time has the property that patterns observed at one sampling rate, say one ms, are statistically similar to patterns observed at a slower sampling rate, say one s. These nested patterns can be described using the concept of self-similarity, a key property

of fractal objects. Exactly self-similar fractal objects are identical regardless of the scale or magnification at which they are viewed [7]. However, biological objects with fractal properties appear statistically self-similar or self-affine when viewed under different magnifications. Similarly, time series can have statistically self-similar or self-affine properties [7,18,19]. This repetition of 'self-likeness' in behavioral time series can be described in different ways. In geometric terms, if variation at different scales of measurement occur along one dimension, such as time, it is called 'self-similar '. If fluctuations appear over two dimensions, such as time and amplitude, they are termed 'self-affine'. In this circumstance, the time series is statistically invariant under a transformation that scales the time and amplitude dimensions by different amounts, and is similar to what is observed in Fig. 1.

The presence of self-similar or self-affine bursts over a number of time scales also results in correlations between events over all time scales. Long range correlations can be examined with methods such as Hurst's rescaled range analysis [7]. In this method, the range (r) of the cumulative deviation of sample values is normalized by the standard deviation (s) in data windows of increasing length. The power law exponent H is measured as the slope of $\log(r/s)$ vs. $\log(n)$; thus H can indicate the existence of correlated fluctuations in a time series collected over minutes, hours or days and can distinguish correlated fluctuations from those of uncorrelated random noise [7]. H can be intuitively understood as a probability directional change — how likely it is that increases in a time series are followed by increases and decreases by decreases, over various time scales. Independent random uncorrelated or shuffled time series have $H = 0.5$ indicating no correlations; $H < 0.5$ suggests that the directions of change will be successively opposite; $H > 0.5$ is called 'persistence' because the directions of change are in the same direction.

Recently, fractal behavior in time has been observed throughout organisms, from bursting in ion channel currents [7] and miniature endplate currents [8], to spike trains in the auditory nerve [9], primary visual cortex [10], and search behaviors in animals [11,12]. In the past this fractal behavior in time was often mistakenly treated as independent random events described by a Poisson distribution with the assumption that correlations between events decay exponentially in time as in a Markoff process [7,8,18]. In fact, this bursting behavior appears Poissonian, lacking long-range correlations, only when short data windows with minimal fluctuations are selected [8]. Long recordings of bursting behavior result in high variability and counting or interval distributions with long tails that can be characterized as non-Gaussian stable distributions using the Lévy formalism [20–23].

Long term 24 h recordings collected over 13 days were used in the present study to guard against the possible problems encountered when applying fractal methods to short data windows [7,8]. The apparent fractal nature of fetal active sleep was investigated by measuring NA period length from EMG recordings obtained from fetal sheep which are in REMS greater than 50% of the time [1]. The measured period lengths were examined to determine the nature of developmental changes in statistical properties of NA, specifically their non-Gaussian characteristics. To examine long range correlations, NA periods were subjected to Hurst analysis.

2. Materials and methods

Experiments were performed at the College of Veterinary Medicine, Cornell University. Animal care was in accordance with institutional guidelines. Five time-mated pregnant ewes (Ovis aries, Rambouillet Columbia stock) obtained from the Cornell University breeding facility provided fetuses for this study. Ewes were acclimatized to the laboratory for one week prior to surgery. Ewes were housed in individual metabolism stalls, which permitted a range of movements and body postures but prohibited turning around so as not to damage catheters and electronic leads. All surgeries were performed at E112–114 using ketamine (5–10 mg/kg) and glycopyrollate preanesthetic and tracheal halothane which also anesthetizes the fetus. Midline laparotomy and incision through the uterine wall provided access to the fetus. Chronic catheters were placed in the external jugular of mother and fetus to monitor blood gases as a means of determining preparation viability [24].

Raw measurements from 3 EMG stitch-electrodes (2 active, 1 indifferent) placed on nuchal (head levator) muscles were differentially recorded in a computerized data acquisition system. Specifically, 50–200 μV signals were amplified up to 2 volt full scale deflections and bandpass filtered (3 Hz low to 300 Hz high), full wave rectified and low pass filtered at 10 Hz to create the envelope of signals. Fetal EMG was then resampled with an 8 bit A/D converter at 32 Hz and averaged over 1 s intervals. Nuchal tone was normalized to 0 to 250 amplitude units and recorded continuously from E121 to 133, then stored in digital form (displayed in the left column of Fig. 1.). Full wave rectified 200 Hz recordings prior to low pass filtering and resampling are displayed in the right column of Fig. 1.

To determine the statistical properties of this apparent scaling behavior, two amplitude partitions of nuchal EMG over the data set (13 days) were examined to help distinguish noise from NA durations. The first partition (P1) was constructed by observing the range of variation of EMG amplitudes. Typically this ranged from ≤ 7 out of a possible 250 arbitrarily scaled amplitude units across 13 days in which ≤ 7 would be considered atonia and events of amplitude ≥ 8 would not. The more stringent partition (P2) was contingent on the total absence of nuchal tone ≤ 3 and was applied by observing the lowest EMG amplitude across the record and counting the duration in seconds

of atonia. Other partitions were used with similar results and are not reported here.

The Lévy formalism provides a means of characterizing the stable properties of Gaussian distributions as well as non-Gaussian distributions with high variance and long tails. In this formalism the distributions are represented as complex valued, exponential distribution functions with four parameters indicating, respectively, location, symmetry, global scale, and rate of convergence of the tail. Disregarding the location and symmetry, working in the reals and letting $\gamma \equiv$ scale, a computable probability distribution is $p(t) = \left(\exp\left(-\gamma|t|^{\alpha}\right)\cos(t)\right)/C, 0 < \alpha < 2$ in which C is an empirical constant, γ controls the amplitude, and α determines the rate of convergence of the tail of $p(t)$ across the range of NA durations in t [20–23]. Then $p(t)$ is used in a nonlinear fit to the real data distribution, $\overline{p}(t)$. For a Gaussian process with finite variance, $\alpha = 2$; if $1 < \alpha < 2$, the variance is nonconvergent but the mean, $\bar{t}$, can be computed; $\alpha = 1$ is the well known Cauchy distribution. If $0 < \alpha < 1$, the process is without a finite mean and will require the use of the median of interquartile indicators to locate the center of the distribution.

Hurst exponents were estimated by a segmentation procedure [7,18]: (1) the mean over the total available time series of NA periods was calculated. (2) A range of window sizes up to and including the total time series length was generated. (3) The accumulated differences for nonoverlapping segments of length equal to the window size were determined by subtracting a period length from the mean of the total record. (4) r, s And ratio r/s determined for each window were then calculated. (5) r/s Ratios for a collection of windows of the same length were then averaged. (6) The procedure was repeated for all window sizes. (7) The logarithms of the average r/s values were then plotted against the logarithms of the window sizes. The linear regression of a region of this line having at least 2 averaged r/s values gave the slope which is an estimate of the Hurst exponent (H). Hurst analysis was validated by the following randomization procedure: a set of random numbers was generated for each file analyzed that ranged from zero to the size of the NA sequence n, and stored in a parallel array. The random numbers were sorted in ascending order by size. In this way the random number corresponding to a particular n was used as an index to reorder the values of an original NA sequence which was then resubjected to Hurst analysis.

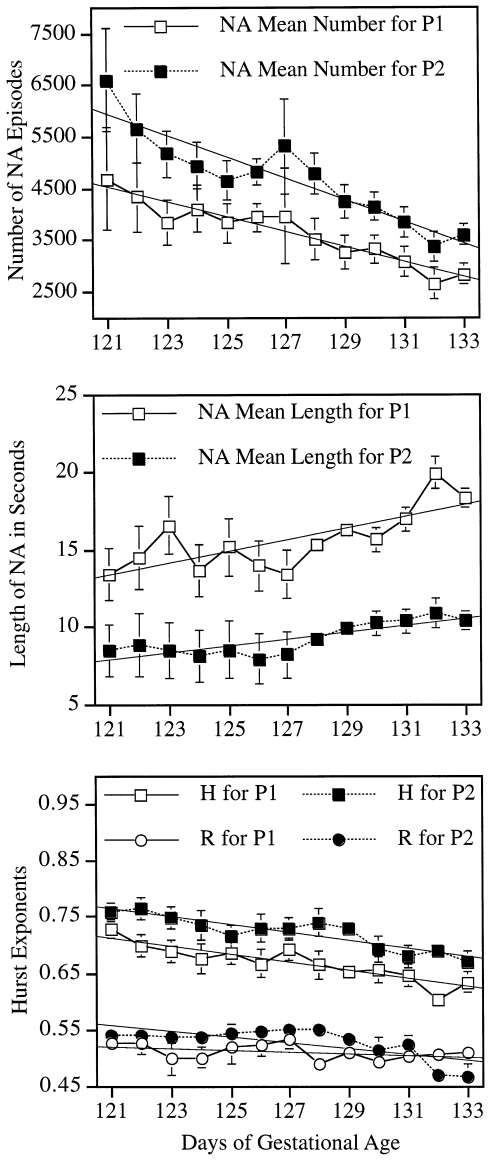

Fig. 2. Developmental changes over days E121-E133 in the linear least squares fits of the mean number of atonia periods (Top) and mean length of atonia periods (Middle) over the gestational period for both partitions (P1, open square □; P2, filled square ■) in all animals. The linear least squares fits of the mean of H illustrate (Bottom) the changes in persistence for each partition. R represents the Hurst values computed following randomization of the sequence data for both partitions, reflecting the expected loss of long range correlations following shuffling of the sequences. Error bars indicate the standard error of the mean for each day.

3. Results

Overall analysis of the statistical properties of NA resulted in the following findings: As the sheep fetus matures, there is a reduction in the number of NA periods (top plot of Fig. 2) and an increase in the mean length of NA periods (middle plot of Fig. 2). The mean number of atonia periods was found to significantly decrease with gestational age for both partitions over the period of observation (P1: $F_{4,12} = 10.460$, $p < .0001$, P2: $F_{4,12} = 4.879$, $p < .05$). While a priori trend analysis indicated that the mean length of NA periods became longer for both partitions, P1($F_{1,64} = 12.831$, $p < .005$) and P2 ($F_{1,64} = 43.117$, $p < .01$).

The distribution of NA intervals, although Poisson in appearance (data not shown), were not found to have

normal Gaussian characteristics. One simple test of whether intervals of NA have the properties of a Poisson distribution is to determine if the mean is equal to the SD. For all gestational days the effects of Day and the cumulative Moments (mean and SD of nuchal atonia events summed progressively over 13 days) were analyzed by separate 2-way repeated measures ANOVA for each partition. This test detected a significant main effect of cumulative Moments generated from Partition 1 ($F_{1,4} = 5.37$, $p < .049$) and Partition 2 ($F_{1,4} = 25.23$, $p < .001$). The robustness of the difference between the cumulative mean and SD for P1 (M = 14.104 vs. SD = 18.85 s) and for P2 (M = 8.539 vs. SD = 24.201 s) argues against describing periods of NA as having the statistical properties of a Poisson process.

The tails of NA distributions generated from the first days 121–3 and last days 131–3 of development observed were described by a convolutionally stable Lévy law [20–23]. Fitting $p(t)$ to the probability distributions of NA as a histogram of the real data to $\overline{p}(t)$ yielded estimates of α ranging from 1.8224 to 1.8300 and γ's from 3.0062 to 3.0745 across animals and days. These single parameter, least squares, Simplex estimates converged quickly and had small asymptotic standard error estimates (all A.S.E. < 0.008). No consistent changes in α or γ were found between animals or within each animal across gestational days.

As illustrated in the bottom graph of Fig. 2, Hurst analysis of 24 h records of NA periods yielded values of H that range from 0.57 to 0.93 over E121 to E133 of development, unlike Poisson distributed variables which lack long range correlations. Over all days examined, H estimates for P2 were higher than those for P1. In addition, H estimates decreased with Day regardless of Partition ($F_{1,129} = 47.533$, $p < .0001$). Also illustrated in the bottom graph of Fig. 2, H calculated from randomized surrogate data sets (R) of P1 and P2 ranged from 0.430 to 0.587 and 0.408 to 0.590, respectively, and were found to be significantly different, independent of Partition, from estimates derived from the original data (2 Hurst Estimates $\times 2$ Partitions: P1, $F_{1,4} = 572.221$, $p < .0001$, and for P2, $F_{1,4} = 723.525$, $p < .0001$).

4. Discussion

Four findings, three previously undescribed, emerged from this analysis. First, in agreement with previous findings, the mean length of NA periods increased while the number of these periods declined with gestational age. Second, supporting the hypothesis that the temporal patterns of NA have fractal characteristics, the cumulative mean and variance of NA periods diverged over development, indicating that this marker of REMS has a non-Poisson distribution and statistical properties typical of fractals [7]. Third, supporting both the fractal and non-Poisson nature of fetal active sleep, NA distributions generated from the first 3 and last 3 days were found to be stable and non-Gaussian with long tails described by invariant characteristic exponents in the range of nonconvergent variance, $1 < \alpha < 2$, but having convergent means over this developmental period. Finally, supporting the self affine fractal nature of REMS, Hurst analysis indicated that NA periods were strongly persistent and exhibited long range correlations, despite developmental changes in NA length and number.

The relevance of these NA measurements to REMS is strongly supported by the statistically significant developmental decreases in NA period number with concomitant increases in NA period duration which occurred across all subjects. This decrease is concordant with previous reports of fetal and neonatal REMS in sheep [1,4], other mammals [5] and humans [2], making it unlikely that the observed phasic NA periods are due to noise or recording artifacts.

One signature of fractals is the non-convergence of the statistical moments describing the distribution of a time series [7]. For fractal bursting sequences in time, the longer the period of data collected, the greater the value an outlier may obtain. This signature, common to many fractal time processes, is the antithesis of the Central Limit Theorem governing normal stable Gaussian distributions; that is, as more data points are accumulated, the variance is divergent and, in some cases, the mean as well [7]. We observed that, as the sample size increased, the cumulative variance of NA was divergent and the distribution did not appear to have Poisson characteristics. In fact, the distributions were non-Gaussian with divergent variance as indicated by application of the Lévy formalism. This is contrary to other shorter observations of fetal behavior where motor activities in fetuses have characteristically been treated as independent random events with the inter-event intervals described by a Poisson waiting time distribution [25–27].

The finding of $H > 0.5$ for all fetuses and all days suggests that these burst-within-burst patterns of NA have long-range correlations over 24 h and further supports the view that NA periods are not well described as the independent random events of a Poisson distribution. Other systems with bursting patterns over many time scales such as World Wide Web (WWW) traffic patterns have also been unsuccessfully modeled with Poisson assumptions [23]. When self-similarity was assessed in WWW traffic with Hurst analysis and the Lévy formalism, correlated H and α values were observed to reoccur over different time periods, supporting the complementary nature of these measures for self-affine burst-within-burst behavior [22].

In keeping with the developmental decline in NA period number, and in contrast to the correlated nature of H and α values, a significantly decreasing linear trend in Hurst exponent means with day was also observed. This trend is not unexpected due to the developmental decrease in nuchal atonia event numbers and the effects of smaller sample sizes on Hurst estimates [28]; however it might also indicate a developmental change in the fractal pattern of NA. Extended recording of nuchal EMG at faster sampling

rates is needed to counter the developmental effect of the declining number of NA periods before the existence of a developmental trend in the Hurst exponents can be confirmed. Our analysis was limited to three orders of magnitude due to the necessity of examining 24 h 1 Hz records (defined as one gestational day). It should be noted that recent applications of Hurst analysis to nonbiological data argue for five or more orders of magnitude to rule out crossover effects [29].

Fetal and neonatal sleep states, due to their highly variable nature, have in the past proven more difficult to characterize than adult sleep states, although adult sleep states also demonstrate greater variability (i.e., brief state transitions and microsleeps) when viewed over shorter time windows [2,3,14]. The restriction of fetal state definitions to a single arbitrary time window, as is standard practice in adult EEG measurements [30], may effectively alias the higher frequency variability into the more slowly sampled time windows. Thus, the variable nature of fetal states could be explained by the higher frequencies of phasic events contained in the fractal nature of fetal state markers. In support of the general fractal nature of other fetal state markers, Szeto et al. [31] have found fractal scaling in the bursting of fetal sheep breathing patterns over the last trimester, which are also characteristically associated with REMS [1,4]. The first author has also measured fractal bursting patterns in nuchal EMG recorded from 2 to 12 day old postnatal rats with values of H and α similar to fetal sheep [13]. The variable nature of these state markers at macroscopic scales may result from vertical summation of microscopic sources of fractal bursting [6], analogous to what has been observed for the origins of fractal bursting patterns of WWW traffic [22,32]. For example, Lowen et al. [8] have observed fractal bursting in miniature endplate currents from single embryonic Xenopus motor neuron-myocyte synapses, which are remarkably similar to fractal bursting in NA (compare Fig. 1 with Figure 1 in [8]). If motor neurons fire with similar patterns, the asynchronous nature of fractal bursting may provide a mechanism to differentiate cartels of synapses in polyneuronally innervated muscle fibers [3,14]. From this perspective, twitching observed in the gross behavior of fetal animals may have its origin in vertically summed fractal bursting in developing motor neuron pools. Parsimoniously, the repetition of statistically similar patterns on different time scales could explain why the REMS state is relatively robust to deprivation effects and is pervasive within an organism and over behavioral development: it can provide patterns of stimulation to developing neuronal and organ systems that are independent of time and level of organization.

In conclusion, we found support for the hypothesis that NA, a behavior associated with REMS, has recurrent fractal organization in time that may serve to structure developmental processes. Fractal organization was observed over each 24 period of 13 day in utero recordings of NA during the third trimester in fetal sheep. Normal developmental consolidation of NA was accompanied by statistical properties typical of fractals such as divergent SD and long range correlations which were present throughout this period. The highly variable behavior of macroscopic state markers associated with REMS may arise from the vertical convergence of statistically self-affine patterns from microscopic sources. Thus difficulties characterizing fetal behavioral states may ultimately result from the intrinsic variability present in state markers regardless of the time period over which they are observed.

Acknowledgements

CMA received support from the Department of Psychology and FAU Foundation at Florida Atlantic University in addition to support from MH-53636-01. AJM and KAS were supported by the Office of Naval Research, Biological Intelligence Division. WPS, CHW and SSR were supported by NIMH-MH19116 and NICHD HD-28014. The authors thank M.R. Kolodny for editorial assistance and Drs. S.B. Lowen, F. Schiffer and M.H. Teicher for many helpful comments. Finally, the authors wish to thank the referees for their considerable efforts, which significantly improved this paper.

References

[1] H.H. Szeto, D.J. Hinman, Prenatal development of sleep-wake patterns in sheep, Sleep 8 (1983) 347–355.
[2] M.S. Scher, D.A. Steppe, G. Dokianakis, R.D. Guthrie, Maturation of phasic and continuity measures during sleep in preterm neonates, Pediatric Res. 36 (1994) 732–737.
[3] M.S. Blumberg, D.E. Lucas, A developmental and component analysis of active sleep, Dev. Psychobiol. 25 (1996) 1–22.
[4] F. Clewlow, G.S. Dawes, B.M. Johnston, D.W. Walker, Changes in breathing, electrocortical and muscle activity in unanaesthetized fetal lambs with age, J. Physiol. 341 (1982) 463–476.
[5] D. Jouvet-Mounier, L. Astic, D. Lacote, Ontogenesis of the states of sleep in rat, cat, guinea pig during the first postnatal month, Dev. Psychobiol. 2 (1970) 216–239.
[6] C.M. Anderson, A.J. Mandell, Fractal time and the foundations of consciousness: vertical convergence of 1/f phenomena from ion channels to behavioral states, in: E. Mac Cormac and M.I. Stamenov (Eds.), Fractals of Brain, Fractals of Mind, vol. 7, John Benjamins, Amsterdam, 1996, pp. 75-126.
[7] J.B. Bassingthwaighte, L.S. Liebovitch, B.J. West, Fractal Physiology, Oxford University Press, New York, 1994, 364 pp.
[8] S.B. Lowen, S.S. Cash, M. Poo, M.C. Teich, Quantal neurotransmitter secretion rate exhibits fractal behavior, J. Neurosci. 17 (1997) 5666–5677, (**http://engc.bu.edu/ ~ lowen/jnsci.ps.gz**).
[9] K. Ehrenberger, D. Felix, K. Svozil, Origin of auditory fractal random signals in guinea pigs, Neuroreport 6 (1995) 2117–2120.
[10] M.C. Teich, R.G. Turcott, R.M. Siegel, Temporal correlation in cat striate-cortex neural spike trains, IEEE Eng. Med. Biol. Mag. 15 (1996) 79–87.
[11] B.J. Cole, Fractal time in animal behaviour: the movement activity of Drosophila, Animal Behaviour 50 (1995) 1317–1324.
[12] G.M. Viswanathan, V. Afanasyer, S.V. Buldyrev, E.J. Murphy, P.A. Prince, H.E. Stanley, Lévy flight search patterns of wandering albatrosses, Nature 381 (1996) 413–415.

[13] C.M. Anderson, The Fractal Time Behavior of Spontaneous Perinatal Behaviors Associated with REM Sleep: A Possible Ontogenetic Adaptation and Source of Plasticity Underlying the Emergence of Behavioral Neophenotypes, University Microfilms International, Ann Arbor, 9608951, 1995, (**http://remfractal.mclean.org:8080/cv.html**)
[14] M.J. Parks, Sleep and wakefulness: do they occur in utero? in: M.A. Hanson (Ed.), The Fetal and Neonatal Brain Stem: Developmental and Clinical Issues, Cambridge University Press, Cambridge, 1991, pp. 230-256.
[15] M.H. Chase, F.R. Morales, The atonia and myoclonia of active (REM) sleep, Annu. Rev. Psychol. 41 (1990) 557–584.
[16] G. Dewasmes, F. Cohen-Adad, H. Koubi, Y. Le Maho, Polygraphic and behavioral study of sleep in geese: existence of nuchal atonia during paradoxical sleep, Physiol. Behav. 35 (1985) 67–73.
[17] R.T. Pivik, S. Sircar, C. Braun, Nuchal muscle tonus during sleep, wakefulness and tonic immobility in the rabbit, Physiol. Behav. 26 (1981) 13–20.
[18] E.W. Montroll, M.F. Shlesinger, The wonderful world of random walks, in: J.L. Lebowitz. E.W. Montroll, (Eds.), Nonequilibrium Phenomena: From Stochastics to Hydrodynamics, North-Holland, Amsterdam, 1984, pp. 1-121.
[19] M.F. Shlesinger, Fractal time and 1/f noise in complex systems, Ann. N.Y. Acad. Sci. 504 (1987) 214–228.
[20] R.N. Mantegna, Lévy walks and enhanced diffusion in Milan stock exchange, Physica A 179 (1991) 232–242.
[21] M. Shao, C.I. Nikias, Signal processing with fractional lower order moments: stable processes and their applications, Proc. IEEE 81 (1993) 986–1010.
[22] M.E. Crovella, A. Bestavros, Self-similarity in world wide web traffic: evidence and possible causes, in: Proceedings of the 1996 ACM SIGMETRICS, International conference on measurement and modeling of computer systems, May 1996, (**http://www.cs.bu.edu/~best/res/papers/sigmetrics96.ps**).
[23] W. Willinger, M.S. Taqqu, A. Erramilli, A bibliographical guide to self-similar traffic and performance modeling for modern high-speed networks, in: F.P. Kelly, S. Zachary, I. Ziedins (Eds), Stochastic networks: theory and applications, Clarendon Press (Oxford University Press), Oxford, 1996, pp. 339-366, (**http://math.bu.edu/people/murad/pub/guide-posted.ps**).
[24] S.R. Robinson, C.H. Wong, S.S. Robertson, P.W. Nathanielsz, W.P. Smotherman, Behavioral responses of the chronically instrumented sheep fetus to chemosensory stimuli presented in utero, Behav. Neurosci. 109 (1995) 551–562.
[25] M.S. Blumberg, D.E. Lucas, Dual mechanisms of twitching during sleep in neonatal rats, Behav. Neurosci. 108 (1994) 1196–1202.
[26] C.H. Narayanan, M.W. Fox, V. Hamburger, Prenatal development of spontaneous and evoked activity in the rat, Behavior 40 (1971) 100–134.
[27] S.R. Robinson, W.P. Smotherman, Chance and chunks in the ontogeny of fetal behavior, in: W.P. Smotherman, S.R. Robinson (Eds.), Behavior of the Fetus, Telford Press, Caldwell, 1988, pp. 95-115.
[28] J.B. Bassingthwaighte, G.M. Raymond, Evaluating rescaled range analysis for time series, Ann. Biomed. Eng. 22 (1994) 432–444.
[29] L.I. Berge, N. Rakotomalala, J. Feder, T. Jøssang, Crossover in rescaled-range analysis and power spectra: measurements and simulations, Phy. Rev. E 50 (1994) 1978–1984.
[30] W.C. Dement, M.M. Mitler, An introduction to sleep, in: O. Perte-Qaudens, J.J. Schlag (Eds.), Basic Sleep Mechanisms, Academic Press, London, 1974, pp. 271-296.
[31] H.H. Szeto, P.Y. Cheng, J.A. Decena, Y. Cheng, D. Wu, G. Dwyer, Fractal properties in fetal breathing dynamics, Am. J. Phys. 263 (1992) R141–R147.
[32] W. Willinger, M.S. Taqqu, R. Sherman, D.V. Wilson, Self-similarity through high-variability: statistical analysis of Ethernet LAN traffic at the source level, IEEE/ACM Transactions on Networking 5 (1997) 71–96, (**http://math.bu.edu/people/murad/pub/source-printed-version-posted.ps**).