Biological and Behavioral Correlates of Quiet Sleep Respiration Rates in Infants

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MONTGOMERY-DOWNS, H. AND E. B. THOMAN. Biological and behavioral correlates of quiet sleep respiration rates in infants. PHYSIOL BEHAV 64(5) 637–643, 1998.—The sleep and respiration of 88 infants were recorded for 24-h periods on the first 2 postnatal days and again at 6 months. The recordings were made with the Motility Monitoring System, which does not require instrumentation of the infants. Quiet sleep respiration rates (QSRR) increased over the first 2 days (mean = 42.2, SD = 1.0 and mean = 44.5, SD = 1.1, respectively), then decreased by 6 months (mean = 25.3, SD = 0.5); females showed lower QSRR on the first 2 days; infants delivered vaginally showed lower QSRR at 6 months; by 6 months QSRR was significantly higher during the day than at night; and significant individual differences across age and from day to nighttime were found at each age. Delivery mode, maternal age and education, and mental scores at 6 and 12 months were negatively related to QSRR at 6 months. Taken together, these data suggest a developmental advantage of slower QSRR and evidence for the role of the higher central nervous centers in the regulation of QSRR.

Quiet sleep respiration  Respiration rates  Infant respiration  Sleep

“MOST parameters of breathing in NREM sleep are, indeed, reduced versions of those in quiet wakefulness” (26, p. 342). Orem’s statement, which refers to the interconnections between respiration in sleep and waking processes, was the impetus for the present study of quiet sleep respiration rates (QSRR) in infants as a reflection of central nervous system functioning. Quiet sleep in infants, as well as nonrapid eye movement (NREM) sleep in adults, is characterized by respiration rates that are slower and more regular than those seen during active (REM) sleep or wakefulness. Considerable research has focused on the physical, physiological, and central regulatory controls of respiration patterns in infants (14); however, the point made by Haddad in 1978 still holds, namely “long-term measurements have seldom if ever been made under wholly non-invasive conditions” (21, p. 85). The present report addresses this issue by describing QSRR from prolonged, non-intrusive recordings of infants’ sleep.

Studies of respiration rates go back many decades but, prior to the mid-sixties, many of the researchers did not differentiate sleep and waking for their measures. Later studies were primarily interested in demonstrating that respiration rates in the two sleep states differed. Reports of QSRR still vary widely (18). For example, in a review on the development of respiration, Gaultier (19) cites studies of 1-month infants with QSRR ranging from 33 bpm (7) to 54 bpm (33). The divergences were attributed, at least in part, to differences in instrumentation for measurement, which range in intrusiveness from a simple strain gauge to thermisters to having the baby inside a plethysmograph, placing a facial mask on the baby, or even inserting an esophageal balloon in the baby; procedures vary also with respect to durations of recordings and time of day or night in which recordings are made (18).

In addition to studies aimed at establishing norms for QSRR at successive ages (30), investigation has been aimed at understanding neuromuscular control and mechanics of upper airway movements, as well as the neural correlates of normal and abnormal respiratory patterns. For these purposes, it is appropriate to include infants over a range of ages, such as the first postnatal week or 10 days, or monthly ages. However, the goals of the present study could not have been achieved by such a strategy.

For this study, we recorded the sleep and respiration of infants during the first 2 postnatal days and again at 6 months. This longitudinal approach permitted description of QSRR at each of these ages and assessment of individual differences over age. It also allowed us to describe change within QS bouts, change over the first 2 postnatal days, from daytime to night, and from the newborn period to 6 months. We were not able to find any studies that assessed stability within and over age or that separately examined the first 2 postnatal days.

At the same time, previous studies have not investigated demographic and environmental factors that might contribute to QSRR development. Yet there are good reasons to expect relationships to exist, even in normal infants, since regulatory control of respiration is influenced at many levels of the nervous system (3,22,25,26,28). It can be noted that the relationship between cognitive competence and QSRR was anticipated by Phillipson, when he concluded that “knowledge derived from studies of breathing during sleep has even broader implications than were

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Subjects study confirm Phillipson's expectation. The findings from this undoubtedly continue to yield information that applies to more respiratory control, and ventilatory mechanics during sleep will perhaps originally anticipated. Further investigation of breathing, continuous 24-h monitoring in the hospital or the home without requiring any changes in caregiving activities. The MMS is composed of a thin (3/16") capacitance-type sensor pad that is placed under the bedding in the infant’s crib. This pressure sensitive pad generates a single channel of signals from the infant’s respiration and body movements. It is connected to a battery-driven amplifier and a 24-h data recorder, which are placed in a small case that is suspended on the crib so that the crib is mobile. The provision for mobility is especially important for the recordings obtained in the hospital. In the laboratory, the signal files are computer scored in 30-s epochs for the sleep/wake states, using a pattern recognition program. Then the complete signal file is printed out and visually edited. Thus, the scoring is a computer-aided procedure. Our previous studies, cited above, have demonstrated measurement reliability for each of the sleep variables measured as well as agreement with other recording procedures including electroencephalograph (EEG) (also see review in Ref. 36).

**Procedures for Measurement of QSRR**

From the printout of the analog signals, each bout of quiet sleep lasting 15 min or longer was identified. Respiration rates were taken from these bouts. From each bout, 1-min counts of respiration were made during the first, middle, and last 5-min segments. The counts were made during periods when no movements or apneas occurred. As an example, Fig. 1 shows sleep signals, with a bout of quiet sleep indicated. Previous studies of infants and adults indicate measurement reliability for this procedure for determining respiration rates (4,38,41,43).

**Data Analysis**

The data for postnatal Days 1 and 2 were analyzed separately because previous research has shown significant differences in the sleep measures and overall state organization for these 2 days (5,16,32). The data obtained at 6 months were analyzed separately for the 2 days of recordings to assess reliability of measurement, then the 2 days were combined for the remaining analyses. To calculate the QSRR for each infant, a single measure of respiration rate was obtained for each quiet sleep bout by averaging the three 1-min counts for each bout of quiet sleep in the recording; these were then averaged to yield the infant's QSRR for that recording.

**RESULTS**

To determine whether the mean respiration rate was influenced by the number of bouts observed or the mean bout length, these measures were correlated. No significant relationship was found. The means of the QS measures did change markedly from the newborn period to 6 months: the number of bouts of QS was 7.8 ± 3.1 on Day 1; 6.9 ± 3.1 on Day 2; and 18.9 ± 6.1 at 6 months. The mean length of quiet sleep bouts at the three ages was 22.2 ± 0.3 min on Day 1; 20.2 ± 0.3 min on Day 2; and 29.2 ± 0.4 min at 6 months.

**QSRR at the Three Ages and Sex Differences**

Table 2 presents the overall mean for QSRR on Day 1, Day 2, and 6 months, as well as the means presented separately for males and females. The data were evaluated via analysis of variance (ANOVA). Because the number of subjects varied across age and sex and involved repeated measurements, to put all the data into one overall factorial design would have caused us to discard

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>DEMOGRAPHIC AND MEDICAL INFORMATION</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Males (%)</td>
<td>54</td>
</tr>
<tr>
<td>Vaginal delivery (%)</td>
<td>55</td>
</tr>
<tr>
<td>Birth weight (lbs)</td>
<td>7.6 (1.2)</td>
</tr>
<tr>
<td>5-min Apgar</td>
<td>9.4 (0.5)</td>
</tr>
<tr>
<td>Maternal age</td>
<td>26.0 (5.7)</td>
</tr>
<tr>
<td>Maternal education (years)</td>
<td>12.9 (2.4)</td>
</tr>
</tbody>
</table>
more than half of our subjects. Therefore, individual comparisons were made.

Using a repeated measures design, QSRR increased significantly from Day 1 to Day 2 \(F(1, 62) = 5.85, p = 0.01\), then decreased markedly from Day 2 to 6 months \(F(1, 31) = 161.80, p = 0.001\).

The females had lower respiration rates at each age, with the sex difference being marginally significant on Day 1 \(F(1, 82) = 3.43, p = 0.07\), significant on Day 2 \(F(1, 61) = 13.99, p = 0.001\), and not significant at 6 months \(F(1, 44) = 2.10\).

### Individual Differences in QSRR

QSRR for Day 1 was significantly correlated with QSRR on Day 2 \((r = 0.76, df 61, p < 0.0001)\); and the mean of the first 2 days was significantly correlated with QSRR at 6 months \((r = 0.34, df 33, p < 0.05)\). For those subjects who had QSRR scores on Day 1, Day 2, and 6 months, ANOVA for repeated measures found significant individual differences over the three ages \(F(3, 62) = 96.69, p < 0.0001\). Thus, individual infants were consistent with respect to their QSRR relative to other infants from the first postnatal day.

### Changes in QSRR from the Beginning to the End of Quiet Sleep Bouts

Table 3 presents the mean QSRR during the first, the middle, and the ending 5-min segment of the quiet sleep bouts. Trend analyses determined that respiration rate declined linearly from the beginning to the end of the bouts at each age. Fig. 2 shows these changes from the first to the last 5-min segment of the bouts, for each subject. The consistency among subjects in showing reduced rates over the bout is apparent, as well as the diminished variability among the subjects at the later age.
**TABLE 3**

**MEAN (SE) QSRR AT THE BEGINNING, MIDDLE, AND END OF THE QUIET SLEEP BOUTS AND F FOR ANOVA FOR LINEAR TRENDS**

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Beginning</th>
<th>Middle</th>
<th>End</th>
<th>F</th>
<th>Linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>84</td>
<td>45.0 (1.1)</td>
<td>41.1 (1.0)</td>
<td>40.6 (1.0)</td>
<td>139.15***</td>
<td></td>
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<tr>
<td>Day 2</td>
<td>61</td>
<td>46.5 (1.1)</td>
<td>43.7 (1.1)</td>
<td>43.2 (1.2)</td>
<td>53.89***</td>
<td></td>
</tr>
<tr>
<td>6 Months</td>
<td>46</td>
<td>26.2 (0.6)</td>
<td>25.3 (0.6)</td>
<td>24.4 (0.5)</td>
<td>116.53***</td>
<td></td>
</tr>
</tbody>
</table>

***p < 0.001.

**TABLE 4**

**MEAN (SE) QSRR DURING THE DAYTIME (0600 TO 2200 H) AND NIGHTTIME**

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Day</th>
<th>Night</th>
<th>F</th>
<th>Linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>76</td>
<td>41.6 (1.1)</td>
<td>41.8 (1.1)</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Day 2</td>
<td>51</td>
<td>45.2 (1.3)</td>
<td>45.5 (1.3)</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>6 Months</td>
<td>46</td>
<td>26.1 (0.5)</td>
<td>24.5 (0.6)</td>
<td>37.49***</td>
<td></td>
</tr>
</tbody>
</table>

***p < 0.001.

**Diurnal Differences in QSRR**

Table 4 presents the mean QSRR during the daytime (0600 to 2200 hours) and nighttime at each age. There are no day–night differences on either of the first 2 days, but by 6 months QSRR was significantly higher during the daytime. There were also significant correlations between the infants’ daytime and nighttime rates at each age (Day 1, r = 0.79, df 74; Day 2, r = 0.81, df 49; 6 months, r = 0.90, df 44; p < 0.0001 for each of the day/night correlations).

**Relationships of Demographic Variables and Mental Scores at 6 Months and 1 Year with QSRR at Each Age**

Table 5 presents the Pearson product–moment correlations for QSRR and the following measures: birth weight, delivery mode, sex, maternal age, maternal education, 6-month mental scores, and 1-year mental scores. N is shown for each analysis. These vary for a number of reasons: circumcision of males, follow-up recordings or tests could not be carried out for subjects who moved away, or demographic information was not available from the medical records. Probability levels are shown for all instances where p was 0.10 or less.

Considering only those correlations with p < 0.05 or less, there were no significant relationships between any of these variables and QSRR on Day 1. On Day 2, sex was significantly correlated, and this was the only age at which sex was correlated. No other relationships were significant on Day 2.

At 6 months, mode of delivery, maternal age and education, as well as mental scores at 6 months and 1 year were significantly correlated with QSRR. It should be noted that all of the significant relationships varied for a number of reasons: circumcision of males, follow-up recordings or tests could not be carried out for subjects who moved away, or demographic information was not available from the medical records. Probability levels are shown for all instances where p was 0.10 or less.

**FIG. 2** Changes in mean QSRR from the beginning to the end of quiet sleep bouts for each subject, on Day 1, Day 2, and 6 months.
correlations were negative, indicating that lower QSRR was associated with vaginal delivery, females, higher maternal age and education, and higher mental scores at 6 months and 1 year.

**DISCUSSION**

The results of this study indicate that a number of factors in infants’ biological and experiential history are reflected in their respiration rates during quiet sleep (QSRR). When the five factors that correlate with 6-month QSRR—delivery mode, maternal age and education, and the mental scores at 6 months and 1 year—are entered into a multiple regression, they account for 37% of the variance in QSRR at that age. None of the variables showed significant relationships with QSRR on the first 2 postnatal days. Sex alone showed a significant relationship with QSRR during the immediate postnatal period. One can only speculate on the possible processes that might account for the delay in appearance of these relationships, but any explanation would have to include the accrual of experience with mothers whose behaviors differ as a function of her age, education, and her mode of delivery. It would also be necessary to include the possible cumulative physiological effects on infants of these same variables. Thus, it would seem that QSRR development is a reflection of the integrated processes of a maturing nervous system as it is affected by complex interactions between the infant’s endogenous status and the environment.

Phillipson (28) proposed that QSRR is influenced by central nervous system function at levels higher than the brain stem, where respiration is presumptively controlled. He points out that breathing is controlled by two anatomically separate but functionally integrated elements: the metabolic (or automatic) control system and the behavioral (or voluntary) control system. The metabolic system, which arises in brainstem structures of the pons and medulla, is concerned primarily with acid-base and O₂ homeostasis, whereas the behavior system, which arises in cortical and forebrain structures, is involved in activities that use the ventilatory apparatus for nonrespiratory purposes.

“Most knowledge of respiratory control during sleep has been derived from studies of integrated ventilatory responses to a variety of respiratory stimuli. These stimuli have generally, but not exclusively, been those involved in metabolic respiratory control, not only because of extensive familiarity with this system, but also because of the assumption (possibly incorrect) that behavioral respiratory control is inactive during sleep” (Ref. 28, p. 912).

The findings from the present study provide evidence for a relationship between QSRR and cognitive functioning in normal infants and, thus, highlight the significance of the role of the higher centers in the regulation of QSRR.

All of the relationships between the variables measured and QSRR were in a negative direction, that is, lower QSRR was associated with higher maternal age, higher maternal education, and higher mental scores. Female infants showed lower QSRR, as did infants delivered vaginally rather than by surgery. The notion of a developmental advantage of slower QSRR in infants is supported by findings from other studies, particularly those of infants with risk factors. QSRR is negatively related to birth weight (17,29), a relationship that was marginally significant in this study; premature infants have faster respiration rates than full-term infants at matching ages (13, as cited in Refs. 19,8,10–12,24); Sudden Infant Death Syndrome (SIDS) victims have had increased respiration rates (31,34); infants of substance abusing mothers have higher sleeping respiratory rates (44); and, in animals, hypoxic kittens show elevated respiratory rate in both sleep states (2). However, these findings are all relative to selected control groups, and there is, as yet, no determination of thresholds for “normal” or “abnormal” rates at any age (15).

Descriptive findings in this study included decreased QSRR from the beginning to the end of quiet sleep bouts. This phenomenon has been reported for infants as early as 2 weeks postnatally (27). Paul and collaborators (27) also found the decrease was associated with changes in EEG activity, although this association did not appear until the infants were 6 weeks old. With increasing age, the patterns of EEG activity differed, with slow waves becoming more frequent at the end of QS bouts than at the beginning and more rapid waves becoming more frequent at the beginning than at the end of quiet sleep bouts. The significance of the trend within bouts is still not clear, but Paul suggested that the changes are important for onset of active sleep. This may be so insofar as respiration is concerned because, as already indicated, the changes in EEG activity were not detected during the first 6 weeks. The researchers point out that the changes are important, nevertheless, because they represent a change in the functional state of the central nervous system.

The significant increase in QSRR from the first to the second postnatal day has not been previously described, primarily because the first day has not been included in most studies, and the second day has not been studied independently. Rather, the second day has usually been included within the first week or 10-day period after birth. The change over the 2 days is notable because it is contrary to the subsequent developmental decrease in respiration rates (9,20,23,30,33). However, the finding of paradoxically low levels on Day 1, which might seem trivial, is consistent with recent evidence that the sleep/wake states also change over the first 2 days in both human and animal infants, and most of the changes in the states are in a direction which suggest greater “maturation” on the first postnatal day (Carrol, Thoman, & Denenberg, unpublished.

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**TABLE 5**

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
<th></th>
<th>Day 2</th>
<th></th>
<th>6 Months</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>p</td>
<td>n</td>
<td>r</td>
<td>p</td>
<td>n</td>
</tr>
<tr>
<td>Birth weight</td>
<td>-0.10</td>
<td>0.07</td>
<td>84</td>
<td>0.10</td>
<td>0.06</td>
<td>63</td>
</tr>
<tr>
<td>Delivery mode</td>
<td>-0.07</td>
<td>0.07</td>
<td>76</td>
<td>-0.24</td>
<td>0.01</td>
<td>63</td>
</tr>
<tr>
<td>Sex</td>
<td>-0.20</td>
<td>0.07</td>
<td>84</td>
<td>-0.43</td>
<td>0.01</td>
<td>63</td>
</tr>
<tr>
<td>Maternal age</td>
<td>-0.07</td>
<td>0.07</td>
<td>76</td>
<td>-0.07</td>
<td>0.11</td>
<td>59</td>
</tr>
<tr>
<td>Maternal education</td>
<td>-0.12</td>
<td>0.07</td>
<td>76</td>
<td>-0.11</td>
<td>0.08</td>
<td>58</td>
</tr>
<tr>
<td>6-month mental</td>
<td>-0.22</td>
<td>0.10</td>
<td>57</td>
<td>-0.28</td>
<td>0.08</td>
<td>42</td>
</tr>
<tr>
<td>12-month mental</td>
<td>-0.18</td>
<td>0.07</td>
<td>45</td>
<td>-0.16</td>
<td>0.10</td>
<td>32</td>
</tr>
</tbody>
</table>
observations; Refs. 16,31). Similarly, recent findings indicate that infant rat pups also show lower QSRR on the first postnatal day than on the second (Carroll, Denenberg, & Thoman, unpublished observations). Thus, we interpret the increase in QSRR from Day 1 to Day 2 as indicative of another form of immediate postnatal precocity as a response to the stress of the birth experience. Numerous studies indicate that stress can temporarily accelerate developmental processes. In fact, it seems plausible that the stress response may be the potent reason that the factors that are related to QSRR at 6 months do not show relationships on the first 2 postnatal days.

Finally, the difference in QSRR as a function of mode of delivery at 6 months is notable because it is often assumed that any differences in the infants do not persist beyond the immediate postnatal period. It is unclear whether this difference reflects persistence of physiological effects of surgical delivery, including drugs administered for the surgery or whether it reflects ongoing differences in mother-infant patterns of interaction that differ during the immediate postnatal period (Freudigman & Thoman, unpublished observations). It is also unclear whether this difference in QSRR as a function of delivery mode has implications for the infants’ development.

CONCLUDING COMMENTS

The noninvasive procedures of the Motility Monitoring System permitted recordings of sleep and respiration for prolonged periods without interfering with the infant or care of the infant. The sensitivity of the measures was demonstrated not only by the major findings, as discussed, but also by results indicating reliable individual differences in QSRR over repeated recordings, over age, and from day to nighttime.

The data obtained from the MMS did not provide information on respiration variables such as time spent in inspiration and mean airflow. The findings suggest future study of the role of these and other respiration processes in early neurobehavioral development.

ACKNOWLEDGEMENTS

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REFERENCES


