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▶ **To cite this version:**

Emilie Bourel-Ponchel, Daniele Hasaerts, Marie-Josephe Challamel, Marie-Dominique Lamblin. Behavioral-state development and sleep-state differentiation during early ontogenesis. Neurophysiologie Clinique = Clinical Neurophysiology, 2021, 51 (1), pp.89-98. 10.1016/j.neucli.2020.10.003 . hal-03604343

HAL Id: hal-03604343
https://u-picardie.hal.science/hal-03604343

Submitted on 14 Feb 2023

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Version of Record: https://www.sciencedirect.com/science/article/pii/S0987705320301088
Manuscript_edca186d07af8bfe0cb465ac9c170ce4

COMPREHENSIVE REVIEW

Behavioral-state development and sleep-state differentiation during early ontogenesis

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Running title: Behavioral-state development and sleep-state differentiation

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Abstract

Sleep is a key process in neurodevelopment and essential for the maturation of fundamental brain functions. Premature birth can disturb the initial steps of sleep maturation, which may contribute to the impairment of neurodevelopment. It is thus fundamental to understand the maturation of the various sleep states and the quality of cerebral function in each vigilance state, as well as the development of sleep cyclicity, in at-risk neonatal infants, particularly those born premature. The objective of this review is to provide a precise description of sleep states and cycles and their rhythmic organization in premature and term newborns according to their gestational age. Technical aspects of polysomnography, which requires a high level of expertise in neonates, are also described. Principles of the visual interpretation of polysomnography, including the simultaneous analysis of behavioral (spontaneous motricity and eye movements), polysomnographic parameters (electro-oculogram, electrocardiogram, respiration), and electroencephalography patterns are presented. The neurophysiology of sleep ontogenesis and its interaction with brain maturation are discussed, highlighting the crucial role of sleep states and their duration in premature newborns. In particular, the involvement of myoclonic twitches in functional connectivity in sensorimotor development is discussed. Indeed, sleep quality, determined by combined polysomnographic parameters, reflects either normal or pathological developmental processes during the neonatal period. The fundamental place of neurophysiological explorations in the early detection of sleep disorders is discussed, as well as their potential consequences on neurodevelopmental care to improve the prevention of neurodevelopmental impairment.

Keywords: brain maturation, EEG, electroencephalography, full-term newborn, polysomnography, premature infants, sleep cycle, sleep ontogenesis

Introduction

Sleep is a key process in neurodevelopment and essential for the maturation of fundamental brain functions. Growing research indicates that early sleep disturbances participate in later cognitive, attentional, and psychosocial problems [19,35,37,65].

The various sleep states begin to appear during the 3rd trimester of pregnancy, the key period for prematurity [46]. Premature birth can disturb the initial steps of sleep maturation, which may contribute to impaired neurodevelopment [54,64]. It is thus fundamental to understand the maturation of the various sleep states and the quality of cerebral function in each vigilance state, as well as the development of sleep cyclicity, in at-risk neonatal infants, particularly those born premature.

Electroencephalography (EEG) recordings provide a unique opportunity to observe regional changes in brain activity over the course of cortical maturation. Recording cardiac function, respiration, eye movements, and behavioral changes at the same time as the EEG activity allows the precise analysis of vigilance states and their changes during maturation.

This review describes the normal EEG, clinical, and polysomnographic characteristics of each developing vigilance state during early ontogenesis in very premature to full-term newborns and discusses the place of polysomnography recordings in neonates.

Behavioral states, sleep cycles, and rhythmic processes [13]

Developmental behavioral states

The developmental behavioral states in premature infants and term newborns can be divided into sleep states: quiet sleep (QS) (or non-rapid eye movement (NREM) sleep) and active sleep (AS) (or rapid eye movement (REM) sleep), and non-sleep states: active and quiet wakefulness.

Behavioral and clinical features and EEG activity do not always correspond to a definitive sleep state. These periods correspond to an indeterminate sleep (IS) state, reflecting the immaturity of sleep organization and the between-state transition.

Sleep states

Sleep states are defined as constellations of physiological and behavioral variables, including cerebral electrical activity (EEG), autonomic functions (electrocardiogram (ECG) and respiration), motor activity, and behavior, that are stable and occur repeatedly over time [58].

Quiet sleep (QS) is characterized by the absence of REMs, a regular respiratory rate, the presence of a tonic chin on electromyogram (EMG), and few body movements (Tables 1-2). On EEG recordings, the activity is discontinuous in premature infants, with the duration of quiescent periods depending on the gestational age. At term, EEG activity becomes continuous and takes the aspect of 'tracé alternant' (Figure 1) [1,6].

Active sleep (AS) is characterized by the presence of REMs, an irregular respiratory rate, the absence of a tonic chin on EMG, and body (jerky (myoclonic twitches) or slow limb movements) and facial movements (smiles, sucking, grimaces, blinks) (Tables 1-2). On EEG recordings, such activity is continuous or discontinuous according to gestational age (Figures 2-3) [1,6].

Periods with both AS and QS characteristics are called indeterminate or undifferentiated sleep (IS). The IS state can interrupt an ongoing sleep state and also be observed during the transition between different vigilance states (see between-state transition). Prechtl et al. considered this period to be "no-state", due to the absence of characteristic criteria in state behavioral analysis [58].

Non-sleep states

Quiet wakefulness (Prechtl Stage 3) is characterized by wide open, bright eyes, with or without exploratory eye movements, absent or scarce body movements, stable heart rate, regular respiration, a tonic chin on EMG and low-voltage theta activity on EEG [58,59].

Active wakefulness (Prechtl Stage 4) is distinguished from quiet wakefulness by the presence of gross body movements, eye movements, repetitive eye opening and closing, irregular respiration, and variable heart rate with accelerations. Based on EEG criteria, active wakefulness may be difficult to identify because of artefacts related to movements (Figure 4) [58].

Between-state transition

The transition between behavioral states is generally a gradual, fluctuating process that differs according to gestational age. Sleep-wakefulness and sleep-state transitions have different characteristics [10].

The sleep-wakefulness transition

Sleep can be differentiated from wakefulness based on behavioral criteria: eyes closed, or half closed, vacant stare without exploratory eye movements, no crying or short periods of < 20 seconds of crying and/or gross body movements. In term newborns, as in older children,

eyes are usually opened during wakefulness and closed in the sleep. In preterm infants, the distinction between opened or closed eyes is not sufficient to determine the state of vigilance. Other polysomnographic parameters are more pertinent to define the wakefulness-to-sleep transition. The transition from wakefulness is often marks by the inhibition of chin tone on EMG. The transition from QS to wakefulness is marked by the association of gross body movements with tonic-chin EMG and, less regularly, repetitive eye opening and closing (Prechtl 3) [10,58].

Sleep-state transitions

The transition from active to quiet sleep and vice versa is also a gradual process. The duration of the transition is variable and partially depends on gestational age. Normal values vary depending on the parameters considered for the definition of this state. It is shorter when based on only two parameters (EEG, REMs) than when more than two parameters are considered (EEG, REMs, respiration, tonic chin EMG, movement) [10]. This between-state transition has never been precisely quantified in premature newborns. The first change in full-term newborns during the transition from quiet to active sleep (slightly shorter) is usually a gradual decrease in the tonic-chin EMG and the last, the apparition of REMs. During the transition from active to quiet sleep (slightly longer), REMs disappear first, and tonic EMG activation is usually abrupt [13].

Sleep cycles and rhythmic processes [13]

Sleep-state cycles and ultradian/circadian rhythms appear progressively in premature newborns as the brain matures [7,12,15,56,57].

Sleep cycles

A sleep cycle is defined by successive sleep states (AS-QS-IS), without awakening (Figure 5). One sleep-cycle is measured from the end of post-waking AS to the end of the next AS period (following a QS period).

Rhythmic processes

Rhythmic organization is observable even in preterm newborns and is modulated by a period of wakefulness after successive sleep-cycles. Such rhythmic organization is of two types: ultradian and circadian.

An *ultradian rhythm* is defined by 3 to 4 cycles (SA-SC-SI) without wakefulness between the cycles. Wakefulness is identified only every 3 to 4 sleep cycles. Such ultradian organization is clearly visible in full-term newborns. Ultradian rhythms can be observed in preterm newborns as soon as wakefulness is present.

A *circadian rhythm* is defined by an approximately 24h rhythm with a general concordance between wakefulness with day or light and sleep with night or darkness. An immature circadian rhythm is present in premature and full-term newborns but is masked by ultradian rhythms [7,8,49,66].

Sleep states during early ontogenesis

Sleep state development

Sleep state differentiation appears early in human ontogenesis, concurrent with the development of the interactions between the neuronal networks of subcortical and cortical structures during fetal and early life [17,27,53].

In utero, sleep states are present from the beginning of the third trimester of gestation. A rest-activity pattern in fetuses can be observed as soon as 20 weeks gestational age (wGA) [8,29,50,67]. Facial movements, notably spontaneous smiles, described as a behavior of AS, have been observed for fetuses from 20 wGA [36]. EEG studies of premature infants confirmed the presence of rudimentary sleep states as early as 24 wGA [4,12,62,70]. At 24 to 26 wGA, states with rapid eye movements (REM) and more continuous EEG activity can be distinguished from non-REM (NREM) periods and more discontinuous EEG activity [70].

AS is the first sleep state to mature during brain development. Based on EEG analysis, all 27- to 28-wGA premature infants demonstrate uninterrupted periods of AS than can last more than 13 min. AS are characterized by continuous or near continuous activity and the presence of REMs in non-brain damaged infants [12,15,56,57]. During the same period of development, the first spontaneous facial expressions are also observed [20,21,30,31,73]. The appearance of frequent smiling coincides with the differentiation of the EEG into AS and QS and the presence or absence of REMs (Figure 6).

From 28 to 30 wGA, the QS state progressively develops. A stable concordance between EEG background activity (continuity/discontinuity and EEG-specific features) and the presence or absence of REMs allows differentiation between AS and QS. Despite the progressive development of sleep states, time spent in IS represents a large amount of the recording time (30-50% at 30-31wGA) [13].

With maturation, the time spent in active and quiet sleep increases whereas the time spent in IS decreases to less than 10 to 20% in term-age infants [10,13]. Active and quite wakefulness progressively appear from 30 to 31 wGA. Based on behavioral criteria, active wakefulness appears first. Quiet wakefulness remains rare before 35 wGA and becomes more easily identifiable from 36 to 37 wGA. The continuous activity and "*activité moyenne*" related to active wakefulness may be difficult to visualize by EEG because of movement artefacts.

EEG patterns of the various sleep states

EEG activity associated with maturation of the sleep states is characterized by global decreases in discontinuity. Before 28 wGA, EEG activity is discontinuous for all sleep states. The duration of quiescent periods in AS and wakefulness progressively decrease until they disappear between 30 to 34 wGA [1,6,39]. Quiescent periods can persist in QS until 36 to 37 wGA. After 36 to 37 wGA, the “tracé alternant” is observed in QS. It is characterized by bilateral synchronous bursts of activity lasting 5 to 6 s (varying from 3-8 s) alternating with periods of lower amplitude that have nearly the same duration as the bursts [1,6,39]. Near term, AS, which precedes QS (AS1), differentiates to AS2 following QS. EEG activity associated with active and quiet wakefulness is continuous, evolving to "*activité moyenne*" from 35 to 36 wGA. This activity may be difficult to visualize, notably during active wakefulness at 35 to 36 wGA because of movement-related artefacts [1,6,39].

The amplitude and frequency of EEG-specific features decrease with maturation. For a given gestational age, the EEG activity of QS has a more immature aspect than that of AS. Indeed, the amplitude of EEG features remain higher in QS than AS and wakefulness, with a lower frequency. Age-related specific features disappear later in QS than AS. For example, temporal theta activity in coalescence with slow waves (TTA-SW) disappears at 32 wGA in AS but persists until 34 to 36 wGA in QS [1,6,39] (for more details, please see Bourel-Ponchel et al. in the same issue [6]).

Arousal responses caused by various stimuli (provoked reactivity) are a basic protective mechanism for survival. This response appears progressively from 28 to 30 wGA and becomes constantly and easily distinct around the term [1,6,39].

Duration of sleep states and sleep cyclicity (Figure 6)

The percentage of time spent in each sleep state has been measured for each gestational age range. The values are variable and depend, notably, on the criteria used to score the sleep

states and the total duration of the EEG recording. The duration of sleep states can also vary widely between infants and in a given infant between successive sleep cycles [13].

From *24 to 26 wGA*, immature sleep states last from 10 to 55 min [26,70].

From *27 to 30 wGA*, it is possible to distinguish between AS and QS based on the concordance between the characteristics of the EEG and eye movements for a given state. The use of additional criteria, such as respiratory rate, heart rate, tonic-chin EMG, and body movements, has virtually no effect on the measured amount or duration of AS. In contrast, QS has a more immature aspect, resulting in a poorer concordance between polygraphic parameters and EEG activity. Thus, the measured duration of QS can be reduced in favor of IS by the presence of irregular respiration, inhibited tonic-chin EMG, and body movements [14]. At 27 to 30 wGA, the duration of AS is clearly greater than that of QS and represents approximately 40% of the total sleep states (TST) [12]. QS appears mostly as an indeterminate state and represents approximately 30% [12].

From *31 to 34 wGA*, the percentage of time spent in AS and QS increases significantly (45-50% and 25-30% of TST, respectively) [25]. With the development of AS and QS, the time spent in the indeterminate state decreases from 30% at 30-31 wGA to < 20% at term [12].

Near term, 55% to 65% of TST is spent in AS versus approximately 20% in QS [12].

Sleep cycles are present in preterm infants. Before 35 wGA, sleep cycles are short, with a mean duration of 45 to 50 min. With maturation, their duration tends to increase. From 35 to 36 wGA to term, the duration of the sleep cycle is approximately 55 to 65 min [11].

Ultradian and circadian rhythm development during early ontogenesis

Ultradian organization of activity is present in premature newborns. Rhythmic cycling of activity has been recorded in utero, between 20 and 28 wGA [57,67]. An ultradian rhythm of 40 min has also been found in premature infants of less than 32 wGA [62]. The duration of the ultradian rhythm increases with maturation. Near term, the neonate expresses a clear ultradian sleep rhythm: 3 to 4 sleep cycles of 50 to 60 min alternating with episodes of wakefulness every 3 to 4 h [11].

Sleep circadian rhythms are apparent as early as 18 wGA [60] but their maturation is not complete until three years of age [8]. In the fetus, circadian cycles are clearly present for heart rate, movements, and respiration at approximately 20 to 22 wGA [71], guided by the maternal circadian rhythm (cortisol, melatonin, rest-activity cycle, light/dark cycle). In

premature infants aged between 28 and 34 wGA, circadian rhythms of around 25 h have been described for body temperature and the rest-activity cycle [50]. After birth, sleep/wake circadian rhythms are present in full-term newborns but are masked by prominent ultradian rhythms [8,41,48].

Sleep, brain maturation, and neurodevelopment

Sleep, the predominant behavioral state in newborns, is an important regulatory function throughout life.

Development of the sleep-wake cycle is a measure of brain maturation. The development of cortical and sub-cortical networks give rise to more stable organization of the sleep-wake cycle [17,50].

The endogenous activity of sleep may itself participate in brain maturation and the development of neuronal networks. Studies suggest that AS promotes functional connectivity in developing sensorimotor networks [16,40,68]. Myoclonic twitches, which are self-generated movements observed exclusively during AS, may be triggered by sensory feedback neuronal oscillations, especially in sensorimotor networks [5,37,68]. Such neuronal oscillations are thought to be involved in neuronal guidance, synaptogenesis, and the activation of functional cortical cells [3,22,34,51]. They contribute to the functional optimization of transient neural networks, which are necessary for the future establishment of complex sensory-sensitive networks [5,9,42–44,72].

Premature birth can affect the quality of sleep in preterm infants. Medical and support care (theophylline, caffeine, high light levels, acoustic stimuli, temperature, type of respiratory support, etc.), as well as medical conditions (bronchopulmonary dysplasia, hypoxic ischemic encephalopathy, intraventricular hemorrhage, and seizures with sedative medication), may qualitatively and quantitatively alter sleep in the NICU (for a review [24] and [17]). Early alterations of sleep could have a lasting impact on the maturation of neural networks, resulting in functional disorders [19,23,47,61].

Technical aspects and indications for polysomnography in neonates

Qualitative assessment of neonatal sleep is an essential and valuable measure of functional brain integrity [17,35,65]. Perinatal insults may adversely influence the organization of neonatal sleep.

Technical aspects

Routine polysomnography of newborns requires a high level of expertise for both recording and interpretation. The nurse/technician in charge of the recording must be specialized in neonatal care and the physician in charge of the interpretation must be highly familiar with age–related EEG characteristics of premature and full-term newborns.

Technical constraints must be respected to assure the quality of the exam. Polysomnography of premature and term newborns combines the synchronized recording of EEG, ECG, eye movements, EMG, and respiration, as well as oxygenation parameters. The technical recommendations for EEG are similar to those for standard EEG (for details see Malfilâtre et al., in the same issue [45]). For eye movements, piezo-crystal quartz accelerometry recording is the most reliable method for detecting REMs in premature and full-term infants. Naso-oral airflow, as well as thoracic and abdominal respiratory movements, must be recorded for complete respiration analysis. Airflow can be measured by thermistors or thermocouples and more accurately by nasal flux pressure measurement. The measurement of nasal flux requires a high performance proflow nasal sensor, adapted to the neonatal population, connected to the nasal cannula. Thoracic and abdominal respiratory movements are recorded by strain gauges, as well as inductance plethysmography or thoracic impedancemetry. Aside from these measures, it is important to register diaphragmatic EMG via skin electrodes to detect accessory respiratory muscle contraction during breathing. Oxygenation is evaluated from the saturometry of pulsed oximetry and capnia values from a transcutaneous electrode. Chin EMG is also required to determine the basal tonic state, as well as facial movements.

The length of the recording must cover at least one complete sleep cycle, preferentially 3 to 4h to evaluate ultradian organization. Longer recordings allow the study of circadian rhythmicity. Moreover, serial neurophysiological studies can more accurately document normal ontogeny or the evolution of delayed or abnormal changes of the brain.

Qualitative and quantitative visual sleep assessment

The combination of behavioral observation and polysomnographic EEG recording is used to determine vigilance states. Sleep-wakefulness states are divided into QS, AS, quiet wakefulness, active wakefulness, and crying. Periods that show discrepancies from the main criteria of these states (behavior, cardio-respiratory criteria, and EEG tracing) are scored as IS [50]. The criteria of the sleep-wakefulness states are based on behavioral parameters (facial mimics, twitches and jerky or gross body movements, and crying), whether the eyes are open

or closed, the presence or absence of eye movements, regular or irregular respiration, apnea and hypopnea and concordance with EEG patterns. Scoring is performed epoch by epoch (30s). Stability of concordance between parameters throughout successive epochs (wakefulness, crying, AS and QS) is required before a recording period can be assigned to a given state. Generally, a state is defined as the presence of the corresponding constellation of state-specific criteria for at least 1 min [13].

Polysomnography in neonates, from breath disorders to sleep quality analysis

Polysomnography provides a precise evaluation of sleep and cardio-respiratory maturation in normal premature and newborn infants. Abnormal polysomnographic parameters, as well as unusual EEG patterns, can reflect either cerebral and brainstem immaturity or pathological disorders and diseases.

Currently, polysomnography of neonates is indicated to explore sleep-related breathing disorders. A polysomnography before discharge from the hospital is useful for preterm infants with persistent apnea and/or desaturation to identify those infants who have abnormalities in their breathing pattern (central or obstructive apnea, hypopnea, oxygen desaturation, hypoventilation) and are at risk of having an event at home [28]. Overnight polysomnography is also recommended for infants with bronchopulmonary dysplasia, notably before the cessation of supplemental oxygen (for more details about the indications for polysomnography in sleep related breathing disorders, see Joosten et al., 2017 [28]).

Polysomnography is also indicated to study the sleep quality of preterm infants [65]. The presence of differentiated sleep states in high neurological-risk newborns (notably in cases of suspected cerebral lesions in premature infants) is considered to be a favorable prognostic factor. Conversely, the delayed appearance of cyclicity is associated with developmental impairment [32,33,35,52]. Moreover, as described above, sleep disturbances occur more frequently in premature infants and may contribute to cognitive, psychomotor, and behavioral impairment [2,18,38,50,55,63,69]. Developing qualitative and normative data for premature infants is required to improve our understanding of the impact of neonatal sleep on later neuro-cognitive function [17,65]. Further research is necessary to better define the indications for sleep quality analysis during the neonatal period and guide neonatal developmental care.

Conclusion

Simultaneously recorded behavioral and polysomnographic parameters and EEG activity allow the precise analysis of sleep states and sleep cycles. In preterm infants, who are at high risk of neuro-developmental impairment, analyzing sleep-state development provides fundamental information about brain function and maturation during the neonatal period. Moreover, sleep disorders, from as early as the period of prematurity, may contribute to neuro-developmental impairment. Further studies are required to more precisely define sleep-quality criteria in premature babies, as well as the indications for sleep EEG evaluation, polysomnography recordings, and visual sleep assessment of neonate infants, which requires highly specific expertise.

Conflict of interest

The authors disclose no conflict of interest related to this work.

References

[1] André M, Lamblin M-D, d'Allest AM, Curzi-Dascalova L, Moussalli-Salefranque F, Nguyen The Tich S, et al. Electroencephalography in premature and full-term infants. Developmental features and glossary. Neurophysiologie Clinique/Clinical Neurophysiology 2010;40: 59–124.

[2] Arditi-Babchuk H, Feldman R, Eidelman AI. Rapid eye movement (REM) in premature neonates and developmental outcome at 6 months. Infant Behav Dev 2009;32: 27–32.

[3] Ayoub AE, Kostovic I. New horizons for the subplate zone and its pioneering neurons. Cereb Cortex 2009;19: 1705–7.

[4] Biagioni E, Boldrini A, Giganti F, Guzzetta A, Salzarulo P, Cioni G. Distribution of sleep and wakefulness EEG patterns in 24-h recordings of preterm and full-term newborns. Early Hum Dev 2005;81: 333–9.

[5] Blumberg MS, Coleman CM, Gerth AI, McMurray B. Spatiotemporal structure of REM sleep twitching reveals developmental origins of motor synergies. Curr Biol 2013;23: 2100–9.

[6] Bourel-Ponchel E, Gueden S, Hasaerts D, Heberle C, Malfilâtre G, Mony L et al. Normal EEG during the neonatal period: maturational aspects from premature to full-term newborns. Neurophysiol Clin. In press.

[7] Challamel M-J. Développement des états de vigilance et de la rythmicité circadienne : du nouveau-né à l'enfant. Médecine thérapeutique / Pédiatrie 2013;16: 61–9.

[8] Challamel M-J, Franco P. Development of circadian rhythms from fetus to adolescent. Presse Med 2018;47: 1000–2.

[9] Challamel M-J, Hartley S, Debilly G, Lahlou S, Franco P. A video polysomnographic study of spontaneous smiling during sleep in newborns. 2020;3: e13129.

[10] Curzi-Dascalova L. Between-sleep states transitions in premature babies. J Sleep Res 2001;10: 153–8.

[11] Curzi-Dascalova L. Développement du sommeil et des fonctions sous contrôle du système nerveux autonome chez le nouveau-né prématuré et à terme. Archives de Pédiatrie 1995;2: 255–62.
[12] Curzi-Dascalova L, Figueroa JM, Eiselt M, Christova E, Virassamy A, d'Allest AM, et al. Sleep state organization in premature infants of less than 35 weeks' gestational age. Pediatr Res 1993;34: 624–8.
[13] Curzi-Dascalova L, Mirmiran M. Manuel des techniques d'enregistrement et d'analyse des stades de sommeil et de veille chez le prématuré et le nouveau-né à terme. Ed INSERM. 1996.
[14] Curzi-Dascalova L, Peirano P, Morel-Kahn F. Development of sleep states in normal premature and full-term newborns. Dev Psychobiol 1988;21: 431–44.
[15] Curzi-Dascalova L, Peirano P, Silvestri L, Korn G. Sleep organization in normal premature newborn infants. Polygraphic study. Rev Electroencephalogr Neurophysiol Clin 1985;15: 237–42.
[16] Del Rio-Bermudez C, Blumberg MS. Active Sleep Promotes Functional Connectivity in Developing Sensorimotor Networks. Bioessays 2018;40: e1700234.
[17] Dereymaeker A, Pillay K, Vervisch J, De Vos M, Van Huffel S, Jansen K, et al. Review of sleep-EEG in preterm and term neonates. Early Hum Dev 2017;113: 87-103.
[18] Ednick M, Cohen AP, McPhail GL, Beebe D, Simakajornboon N, Amin RS. A review of the effects of sleep during the first year of life on cognitive, psychomotor, and temperament development. Sleep 2009;32: 1449–58.
[19] El-Dib M, Massaro AN, Glass P, Aly H. Sleep wake cycling and neurodevelopmental outcome in very low birth weight infants. J Matern Fetal Neonatal Med 2014;27: 892–7.
[20] Emde RN, Koenig KL. Neonatal smiling and rapid eye movement states. J Am Acad Child Psychiatry 1969;8: 57–67.
[21] Emde RN, Swedberg J, Suzuki B. Human Wakefulness and Biological Rhythms After Birth. Arch Gen Psychiatry 1975;32: 780–3.
[22] Feller M. Cortical development: the sources of spontaneous patterned activity. Curr Biol 2012;22: R89-91.
[23] Geva R, Yaron H, Kuint J. Neonatal Sleep Predicts Attention Orienting and Distractibility. J Atten Disord 2016;20: 138–50.
[24] Gogou M, Haidopoulou K, Pavlou E. Sleep and prematurity: sleep outcomes in preterm children and influencing factors. World J Pediatr 2019;15: 209–18.
[25] Groome LJ, Swiber MJ, Atterbury JL, Bentz LS, Holland SB. Similarities and differences in behavioral state organization during sleep periods in the perinatal infant before and after birth. Child Dev 1997;68: 1–11.
[26] Hoppenbrouwers T, Sterman MB. Development of sleep state patterns in the kitten. Exp Neurol 1975;49: 822–38.
[27] Janjarasjitt S, Scher MS, Loparo KA. Nonlinear dynamical analysis of the neonatal EEG time series: the relationship between sleep state and complexity. Clin Neurophysiol 2008;119: 1812–23.
[28] Joosten K, de Goederen R, Pijpers A, Allegaert K. Sleep related breathing disorders and indications for polysomnography in preterm infants. Early Hum Dev 2017;113: 114-9.
[29] Kahn A, Dan B, Groswasser J, Franco P, Sottiaux M. Normal Sleep Architecture in Infants and Children. Journal of Clinical Neurophysiology 1996;13: 184–97.
[30] Kawakami F, Yanaihara T. Smiles in the fetal period. Infant Behav Dev 2012;35: 466–71.

[31] Kawakami K, Takai-Kawakami K, Kawakami F, Tomonaga M, Suzuki M, Shimizu Y. Roots of smile: a preterm neonates' study. Infant Behav Dev 2008;31: 518–22.
[32] Kidokoro H, Kubota T, Hayashi N, Hayakawa M, Takemoto K, Kato Y, et al. Absent cyclicity on aEEG within the first 24 h is associated with brain damage in preterm infants. Neuropediatrics 2010;41: 241–5.
[33] Klebermass K, Olischar M, Waldhoer T, Fuiko R, Pollak A, Weninger M. Amplitude-integrated EEG pattern predicts further outcome in preterm infants. Pediatr Res 2011;70: 102–8.
[34] Kostović I, Judaš M, Sedmak G. Developmental history of the subplate zone, subplate neurons and interstitial white matter neurons: relevance for schizophrenia. Int J Dev Neurosci 2011;29: 193–205.
[35] Kuhle S, Klebermass K, Olischar M, Hulek M, Prusa AR, Kohlhauser C, et al. Sleep-wake cycles in preterm infants below 30 weeks of gestational age. Preliminary results of a prospective amplitude-integrated EEG study. Wien Klin Wochenschr 2001;113: 219–23.
[36] Kurjak A, Stanojević M, Predojević M, Laušin I, Salihagić-Kadić A. Neurobehavior in fetal life. Semin Fetal Neonatal Med 2012;17: 319–23.
[37] Kurth S, Olini N, Huber R, LeBourgeois M. Sleep and Early Cortical Development. Curr Sleep Med Rep 2015;1: 64–73.
[38] Lam P, Hiscock H, Wake M. Outcomes of infant sleep problems: a longitudinal study of sleep, behavior, and maternal well-being. Pediatrics 2003;111: e203-7.
[39] Lamblin MD, André M, Challamel MJ, Curzi-Dascalova L, d'Allest AM, De Giovanni E, et al. Electroencephalography of the premature and term newborn. Maturational aspects and glossary. Neurophysiol Clin 1999;29: 123–219.
[40] Lee CW, Blanco B, Dempsey L, Chalia M, Hebden JC, Caballero-Gaudes C, et al. Sleep State Modulates Resting-State Functional Connectivity in Neonates. 2020; 14: 347.
[41] Löhr B, Siegmund R. Ultradian and circadian rhythms of sleep-wake and food-intake behavior during early infancy. Chronobiol Int 1999;16: 129–48.
[42] Mahmoudzadeh M, Dehaene-Lambertz G, Fournier M, Kongolo G, Goudjil S, Dubois J, et al. Syllabic discrimination in premature human infants prior to complete formation of cortical layers. Proceedings of the National Academy of Sciences 2013;110: 4846–51.
[43] Mahmoudzadeh M, Dehaene-Lambertz G, Wallois F. Electrophysiological and hemodynamic mismatch responses in rats listening to human speech syllables. PLoS ONE 2017;12: e0173801.
[44] Mahmoudzadeh M, Wallois F, Kongolo G, Goudjil S, Dehaene-Lambertz G. Functional Maps at the Onset of Auditory Inputs in Very Early Preterm Human Neonates. Cereb Cortex 2017;27: 2500–12.
[45] Malfilâtre G, Mony L, Hasaerts D, Vignolo-Diard P, Lamblin MD[5] Bourel-Ponchel E. Technical recommendations and interpretation guidelines for electroencephalography for premature and full-term newborns. Neurophysiol clin. In press.
[46] Malik S, Vinukonda G, Vose LR, Diamond D, Bhimavarapu BBR, Hu F, et al. Neurogenesis Continues in the Third Trimester of Pregnancy and Is Suppressed by Premature Birth. J Neurosci 2013;33: 411–23.
[47] McCann M, Bayliss DM, Anderson M, Campbell C, French N, McMichael J, et al. The relationship between sleep problems and working memory in children born very preterm. Child Neuropsychology 2018;24: 124–44.
[48] McGraw K, Hoffmann R, Harker C, Herman JH. The development of circadian rhythms in a human infant. Sleep 1999;22: 303–10.

[49] McMillen IC, Kok JS, Adamson TM, Deayton JM, Nowak R. Development of circadian sleep-wake rhythms in preterm and full-term infants. Pediatr Res 1991;29: 381–4.
[50] Mirmiran M, Maas YGH, Ariagno RL. Development of fetal and neonatal sleep and circadian rhythms. Sleep Med Rev 2003;7: 321–34.
[51] Moore AR, Zhou W-L, Jakovcevski I, Zecevic N, Antic SD. Spontaneous electrical activity in the human fetal cortex in vitro. J Neurosci 2011;31: 2391–8.
[52] Natalucci G, Rousson V, Bucher HU, Bernet V, Hagmann C, Latal B. Delayed cyclic activity development on early amplitude-integrated EEG in the preterm infant with brain lesions. Neonatology 2013;103: 134–40.
[53] Nijhuis JG, Prechtl HF, Martin CB, Bots RS. Are there behavioural states in the human fetus? Early Hum Dev 1982;6: 177–95.
[54] Nunes ML, Khan RL, Gomes Filho I, Booij L, da Costa JC. Maturational changes of neonatal electroencephalogram: a comparison between intra uterine and extra uterine development. Clin Neurophysiol 2014;125: 1121–8.
[55] Parmelee AH, Minkowski A, Saint-Anne Dargassies S, Dreyfus-Brisac C, Lézine I, Bergès J, et al. Neurological evaluation of the premature infant. A follow-up study. Biol Neonate 1970;15: 65–78.
[56] Parmelee AH, Schulte FJ, Akiyama Y, Wenner WH, Schultz MA, Stern E. Maturation of EEG activity during sleep in premature infants. Electroencephalogr Clin Neurophysiol 1968;24: 319–29.
[57] Parmelee AH, Wenner WH, Akiyama Y, Schultz M, Stern E. Sleep states in premature infants. Dev Med Child Neurol 1967;9: 70–7.
[58] Prechtl HF. The behavioural states of the newborn infant (a review). Brain Res 1974;76: 185–212.
[59] Prechtl HF, O'Brien M. Behavioral statesof the full-term newborn : the emergence of a concept. 1982: 53–73.
[60] Reppert SM, Weaver DR, Rivkees SA, Stopa EG. Putative melatonin receptors in a human biological clock. Science 1988;242: 78–81.
[61] Scher MS. Normal electrographic-polysomnographic patterns in preterm and fullterm infants. Semin Pediatr Neurol 1996;3: 2–12.
[62] Scher MS, Johnson MW, Holditch-Davis D. Cyclicity of neonatal sleep behaviors at 25 to 30 weeks' postconceptional age. Pediatr Res 2005;57: 879–82.
[63] Scher MS, Steppe DA, Banks DL. Prediction of lower developmental performances of healthy neonates by neonatal EEG-sleep measures. Pediatr Neurol 1996;14: 137–44.
[64] Scher MS, Steppe DA, Dahl RE, Asthana S, Guthrie RD. Comparison of EEG sleep measures in healthy full-term and preterm infants at matched conceptional ages. Sleep 1992;15: 442–8.
[65] Shellhaas RA, Burns JW, Barks JDE, Chervin RD. Quantitative sleep stage analyses as a window to neonatal neurologic function. Neurology 2014;82: 390–5.
[66] Shimada M, Takahashi K, Segawa M, Higurashi M, Samejim M, Horiuchi K. Emerging and entraining patterns of the sleep-wake rhythm in preterm and term infants. Brain Dev 1999;21: 468–73.
[67] Sterman MB, Hoppenbrouwers T. The development of sleep-waking and rest-activity patterns from foetus to adult in man. New York: Academic Press; 1971: 203–225.
[68] Tiriac A, Uitermarkt BD, Fanning AS, Sokoloff G, Blumberg MS. Rapid whisker movements in sleeping newborn rats. Curr Biol 2012;22: 2075–80.
[69] Touchette E, Petit D, Séguin JR, Boivin M, Tremblay RE, Montplaisir JY. Associations between sleep duration patterns and behavioral/cognitive functioning at school entry. Sleep 2007;30: 1213–9.

[70] Vecchierini M-F, d'Allest A-M, Verpillat P. EEG patterns in 10 extreme premature neonates with normal neurological outcome: qualitative and quantitative data. Brain Dev 2003;25: 330–7.
[71] de Vries JI, Visser GH, Mulder EJ, Prechtl HF. Diurnal and other variations in fetal movement and heart rate patterns at 20-22 weeks. Early Hum Dev 1987;15: 333–48.
[72] Wallois F, Routier L, Héberlé C, Mahmoudzadeh M, Bourel-Ponchel E, Moghimi S. Back to basics: the neuronal substrates and mechanisms that underlie the electroencephalogram in premature neonates. Neurophysiol clin. In press.
[73] Wolff PH, Ferber R. The development of behavior in human infants, premature and newborn. 1979;2: 291-307.

Legends

Table 1. Non cerebral features observed in active and quiet sleep

Table 2. Sleep-wake states, related EEG background activity, and provoked EEG reactivity according to gestational age.
Specific related features that differ according to gestational age and vigilance state are not described here. For details, see Bourel-Ponchel et al., in the same issue [6]
AS: active sleep, QS: quiet sleep, IS: indeterminate sleep, AW: active wakefulness, QW: quiet wakefulness. Maximal duration of quiescent periods for the GA considered in cases of discontinuous activity.

Figure 1. Polysomnography recording during QS in a term newborn (30 seconds)
EEG activity showing the 'tracé alternant' associated with regular cardio-respiratory rates (thoracic (THO) and abdominal (ABD) respiratory movements), regular nasal flux recorded with a naso-buccal pediatric canula (NAS) and thermistor (THER), and no REMs on electrooculogram (EOG1 and 2).

Figure 2. Polysomnography recording during AS 1 (before transition to QS) in a term newborn (30 seconds)
EEG activity showing the continuous high-amplitude mixed-frequency trace of AS1, associated with irregular cardio-respiratory rates (thoracic (THO) and abdominal (ABD) respiratory movements), irregular nasal flux recorded with a naso-buccal pediatric canula (NAS) and thermistor (THER), and REMs on electrooculogram (EOG1 and 2) (arrows).*: 'encoches frontales', §: muscular artefacts

Figure 3. Polysomnography recording during AS (after transition from QS) in a term newborn (30 seconds)
EEG activity showing the 'activité moyenne' of AS2, associated with irregular cardio-respiratory rates (thoracic (THO) and abdominal (ABD) respiratory movements), irregular nasal flux recorded with a naso-buccal pediatric canula (NAS) and thermistor (THER), and REMs on electrooculogram (EOG1 and 2) (arrows).

Figure 4. Polysomnography recording during active wakefulness in a term newborn (30 seconds)

EEG activity showing the 'activité moyenne' of active wakefulness, associated with irregular cardio-respiratory rates (thoracic (THO) and abdominal (ABD) respiratory movements), irregular nasal flux recorded with a naso-buccal pediatric canula (NAS) and thermistor (THER), and muscle and movement artefacts

Figure 5. Illustration of a sleep-cycle

A sleep cycle is defined by successive sleep states (AS-QS-IS) without waking. One sleep-cycle is measured from the end of post-waking active sleep to the end of the next AS period (following a QS period). Data acquired for a 35-wGA normal premature infant.

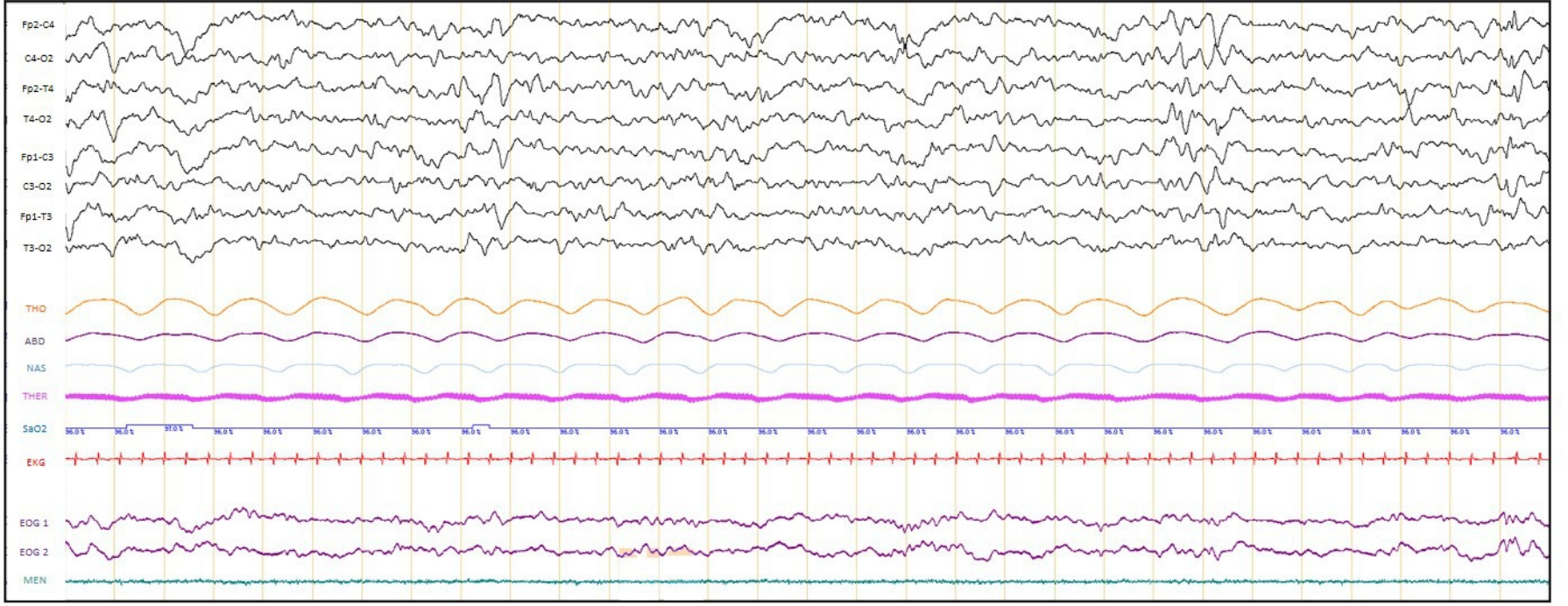
AS: active sleep, QS: quiet sleep, IS: indeterminate sleep. Adapted from Curzi et al., 1996 [13]

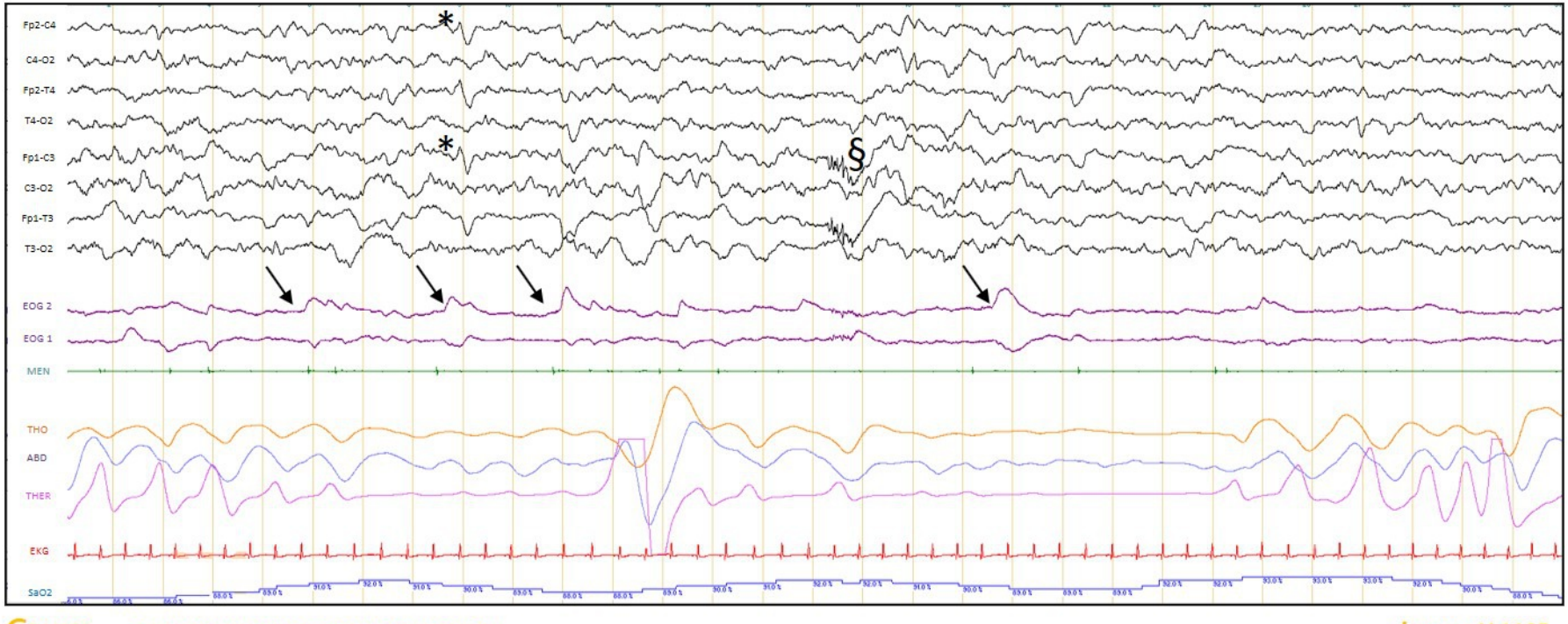
Figure 6. Sleep duration in minutes (A) and percentage of time spent in each sleep state (B)

1A. The duration of the sleep cycle increases from approximately 40 min at 27 wGA to approximately 60 min at 41 wGA. This increase is related to both increases in the duration of AS and QS and a decrease in IS.

1B. The percentage of time spent in each sleep state evolves along with that of sleep duration. Data are based on the first sleep cycle in normal premature and term newborn infants from 27 to 41 wGA. Sleep states are visually scored according to the concordance between EEG and REM criteria.

AS: active sleep, QS: quiet sleep, IS: indeterminate sleep, adapted from Curzi Dascalova et al., 1995 [11]


Fp2-C4
C4-O2
Fp2-T4
T4-O2
Fp1-C3
C3-O2
Fp1-T3
T3-O2
THO
ABD
NAS
THER
SaO2
EKG
EOG 1
EOG 2
MEN


Fp2-C4
C4-O2
Fp2-T4
T4-O2
Fp1-C3
C3-O2
Fp1-T3
T3-O2
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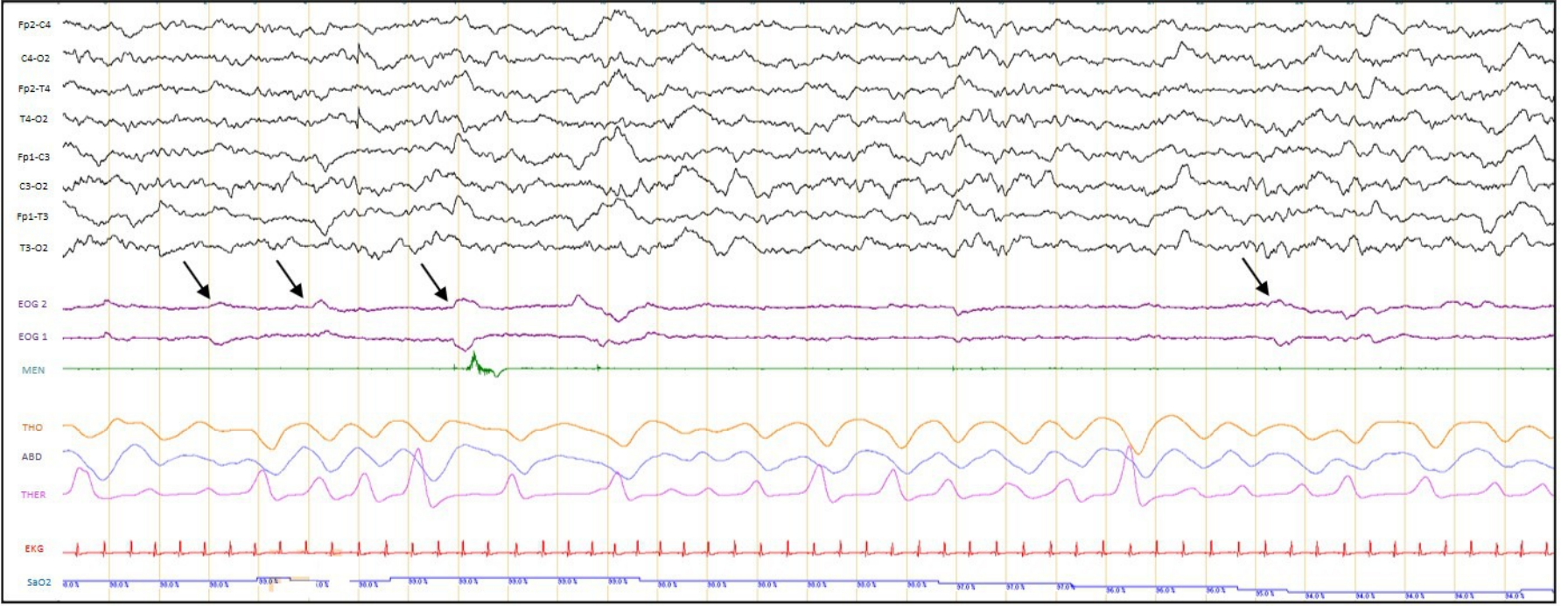
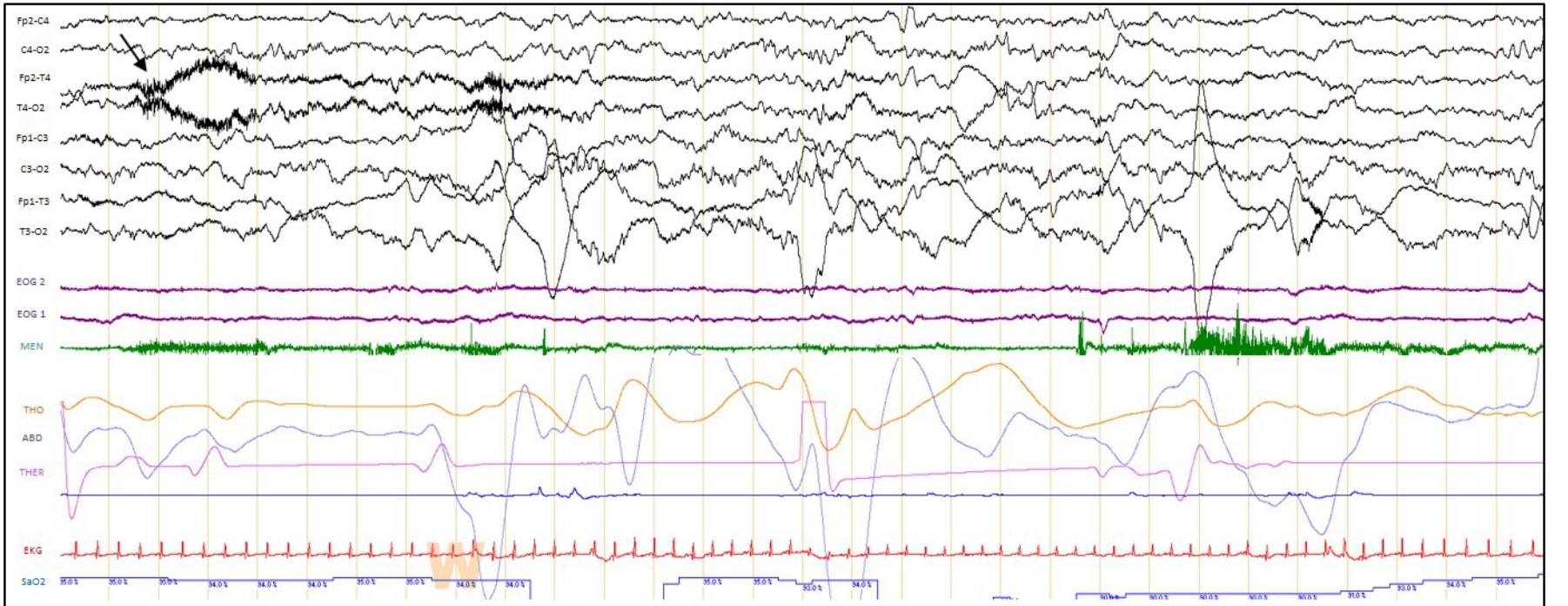
EOG 2
EOG 1
MEN
THO
ABD
THER
EKG
SaO2


Fp2-C4
C4-O2
Fp2-T4
T4-O2
Fp1-C3
C3-O2
Fp1-T3
T3-O2
EOG 2
EOG 1
MEN
THO
ABD
THER
EKG
SaO2


Fp2-C4
C4-O2
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MEN
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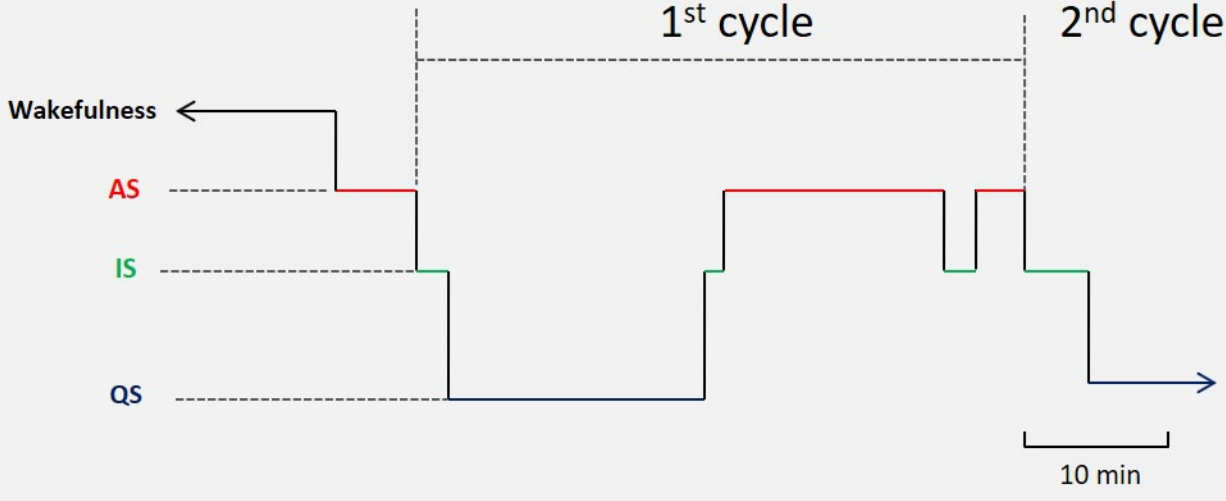
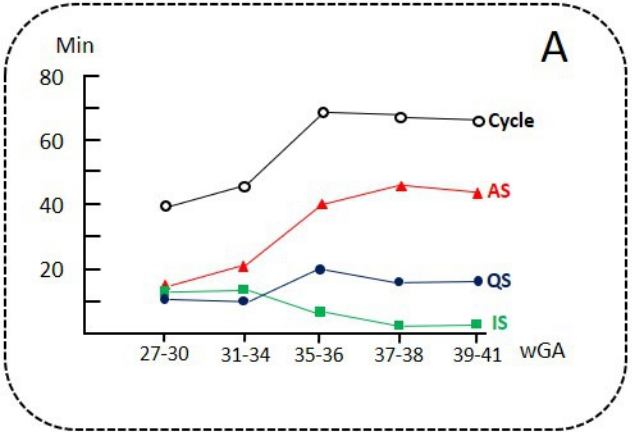


35 wGA


Min
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Cycle
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27-30
31-34
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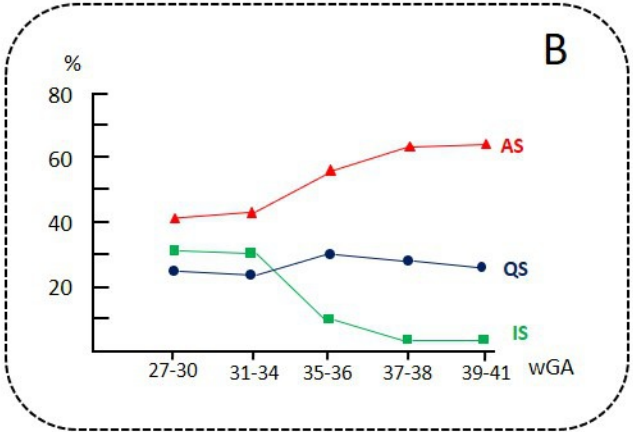
37-38
39-41
wGA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AS
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IS
27-30
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35-36
37-38
39-41
wGA

Non cerebral features	Active sleep	Quiet sleep
Rapid eye movements (REMs)	+	-
Cardiorespiratory rate	Irregular	Regular
Body and facial movements	Head movements Facial mimics Slow or jerky Limbs movements (myoclonic twitches) Gross movements	Small segmental body movements Isolated non nutritive sucking
Tonic chin EMG	-	+

Gestational age	**24-26**	**27-28**	**29-30**	**31-33**	**34-36**	**37-40**
Behavioral state	Rudimentary sleep state differentiation	+/- AS/ QS	+ AW, AS, QS	+ AW, QW (+/-), AS, QS	++ AW, QW, AS, QS	++ AW, QW, AS1, QS, AS2
Background EEG activity	Discontinuous QS (1-35 sec)	Discontinuous QS (1-30 sec)	AW: continuous AS/QS: discontinuous (1-30 sec)	AS: semi-discontinuous (10 sec) QS: discontinuous (15 sec)	QS: discontinuous (10 sec)	AW, QW, AS2: 'activité moyenne' AS1: high amplitude mixed frequencies continuous tracing QS: 'tracé alternant' and 'tracé lent continus'
Provoked reactivity AS QS	-	**+/-** Transient generalized decrease in amplitude	**+** transient generalized decrease in amplitude Transient appearance of continuous EEG	**+** Transient generalized decrease in amplitude Transient appearance of continuous EEG	++ Transient generalized decrease in amplitude Transient appearance of continuous EEG	++ Transient generalized decrease in amplitude Transient reinforcement or generalized decrease in amplitude