

Near-infrared spectroscopy and polysomnography during all-night sleep in human subjects

Sergio Fantini^a, Payal Aggarwal^a, Kathleen Chen^a, Maria Angela Franceschini^{a,b},
and Bruce L. Ehrenberg^{c,a}

^a Department of Biomedical Engineering, Tufts University
4 Colby Street, Medford, MA 02155

^b NMR-Center, Massachusetts General Hospital, Harvard Medical School,
13th Street Bldg. 149 (rm 2301), Charlestown, MA 02129

^c Department of Neurology, Tufts University School of Medicine,
New England Medical Center, Boston, MA 02111

ABSTRACT

We have performed cerebral near-infrared spectroscopy (NIRS) and polysomnography (electro-encephalography, electro-oculography, electro-myography, pulse oximetry, and respiratory monitoring) during all-night sleep in five human subjects. Polysomnography data were used for sleep staging, while NIRS data were used to measure the concentration and the oxygen saturation of hemoglobin in the frontal brain region. Immediately after sleep onset we observed a decrease in the cerebral concentration of oxy-hemoglobin ([HbO₂]) and an increase in the concentration of deoxy-hemoglobin ([Hb]), consistent with a decrease in the cerebral blood flow velocity or an increase in the cerebral metabolic rate of oxygen. An opposite trend (increase in [HbO₂] and decrease in [Hb]) was usually observed after transition to deep sleep (stages III and IV). During rapid eye movement (REM) sleep, we observed an increase in [HbO₂] and decrease in [Hb], consistent with an increase in the cerebral blood flow that overcompensates the increase in the metabolic rate of oxygen associated with REM sleep.

Keywords: Near-infrared spectroscopy, cerebral hemodynamics, sleep, polysomnography, REM stage.

1. INTRODUCTION

Near-infrared spectroscopy (NIRS) allows for non-invasive brain measurements that result from the interplay of physiological factors such as the cerebral blood flow, blood volume, and metabolic rate of oxygen. For this reason, NIRS holds promise for the non-invasive study of brain physiology and brain activation. NIRS is implemented by applying a number of optical fibers (or optodes) to the subject's head, similarly to the way that electrodes are applied to the scalp for electroencephalography (EEG). The optodes can be comfortably worn by the subject, so that NIRS lends itself to long-term monitoring and can be applied to the study of the cerebral hemodynamics during whole-night sleep. On the one hand, NIRS studies during sleep have been aimed at the investigation of the hemodynamic and oxygenation changes associated with the transition between wakefulness and sleep,¹ and with the cyclic succession of awake, REM (rapid eye movement), and non-REM sleep stages.^{2,3} In particular, one multi-channel NIRS study has been devoted to the study of the activation of the visual cortex in REM sleep.⁴ On the other hand, NIRS studies during sleep have been devoted to assessing the effects of sleep disorders such as obstructive sleep apnea,^{5,6} or neurological disorders such as Rett syndrome.⁷ In addition to studies on adult human subjects, NIRS has been applied on newborn infants during sleep, for the study of (1) spontaneous oscillations of oxy-hemoglobin and deoxy-hemoglobin,⁸ (2) cerebral

hemodynamic changes associated with transitions between sleep stages,⁹ (3) regional hemodynamic response to photic stimulation,¹⁰ and (4) the effect of apnea¹¹ or periodic breathing¹² on the cerebral oxygenation and blood volume.

In this contribution, we report NIRS measurements of the cerebral oxygen saturation (StO₂), total hemoglobin concentration ([Hb]_{tot}), oxyhemoglobin concentration ([HbO₂]) and deoxyhemoglobin concentration ([Hb]) in the frontal brain region of adult human subjects during whole-night sleep. Concurrently with the NIRS measurements, we collected polysomnography data, namely electro-encephalography (EEG), electro-oculography (EOG), electro-myography (EMG), pulse oximetry, and respiratory monitoring by a strain gauge around the chest and by a thermistor at the nose. Polysomnography data was used to assess the sleep stage (I, II, III, IV, and REM) throughout the night, and to identify periods of abnormal respiratory patterns or muscle contractions.

2. METHODS

The experimental arrangement is schematically shown in Fig. 1. The NIRS instrument is a two-channel frequency-domain tissue spectrometer (OxiplexTS, ISS, Inc., Champaign, IL) operating at a modulation frequency of 110 MHz and at two near-infrared wavelengths (690 and 830 nm). Two multi-distance probes featuring four source-detector separations of 1.0, 1.5, 2.0, and 2.5 cm were placed on the left and right sides of the forehead as close as possible to the hair line. The multi-distance scheme affords quantitative tissue spectroscopy,¹³ the determination of absolute values for the hemoglobin-related parameters with a temporal resolution of 160 ms, and minimal sensitivity to superficial tissue layers.¹⁴ EEG electrodes were placed on the scalp over the frontal, central, and occipital regions of the brain. Additional electrodes were placed near the eyes (for EOG) and on the chin and legs (for EMG). The NIRS and EEG acquisitions were synchronized using the signal from a button switch, which was pressed by the subject at the beginning and at the end of the measurement session, and when the subject awoke during the night. Respiration was monitored with a strain gauge placed around the chest and with a thermistor placed at the nose. The heart rate, arterial pulse, and arterial saturation were continuously monitored using a pulse oximeter. Finally, the subject was video-recorded during the whole night with an infrared-sensitive video camera to visually verify the correct attachment of the various probes on the subject overnight, and to identify possible sources of motion artifacts in the data. Data was acquired on five human subjects, identified with the letters C, D, E, F, and G (the data on two previous subjects labeled A and B were discarded for technical reasons). Relevant information on these five subjects, as well as the duration of the NIRS/Polysomnography recordings, are reported in Table I. The measurements were performed at the EEG Laboratory of the New England Medical Center (NEMC) in Boston, Massachusetts. The protocol was approved by the NEMC Institutional Review Board, and all subjects gave their written informed consent.

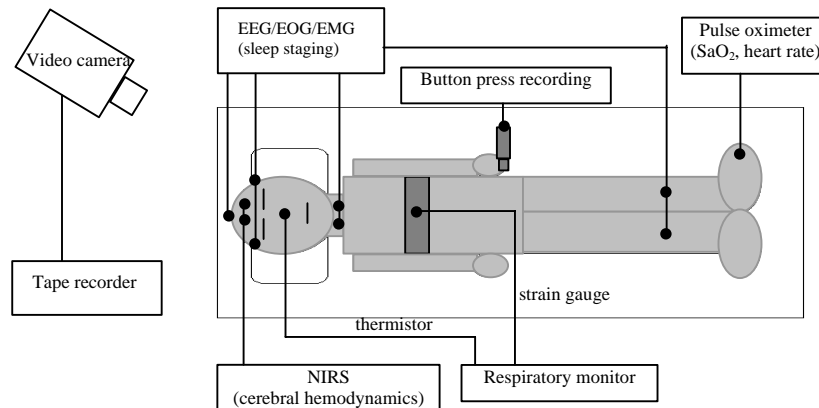


Fig. 1. Experimental arrangement. The subject was lying comfortably on a bed. Two fiber-optic probes were placed on the forehead for near-infrared spectroscopy (NIRS). Multiple electrodes were positioned on the head, chin, and legs for electro-encephalography (EEG), electro-oculography (EOG), and electro-myography (EMG). A pulse oximeter monitored the arterial saturation (SaO₂) and the heart rate. A strain gauge around the chest and a thermistor at the nose monitored respiration. A button press recording was used to synchronize the EEG and NIRS acquisitions. An infrared sensitive video camera was used to visually record the subject overnight.

Table I. Relevant information on the five subjects investigated.

Subject	Sex (M/F)	Age (yrs)	Mismatch with Usual Sleep Propensity Onset (hrs)	Significant Sleep Apnea	Duration of measurement (hrs)
C	M	36	~ +1	No	~8.5
D	F	29	~ -1.5	No	~8.5
E	M	52	~ +2.5	Yes	~ 6.5
F	F	36	~ -0.5	No	~ 7.5
G	M	44	~ +2	No	~ 8

3. RESULTS

Figure 2 displays the recordings of heart rate, respiration, NIRS data (StO_2 , $[Hb]_{tot}$, $[HbO_2]$), and $[Hb]$, and sleep staging for Subject C during all-night sleep. The NIRS traces refer to the signals measured on the left side of the forehead. The NIRS data show some jumps that are usually attributed to motion artifacts (for instance, at times 0:16, 2:50, 4:16, 5:50), especially if the subject is awake. Consequently, care must be taken in the analysis of the relative changes of the NIRS data over the whole night. By contrast, smooth changes in the optical traces and temporal oscillations of the optical signals may provide robust physiological indications. For instance, the evident increase in the amplitude of the optical fluctuations between 2:36 and 2:50 is assigned, at least in part, to a significant change in the respiratory dynamics.

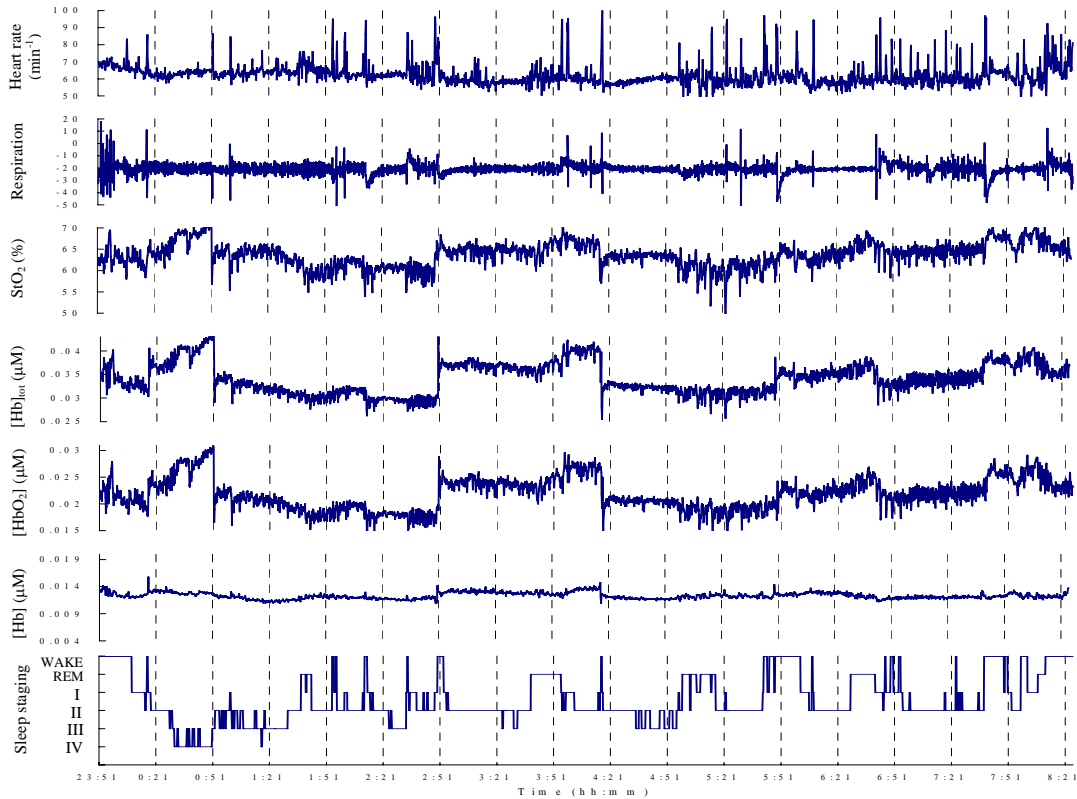


Fig. 2. All-night sleep recordings for Subject C displaying the heart rate, respiration, NIRS recording on the left side of the forehead (namely, cerebral oxygen saturation (StO_2), total hemoglobin concentration ($[Hb]_{tot}$), oxyhemoglobin concentration ($[HbO_2]$) and deoxyhemoglobin concentration ($[Hb]$)), and sleep staging.

Figures 3 and 4 show the traces recorded during the first transition from the awake state to sleep in subjects D and G, respectively. In Fig. 3, which refers to subject D, we observe an initial deoxygenation (decrease in $[HbO_2]$, increase in $[Hb]$) followed by an opposite behavior (increase in oxygenation and $[HbO_2]$, decrease in $[Hb]$) as the subjects reaches deep-sleep stages III and IV. We observed a similar behavior in subjects C, E, and F. The data on subject G reported in Fig. 4, which also shows an initial deoxygenation during stage I sleep, differs in that the transition to deep sleep is associated with a mild deoxygenation.

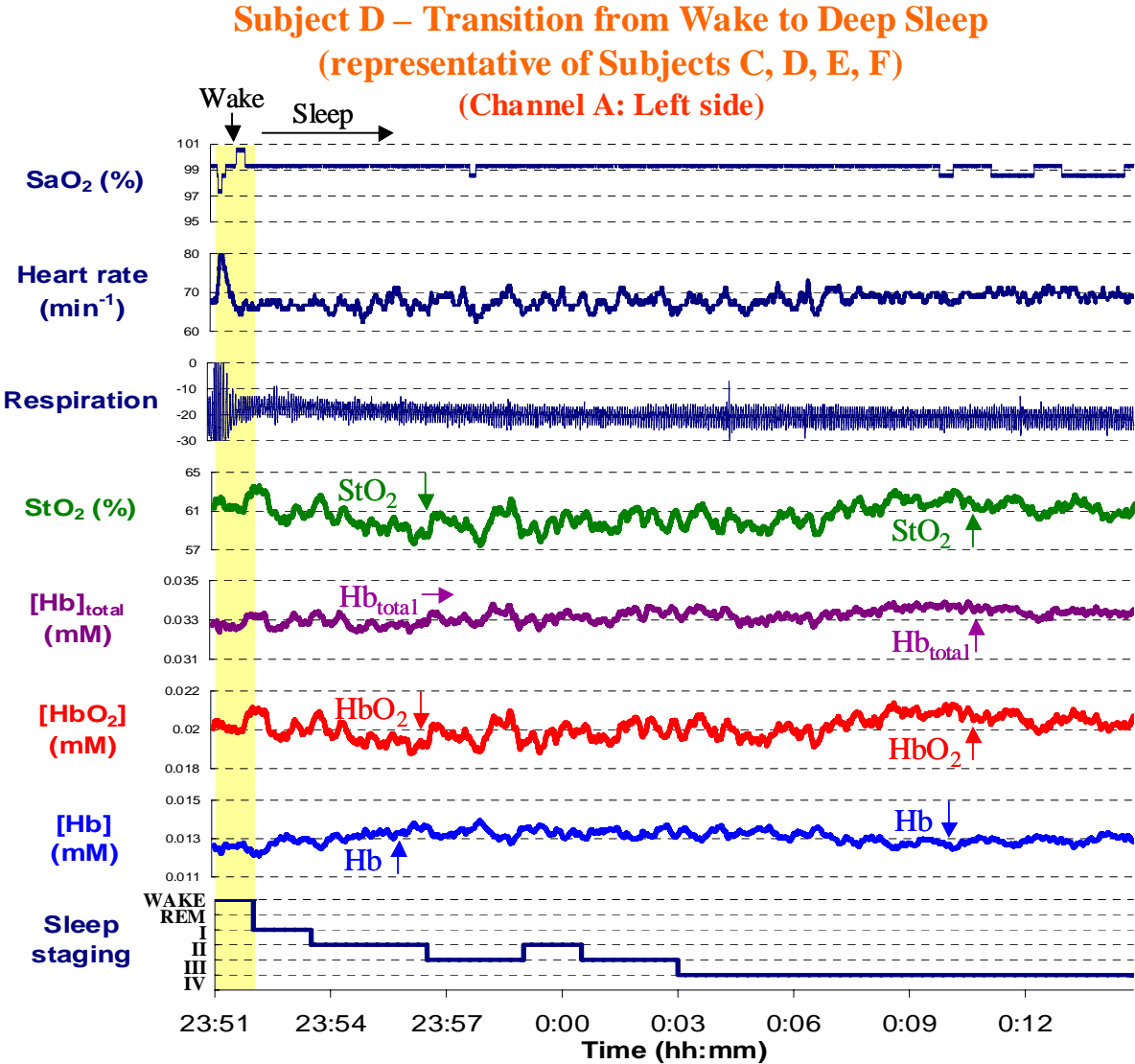


Fig. 3. First transition from the awake state to sleep in subject D. We found similar results in subjects C, E, and F.

Figure 5 shows traces that we have observed during transitions into and out of the REM stage in subject G. We observed a decrease in $[Hb]$ and an increase in $[HbO_2]$, which is a combination of effects that is indicative of an increase

in the blood flow. The fact that this blood flow increase correlates with an increase in the heart rate suggests that our NIRS measurements may also be sensitive to extracerebral tissue (in fact, the cerebral blood flow is autoregulated and should not be affected by changes in the heart rate). This sensitivity to extracerebral tissue may result from the relatively short source-detector distances of 1.0-2.5 cm used by us, even though the multi-distance scheme of data analysis minimizes the sensitivity to superficial tissue layers. The correlation between blood flow increase (concurrent increase in $[HbO_2]$, decrease in $[Hb]$, and increase in $[Hb]_{Total}$) and the increase in heart rate can also be seen in Fig. 6 (beginning at time 1:22:37), which displays traces recorded over a period of 90 s during stage II sleep in Subject G. In this case, one can also observe that the oscillations of $[HbO_2]$, and $[Hb]$ are in-phase with each other and are synchronous with respiration. It has been proposed that these oscillations may be used to quantify the regional venous saturation using a technique called spiroximetry.¹⁵

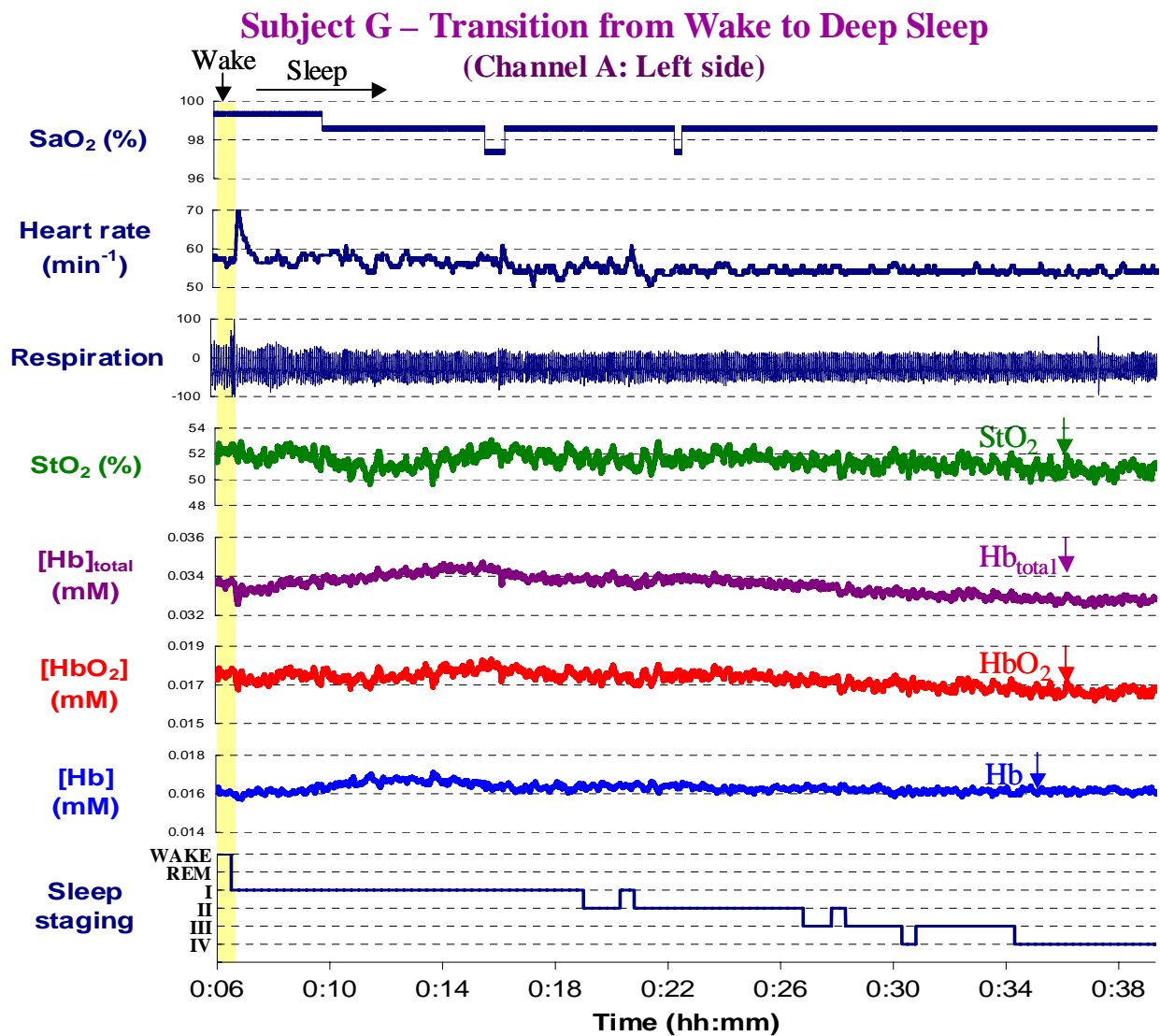


Fig. 4. First transition from the awake state to sleep in subject G.

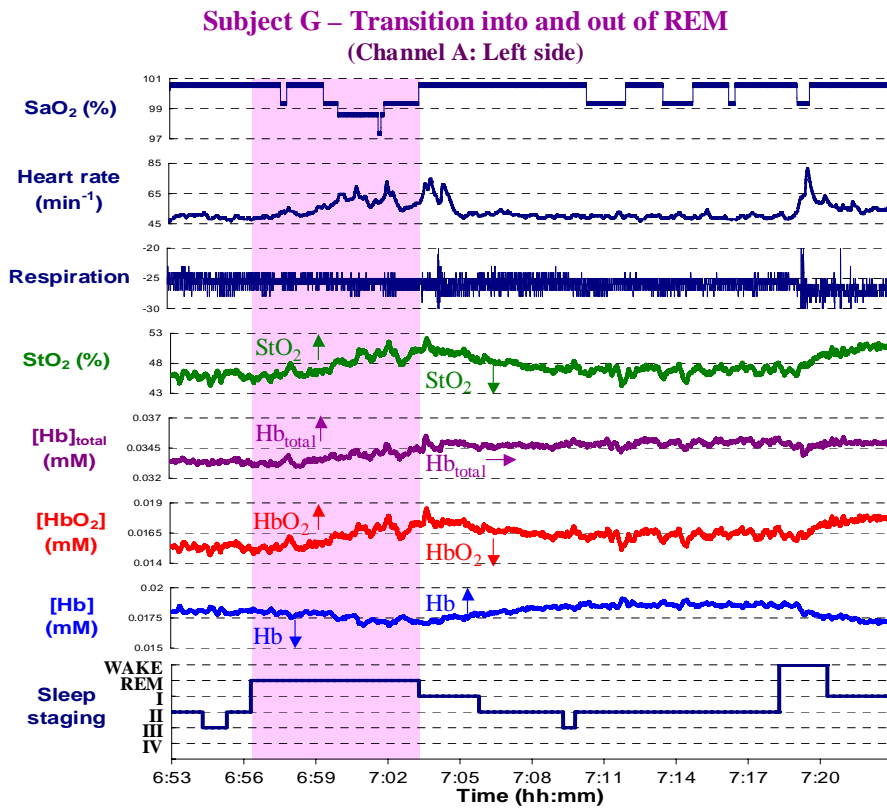


Fig. 5. Transitions into REM and out of REM for subject G.

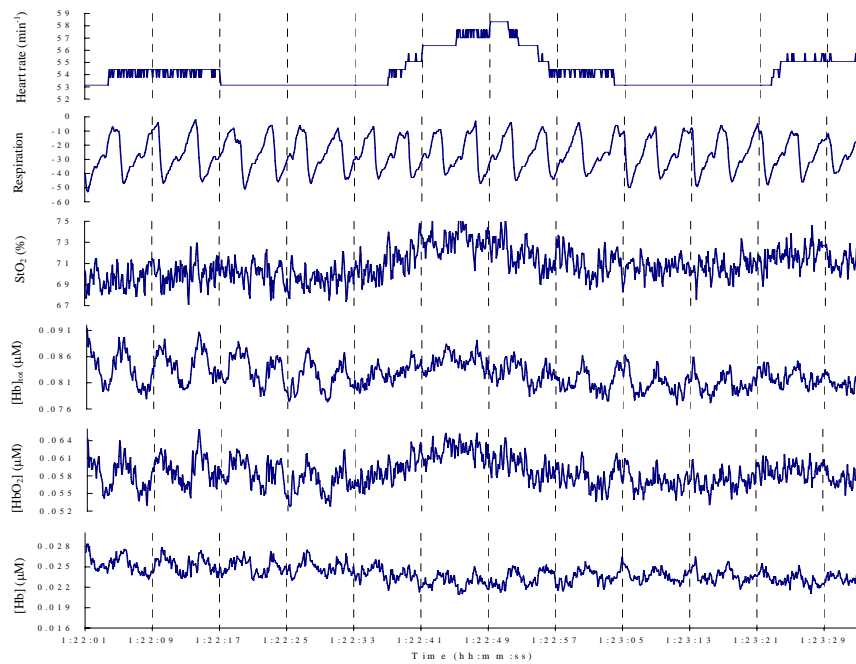


Fig. 6. Temporal traces of $[Hb]$, $[HbO_2]$, $[Hb]_{tot}$, and StO_2 measured by NIRS, and respiratory effort and heart rate measured by pulse oximetry. The respiratory oscillations are synchronous with in-phase oscillations of $[Hb]$ and $[HbO_2]$.

4. DISCUSSION

We have found that the initial effect of the transition from wakefulness to sleep is a decrease in [HbO₂] and an increase in [Hb] (see Figs. 3 and 4) with a resulting decrease in the cerebral oxygen saturation of hemoglobin. These findings are in agreement with the results reported by Hoshi *et al.*² and by Shiotsuka *et al.*³ who concluded that the cerebral oxygen metabolic rate must increase during transition from wakefulness to sleep to account for these results. However, the concurrent combination of a decrease in [HbO₂] and an increase in [Hb] can also be the result of a reduced speed of cerebral blood flow.¹⁶ By contrast, Spielman *et al.*¹ reported a decrease in both [HbO₂] and [Hb] during the 20 s following the wake-sleep transition in afternoon nap studies. The possible origins of this discrepancy are thoroughly discussed by Spielman *et al.*¹ and include the duration of the initial sleep period considered, afternoon versus night sleep differences, the scalp locations of the optodes, and technical differences between the optical instruments used in various studies. When the subjects went into deeper sleep (stages III and IV), we observed a reversed pattern, namely an increase in [HbO₂] and a decrease in [Hb] (see Fig. 4), which is consistent with the decrease in the cerebral metabolic rate of oxygen that characterizes deep sleep.¹⁷ The only exception was subject G (see Fig. 5), where the observed decrease in the concentrations of both [HbO₂] and [Hb] may be the result of the significant reduction in heart rate (which may point to a non-negligible contribution to the optical measurements from extracerebral tissue).

The most common effect of REM sleep on the optical measurements, namely an increase in [HbO₂] and a decrease in [Hb], is reported in Fig. 5. This finding is consistent with an increase in the cerebral blood flow that overcompensates a concurrent increase in cerebral metabolic rate of oxygen, as observed by NIRS studies of brain activation.¹⁸ Similar results were reported by NIRS studies in the frontal region² and in the occipital region⁴ during REM sleep.

5. CONCLUSION

All-night optical monitoring of the human brain concurrently with polysomnography is feasible and provides information on the interplay of physiological parameters such as cerebral blood flow, metabolic rate, and blood volume. Modifications to the cerebral concentrations of oxy-hemoglobin, deoxy-hemoglobin, and total hemoglobin induced by transitions between different sleep stages can help quantify the hemodynamic and metabolic changes associated with such transitions. Furthermore, a study of the changes in the temporal fluctuations of the optical data during different sleep stages may also yield important physiological information. For instance, it was reported that [HbO₂] and [Hb] show larger fluctuations during REM sleep than during non-REM sleep.³ The implementation of spatially-resolved optical monitoring techniques has the further potential to map the hemodynamic/metabolic changes that occur during sleep in various brain areas. These advances may be important to study sleep physiology, characterize sleep disorders, and perform long-term monitoring of a large class of neurological disorders.

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