Modelling the relation of body temperature and sleep: importance of the circadian rhythm in skin temperature

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A close relation between thermoregulatory and arousal related processes in basal forebrain and hypothalamic areas has been substantiated in many studies. It has been demonstrated especially - but not exclusively - in the preoptic area of the anterior hypothalamus (POAH), that a subpopulation of warm-sensitive neurons (WSNs) spontaneously increases firing rate at sleep onset, and that experimental local warming of the POAH induces a similar increase in firing rate and facilitates sleep onset. It has consequently been proposed that brain temperature may be involved in physiological regulation of sleep. However, contrary to the experimental findings of increased sleep onset probability with a locally increased hypothalamic temperature, the likeliness of sleep onset in unmanipulated conditions is actually minimal at the time when the circadian rhythm in temperature reaches its peak. In fact, sleep onset probability increases on the falling limb of the circadian core temperature rhythm. How can this discrepancy of increased sleep with well-controlled experimental local POAH warming be reconciled with increased sleep with local cooling under natural conditions?

A suitable explanation has been put forward: in modelling based on local warming experiments, it has generally been ignored that many of the locally thermosensitive neurons also respond, in a similar way, to changes in skin temperature. Thus, the very changes in cell membrane properties leading to sleep-related alterations in firing rate as induced by local warming in experimental conditions, may be induced by warming of the skin under natural conditions.

Several considerations support the importance of skin temperature. First, after warming of the skin, preoptic WSNs show a markedly increased firing rate to a level that can be reached only by extreme (non-physiological) local warming. Moreover, with elevated skin temperature, WSNs have a high firing rate irrespective of the local temperature, i.e. temperature input from the skin appears to dominate when competing signals are present. Second, sleep appetitive behavior like lying down, covering etc. is associated with a redistribution of warm blood to the extremities, thus increasing their temperature. Third, and
most important, the increase of sleep onset probability that occurs on the falling limb of the circadian core temperature rhythm can now be understood. Since the circadian drop in core temperature is mainly due to increased dissipation of body heat, skin temperature is actually elevated when core temperature is falling.

The preoptic area is by no means exclusive in containing thermosensitive neurons: they are present in many of the brain areas involved in arousal regulation. When sleep onset probability was modelled with human constant routine data\(^3\) of the circadian profiles of core and peripheral temperature as inputs to thermosensitive neurons in these brain areas, we found agreement between habitual sleep onset time and peak modelled onset probability, as shown in the figure. A series of studies is presently being undertaken in order to reveal the relative importance of core and peripheral temperature in the regulation of arousal state transitions.

**Figure:** The upper panel shows the average 24-hour profile of human rectal temperature and temperature at the extremities under constant routine conditions\(^3\). For convenience, the curves have been moved freely on the vertical axis, omitting absolute values on the vertical axis, while the relative magnitude of the amplitudes is preserved in the figure. Both curves affect the probability of sleep-type neuronal firing patterns of thermosensitive neurons in many parts of the brain involved in sleep regulation. High skin temperature is associated with increased probability in some areas, but decreased probability in other areas. The lower panel shows a straightforward (normalized) summation of the resulting sleep probability curves.
of six sleep-related brain structures for which thermosensitivity has been demonstrated. Depending on the setting of a threshold level, a temperature window favourable to sleep onset can thus be determined (indicated with dashed lines). Note that maximal sleep onset probability is indeed at usual bedtime.

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References
Dynamics of cortical EEG power decrease rate during entry into natural hypothermia in European ground squirrels

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Introduction

Hibernation has interested sleep researchers for decades. The cortical EEG patterns during NREM sleep are similar to EEG’s during the first stages of entrance into natural hypothermia (also called torpor). In spite of this resemblance in EEG patterns, torpor and sleep are functionally dissimilar. Short daily torpor bouts (circa 6 hours) in Djungarian hamsters induced an increase in slow wave activity (SWA), which can be interpreted as the result of a sleep debt increase during prior torpor (Deboer & Tobler 1994). Longer torpor bouts (2-12 days) in hibernating ground squirrels induced changes in spectral EEG power during subsequent euthermy, including the spindle (~10-14Hz) and slow wave (~1-4Hz) ranges (Trachsel et al. 1991; Strijkstra & Daan 1997ab). The spectral changes in hibernators were not related to a sleep debt increase caused by prior torpor (Strijkstra & Daan 1998; Larkin & Heller 1999), and may be based on changes in neurotransmission capacity and neuronal connectivity in the brain (see Strijkstra 1999). The findings in both Djungarian hamsters and ground squirrels disprove the idea that torpor and sleep have similar physiological functions.

The physiological changes in the brain of hibernating ground squirrels are most likely produced by effects of the low temperature of neurons during deep torpor. Cortical EEG recordings during the temperature cline at the entry into torpor may reveal information on these effects. We report here on gradual and more abrupt temperature dependencies of cortical EEG power decrease rates during entry into torpor in European ground squirrels.