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Research article

New insights into sucking, swallowing and breathing central generators: A complexity analysis of rhythmic motor behaviors

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HIGHLIGHTS

- Breathing in the lamb is a complex and chaos-like behavior, as in many other animals.
- Swallowing in the lamb also exhibits complex and chaos-like dynamics.
- Sucking in the lamb does not display chaos-like complexity.
- The central pattern generator that drives sucking is functionally different from the ones that drive breathing and swallowing.

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ABSTRACT

Sucking, swallowing and breathing are dynamic motor behaviors. Breathing displays features of chaos-like dynamics, in particular nonlinearity and complexity, which take their source in the automatic command of breathing. In contrast, buccal/gill ventilation in amphibians is one of the rare motor behaviors that do not display nonlinear complexity. This study aimed at assessing whether sucking and swallowing would also follow nonlinear complex dynamics in the newborn lamb. Breathing movements were recorded before, during and after bottle-feeding. Sucking pressure and the integrated EMG of the thyroartenoid muscle, as an index of swallowing, were recorded during bottle-feeding. Nonlinear complexity of the whole signals was assessed through the calculation of the noise limit value (NL). Breathing and swallowing always exhibited chaos-like dynamics. The NL of breathing did not change significantly before, during or after bottle-feeding. On the other hand, sucking inconsistently and significantly less frequently than breathing exhibited a chaos-like dynamics. Therefore, the central pattern generator (CPG) that drives sucking may be functionally different from the breathing CPG. Furthermore, the analogy between buccal/gill ventilation and sucking suggests that the latter may take its phylogenetic origin in the gill ventilation CPG of the common ancestor of extant amphibians and mammals.

1. Introduction

Central pattern generators (CPG) drive rhythmic motor behaviors such as sucking and swallowing. The sucking CPG of guinea pigs and rats is located in the brainstem within the pontine and medullary reticular formation [1–3], where it overlaps with the mastication center [3]. Redundancy in the organization of the sucking CPG is suggested by the observation, in rats and mice, that brainstem sections containing the motor nucleus of cranial V, VII or XII are all able of generating a sucking rhythm [4]. The swallowing CPG is located in the medulla oblongata and depends on two main groups of neurons. The first one is located in the nucleus of the tractus solitarius and in the adjacent reticular formation (dorsal swallowing group). The second group of neurons is located in the ventrolateral medulla just above the nucleus ambiguus (ven-

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tral swallowing group) [5]. Of note, the sucking and swallowing CPGs are located in the same medullary areas as the CPG that drives ventilation [6–8].

Lung ventilation, as well as sucking, is a dynamic motor behavior. While inspiration and expiration alternate in a repetitive pattern that may seem regular, analysis of the flow in humans shows that it follows nonlinear complex dynamics, of which trajectories are sensitive to the initial conditions and difficult to predict in the long term [9–11]. Such properties characterize chaotic behaviors, as defined by the theory of chaos. However, since the equations that govern ventilation and that would ascertain its fully deterministic nature are unknown, it remains impossible to state that breathing follows a truly chaotic trajectory. We thus refer to this behavior as chaos-like. Taken altogether, data from the literature show that the chaos-like dynamics of ventilation originate in the automatic command of breathing [10,12–20]. Among physiological functions, chaos-like complexity is not restricted to ventilation. For example, other rhythmic activities like gait [21–23], heart rhythm [24,25] and electro-encephalogram [26,27] all follow similar dynamics. In contrast, certain rhythmic activities such as the buccal ventilatory motor activity of the frog tadpole, provide an intriguing counter-example [12]. At precocious stages of development, this animal breathes water by aspiring it into the mouth and by propelling it through the gills, while closing the glottis when the lungs appear. We previously noticed that this gill motor behavior resembles sucking in mammals. Thus, we suggested that the buccal ventilatory motor activity of the frog tadpole may be the phylogenetic origin of the sucking behavior in mammals [28]. The buccal motor activity persists at later stages of development when the gills have disappeared and the animal breathes air through its lungs. While the lung motor activity adopts a complex behavior, the buccal does not, whether it is at pre- or at post-metamorphic stages of development [12,19].

Therefore, the main goal of the present study was to test the hypothesis that while ventilation is a chaos-like behavior in the newborn lamb as it is in many other species, including humans, rats, mice, piglets and frog tadpoles [10–12,19,29–32], sucking would not follow a chaos-like or complex trajectory. On the other hand, given the strong functionnal interactions between breathing and swallowing [33,34], we supposed that the latter would adopt complex dynamics. A secondary aim was to assess whether sucking interferes with breathing complexity.

2. Materials and methods

2.1. Animals

Experiments were conducted in seven mixed-bred term lambs aged between 4–5 days. The study was approved by the Ethics Committee for Animal Care and Experimentation of the Université de Sherbrooke.

2.2. Chronic instrumentation and recording equipment

Newborn lambs were instrumented to record: 1) sucking by a pressure catheter inserted in the teat of the bottle; 2) nutritive swallowing from an electromyographic (EMG) recording of the raw and integrated EMG of the thyroarytenoid muscle (EAta, $\int$EAta, a glottal constrictor); 3) respiratory movements by the use of inductance plethysmography. All signals were transmitted *via* radiotelemetry [35] and recorded using AcqKnowledge software (Santa Barbara, CA).

2.3. Design of the study

All lambs were cared for without their mother and were placed in a Plexiglas chamber in which they could drink freely from a bottle filled with reconstituted ewe's milk. Standardized bottle-feeding of 60 ml of heated (39 °C) reconstituted ewe's milk [36] was performed a few days after arrival. Two standardized bottle-feeding spaced 2 h apart were performed in each lamb. Recordings were continued for 15 min after bottle-feeding.

2.4. Data analysis

All respiratory signals (inspiratory time (Ti), expiratory time (Te) and Ti/total duration of respiratory cycle (Ttot)) were analysed in relation to the time period (before, during or after bottle-feeding). Hence, two-minute recordings of respiratory movements were analyzed before and after each bottle-feeding attempt. Signals during bottle-feeding attempts were of variable lengths and were determined by the time spent by each lamb to drink the entire bottle.

2.5. Analysis of nonlinear complexity of the chaos-like type

The analysis of the nonlinear complexity was conducted as previously described (for details see [10,19,37,38]). Briefly, the overall trajectory of the signals (sucking pressure, $\int$EAta and respiratory movements) was analyzed. Each digitized file was subsampled at a frequency (7.8 Hz for respiration, 15.6 Hz for swallowing and 62.5 Hz for sucking) four to five times larger than the highest frequency contained in the original recording. Then, the chaos-like complexity of each signal was assessed through calculation of the Noise Limit (NL) value. If the calculation does not detect any nonlinearity or if NL is equal to zero, then the signal does not follow a complex chaos-like trajectory. On the other hand, a value of NL above zero means that the dynamics is nonlinear, complex and compatible with chaos. Furthermore, the NL value provides an estimate of the intensity of the complexity. The calculation of NL requires choosing a combination of K (embedding dimension) and d (degree of nonlinearity). To minimize the risk of false positive detection of chaos-like complexity, we used a fixed value of 4 for d and of 6 for K [39]. With these parameters, the calculation of NL required at least 420 data points. Therefore, recordings including at least one file of less than 420 data points were excluded from the analysis. Five calculations of NL were performed for each signal, by using a cluster of computers, at the Brain and Spine Institute (ICM) in Paris, France. The average of the five NL values was used for further analyses [39]. Phase portraits of the signals, all resampled at 62.5 Hz, were built after having determined the proper time delay and the proper embedding dimension. The time delay corresponded to the time of the first return to zero of the autocorrelation function. The embedding dimension was calculated by using the method of the false nearest neighbors [40]. The sensitivity of the signals to the initial conditions, which also means instability, was assessed through the calculation of the Largest Lyapunov Exponent (LLE, Matlab routine by Merve Kizilkaya on the Matlab forum) according to the concept of Rosenstein et al. [41].

2.6. Statistical analysis

The data corresponding to each bottle-feeding were averaged for each animal. The distribution of the variables was then assessed using the Kolmogorov-Smirnov normality test. When it was Gaussian, the variables were compared using a paired *t*-test or a repeated measures analysis of variance (RM-ANOVA), followed by a Tukey post-hoc test when appropriate. In cases of non-Gaussian distribution, the variables were compared using Wilcoxon signed rank