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Assessment of nocturnal sleep architecture by actigraphy and one-channel electroencephalography in early infancy

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A B S T R A C T

Objective: To elucidate characteristic sleep architecture of different nocturnal sleep patterns in early infancy.
Methods: Participants were 27 infants at the same conceptional age of 3–4 months. Nocturnal sleep of these infants was monitored at home by simultaneously using actigraphy and a one-channel portable EEG device. According to the infants' activity for 6 h from sleep onset, each night's sleep pattern was classified into three categories: sleeping through the night (STN), sleeping with weak signals (crying/fuss episodes <10 min or fed), and sleeping with strong signals (crying/fuss episodes ≧ 10 min). Associations of sleep patterns with sleep variables (percentage of time in sleep stages, pattern of slow-wave sleep (SWS) recurrence, etc.) were investigated.
Results: Analysis was conducted in 95 nights. STN pattern (n = 36) was characterized by suppressed body movements while EEG represented a state of wakefulness. Weak signal pattern (n = 27) tended to indicate rich and regular distributions of SWS across the night. Strong signal pattern (n = 32) was characterized by reduced sleep time, although the amount of SWS was not reduced to that degree. Exclusively breastfed infants accounted for 78% of weak signal patterns, whereas formula-feeding infants, 67% of STN patterns. In several nights with STN or strong signal pattern, SWS did not occur in >50% of the sleep cycles. Multiple regression analysis showed that exclusive breastfeeding may increase the proportion of SWS in non-REM sleep.
Conclusions: Each nocturnal sleep pattern was associated with some sleep architecture, part of which would be attributed to infant's feeding methods.

1. Introduction

Although newborns frequently repeat sleep–wake cycles without distinguishing between day and night, in the subsequent few months, their sleep gradually becomes consolidated and fixed to nighttime. Around 3–4 months of age, infants begin to sleep continuously for a long period of time during the night [1,2], and crying that temporarily increased around 2 months of age begins to subside [3]. As a result, according to a recent survey conducted by Henderson et al., approximately 50% of infants sleep from night until morning without disturbing their mothers, a state that is termed “sleeping through the night” (STN) [4,5]. On the other hand, a considerable number of infants continue to demand feeding or nursing and cry at night [6].

Numerous previous studies have been conducted to discover the cause of individual differences in sleep patterns that manifest during this early infant stage; however, some aspects are not completely understood. When observing a video of an STN infant throughout the night, the infant awakens several times, but naturally falls back asleep. Therefore, the difference between STN infants and non-STN infants is whether they send signals of crying or fussing when they wake their parents, rather than simply whether they awake during the night [7]. Some of the reasons why infants send such signals include childcare factors such as parents' involvement at sleep onset [8], exclusive breastfeeding [9,10], and sleeping in the parental bed (“co-sleeping”) [11,12]. However, a study has shown that night-crying continues for a long time in infants born to mothers who suffered a great deal of mental stress during pregnancy [13], indicating that there may be some type of intrinsic problem in infants who send these signals [14].

Marked changes occur in the infant's sleep structure during early infancy. The sleep structure of a newborn differs significantly from that of an adult. Newborn sleep cycles are short, ranging between 40 and 60 min, and active sleep, the infant's equivalent of rapid eye movement (REM) sleep, accounts for 50% of total sleep. Active sleep diminishes with age, accounting for 20–30% of total sleep by 3–4 months of age [1,2]. Around this stage, sleep electroencephalography (EEG) activity transitions from the newborn to the infant type, and the differentiation of non-REM sleep becomes pronounced [15–19]. Consequently, the physical activity level during sleep decreases [20], and the infant's

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sleep appears to be stabilized. How such physiological changes in sleep relate to an infant's sleep pattern is an interesting issue. This knowledge would be useful in understanding the etiology and real nature of individual differences in sleep patterns during the early infant stage.

The purpose of this study was to elucidate the characteristic findings of sleep structure and physical activity level in different nocturnal sleep patterns in early infancy. The study subjects were infants at 3–4 months of age, when individual differences in the development of sleep–wake rhythms become significant. The infants' nocturnal sleep at home was monitored by simultaneously using actigraphy and a one-channel portable EEG device. Data collection was conducted according to conceptional age, based on evidence that the development of sleep structure in early infancy is dependent on age since last menstrual cycle rather than age since birth [1]. We subsequently investigated the association of infants' nocturnal sleep pattern with sleep structure and with physical activity level inferred from collected nighttime data.

2. Methods

2.1. Participants

The participants included mothers who gave birth to a normal, healthy infant at a university hospital and did not encounter abnormalities during the course of pregnancy or delivery. Recruitment was conducted using written and verbal explanations of the study objectives. The study included single births only, and mothers with smoking and drinking habits were excluded. Data collection was conducted under a normal sleep environment at the infant's home for a total of 4 days, 2 days each at the conceptional ages of 54–55 weeks (hereinafter referred to as “3 months old”) and 58–59 weeks (hereinafter referred to as “4 months old”). This study was approved by the Ethics Committee of Akita University Graduate School of Medicine and School of Medicine (September 25, 2012, No. 1482).

2.2. Analysis of sleep stages using actigraphy

On the morning of the first day of data collection, the mothers were asked to attach a small, wristwatch-type high-sensitivity acceleration sensor (Actigraph, Ambulatory Monitoring, Inc., Ardsley, NY, USA) on the infant's ankle. For the subsequent 48 h, the mothers were requested to keep the device on their infant with the exception of when the infant was having a bath. Sensor sensitivity was set up such that data were recorded every 1/10 s if the acceleration was ≥0.01 g.

Acceleration data recorded on the sensor were imported into a computer on a later date using a specific software program, ACTme (Ver. 3.10.0.3, Ambulatory Monitoring Inc.), to create actigraphs. One-minute epochs on the actigraphs were divided into three stages, wakefulness (W), light sleep (LS), and deep sleep (DS), using a specific software program, AW2 (Ver. 2.4.20, Ambulatory Monitoring Inc.), based on specific algorithms for infants [21,22] Subsequently, for every night's sleep data on the actigraph, the time at which the infant began his/her nocturnal sleep (time of sleep onset) was determined. As a general rule, the start of nocturnal sleep was defined as the onset of sleep after 18:00 that continued for at least 30 min. For each night, a custom interval was specified on the actigraph from sleep onset until 6 h later, and the number of epochs in each stage, W, LS, and DS, was calculated during this time period.

2.3. Analysis of sleep stages using sleep EEG

An EEG during the infant's nocturnal sleep was measured on the night of each day of data collection using a one-channel portable EEG device (Sleep Scope, SleepWell Co., Osaka, Japan). After sleep onset, the mothers were asked to promptly attach one of two Sleep Scope electrodes in the middle of the infant's forehead, and the other electrode behind the ear on one side, and then starting the EEG measurements. The mothers were requested to continue measurements in this state until the morning; however, if the infant awakened at night and refused the electrode attachments, the measurements were aborted at that point. On a later date, data from the Sleep Scope were extracted and forwarded to the SleepWell Company via the internet in a large compressed file form for analysis.

At the SleepWell company, forwarded EEG data are routinely analyzed and categorized into different sleep stages by specialists [23, 24]. First, spectral analysis of the frequency component of a sleep EEG is performed for every 30-s epoch. The sleep stages are determined based on these measurements using an automatic system developed at the company. Non-REM sleep is considered to consist of two stages in infants due to the immaturity of the brain waves. Total sleep is therefore divided into the following four stages: all epochs of wakefulness (WAKE), REM sleep (REM), stages 1–2 of non-REM sleep (S1–2), and stages 3–4 of non-REM sleep (slow-wave sleep, SWS). Subsequently, the validity of sleep stage classification is visually evaluated for every epoch in accordance with previous reports [25–27], and necessary corrections are added. As a general rule, SWS is defined as epochs predominantly composed of delta waves with ≥75-μV amplitude waves, accounting for ≥20% of all waves [26,28].

The results of sleep stage classification for each night were imported into Excel spreadsheet software, and every other 30-s epoch was extracted and defined as a 1-min epoch. Subsequently, the number of epochs in WAKE, REM, S1-2, and SWS was determined in the 6-h time period from sleep onset. For the missing data during the time between sleep onset and the start of EEG measurements, data from the actigraphs were used. Specifically, LS and DS on the actigraph at the same time point were regarded as S1-2 and SWS, respectively. The results of the sleep stage classification on the actigraphs at the same time points were imported into the adjacent column on the Excel spreadsheet, and the proportions of W epochs by actigraphs among WAKE epochs by EEG (W/WAKE) were calculated for each night's data. Then, hypnograms were created from these EEG time-series data and compared with the actigraphs, and the sleep cycle patterns were examined.

For the classification of sleep cycles, hypnograms of non-REM sleep (S1-2 and SWS together) and REM/wakefulness were created. On these hypnograms encompassing the two stages, one sleep cycle was defined as the succession of a non-REM sleep episode lasting at least 15 min and an REM/wakefulness episode of at least 5 min' duration [27]. However, if duration from the start of non-REM sleep to the end of REM sleep/wakefulness was less than 30 min, the cycle was not counted. For the first REM episode, no minimum criterion was applied [27]. Sleep cycles from one night's data contained a mixture of cycles with SWS (SWS epoch of ≥2 min) and without SWS (SWS epoch of <2 min or none at all) [28,29]. In examining the pattern of SWS recurrence in the sleep cycles according to each night's data, it was evident that many of the data showed the occurrence of a relatively long SWS in the first to second cycle after sleep onset and subsequently alternated between sleep cycles with SWS and without SWS, or sleep cycles with long SWS and short SWS (“alternating pattern”). However, other patterns were also observed. These included the “constant pattern”, where SWS occurred evenly in almost all sleep cycles, and the “atypical pattern,” where SWS did not occur in >50% of the sleep cycles. For each night's data, the total number of sleep cycles and number of sleep cycles with SWS that could be observed within the first 6 h from sleep onset were counted, and the patterns of SWS recurrence in sleep cycles were divided into the three patterns described above (alternating, constant, and atypical). The data in which SWS was absent in one or two cycles and the rest of the sleep cycles with SWS that did not show an alternating pattern were classified into the constant pattern.

2.4. Sleep pattern assessment through nocturnal sleep timetable

On the data collection day, the mothers were asked to record the times for feeding, bathing, infant's crying and fussiness, and sleep on a