Proceedings of ICMMGH 2026 Symposium: Biomedical Imaging and AI Applications in Neurorehabilitation
DOI: 10.54254/2753-8818/2026.AU30033

Progress in the Study of Characteristics and Regulatory Mechanisms of Sleep in Biological Evolution

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Abstract. From the human perspective, sleep is vital for the normal functioning of many advanced functions, such as learning and memory. Therefore, the importance of high-quality sleep is apparent. Although we already have certain research about the functions and mechanisms of sleep, there is still a long way to go to master sleep regulation and its complete application in treatment. In the context of biological evolution, researchers should compare the characteristics and mechanisms of sleep in different animal species to further understand the evolutionary origin of sleep and relationships between sleep and other advanced functions, which will help humans manage and utilize sleep beneficially. This review discusses the sleep characteristics of different animals that have critical significance in sleep research, including mammals, birds, and non-avian reptiles, as well as the current research progress of associated regulatory mechanisms. Finally, we outline the potential applications and challenges of research in the sleep mechanism.

Keywords: sleep characteristic, sleep regulation, mammal sleep, bird sleep, non-avian sleep

1. Introduction

Sleep is a vital life activity for almost all animals since its normal progress is considered to have important impacts on various life activities, such as memory consolidation, emotional stability, physical recovery and the development of nervous systems [1]. At present, humans are regarded as the main subject in sleep research. The sleep structure of humans includes several 90-120-minute sleep cycles consisting of rapid eye movement (REM) sleep and non-REM (NREM) sleep, in which this cycle occurs four to six times every night and is started with NREM sleep [2]. In the first several cycles, deep NREM sleep predominates. Toward morning, REM periods with dreams and muscle paralysis become longer [3]. Besides, sleep is vital to human health and thereby it becomes more necessary to lucubrate the features and rules of sleep. Locating sleep in an evolutionary context for comparative analysis can help us better understand sleep's function and evolutionary origin. Sleep can be defined by behavior and electroencephalography (EEG). Currently, diverse types of sleep have been found in different species, such as REM and NREM sleep in birds and mammals, two-state sleep in fish and reptiles and sleep only defined by behavior in flies and frogs [4]. In this review, we will follow the route of biological evolution, according to the relevant

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research in recent years, then take organisms with key significance for research as objects and discuss their related characteristics of sleep.

2. Sleep of mammals

Mammals are generally regarded as the top of the evolutionary chain in nature, and they possess various specific morphological and structural features, including viviparous reproductive mode, nearly constant body temperature, and complex physiological structures and systems. Among all kinds of systems, the mammalian nervous system is particularly complex and significant because mammals commonly have a more developed brain compared to other animals. Since sleep is closely related to the brain, the researcher paid more attention to mammals, and the characteristics of mammalian sleep have been relatively thoroughly studied. Thus, this review mainly discusses the associated mechanisms of mammalian sleep.

3. Sleep of common mammals

Until now, researchers have generally believed that mammals have two stages of sleep: REM sleep and NREM sleep, which are primarily investigated through human, mice, cats, dogs, etc. The mammalian REM sleep stage has several evident characteristics: low-amplitude EEG activities like wakefulness, rapid eye movement, decreased muscle activity with twitching, fluctuation of heart and breath rate and inhibited body temperature regulation [5]. The feature of NREM is mainly reflected in several delta bands (0-4Hz) of the EEG pattern, which is closely associated with processes like body recovery since the slow wave activities show significant rebound after long-term sleep deprivation [6]. Among mammals, mice are major model animals used to study the mechanisms and functions of mammalian sleep, which can provide clear EEG/EMG recordings of sleep and wakefulness to researchers and various gene-modified species [4]. In addition, compared with humans, mice also have more and shorter sleep cycles in a single sleep, which is conducive to the analysis of sleep structure [7]. Based on all these advantages, humans have achieved many advances in sleep regulation mechanisms by investigating mice.

Cellular regulation plays a vital role in mammalian sleep. Neuroglial cells, including microglia and astrocytes, are an essential group of cells that protect and support the function of the nervous systems, which play a crucial role in regulating diverse intricate activities like sleep. Chenyan Ma et al. found that in mice, the activation of P2Y12, a G protein-coupled receptor on the Gi channel of microglia, significantly increased the level of calcium in microglia and decreased the level of norepinephrine and thus promoted the sleep of mice. Furthermore, pharmacological blockade of P2Y12 receptors can obviously reduce the sleep behavior of mice [8]. Shefeeq et al. found in a mouse model that adenosine can mediate and promote sleep in mice by activating the adenosine A2B receptor on astrocytes, while inhibiting the expression of the A2B receptor can disturb sleep [9]. In addition to the regulation mechanism of sleep, various phenomena and related mechanisms during sleep can also be studied through mouse models. Bing et al. found that cortical ignition, a mechanism associated with consciousness, is strongly suppressed during NREM sleep of mice due to a significant reduction of transmission activity from the visual cortex (V1) to other brain regions. Moreover, this process is strongly regulated by basal forebrain cholinergic neurons [10].

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4. Sleep of hibernating mammals

The hibernation of mammals is a special sleep phenomenon, which shows many characteristics different from the general sleep process: the core body temperature of small hibernating animals, such as marmots, ground squirrels and bats, will regularly reduce to the freezing point during hibernation, and they are periodically awakened to normal body temperature. In addition, their metabolic rate commonly decreases to 2% to 5% of the basal metabolic rate [11]. The hibernating state is characterised by low energy consumption and no apparent physiological damage after recovery. Therefore, inducing humans to enter a hibernation-like state shows a fascinating prospect in the therapeutic field. Tohru et al. discovered the presence of a kind of hypohtalamic population of neurons that expresses pyroglutamylated RFamide peptide in anteroventral periventricular nucleus (AVPe) and medial preoptic area (MPA), which can be stimulated to induce a long-lasting and controllable state: O-neuron-induced hypothermia and hypometabolism (QIH). This state has hibernation-like features, and mice can spontaneously recover from it [12].

5. Sleep of a bird

The study of sleep in birds is not only of great significance in understanding the evolutionary origin of sleep, but also helps to compare and study the structure and function of sleep, since it has a similar REM sleep and NREM sleep structure to mammals. However, bird sleep has many characteristics that are different from mammalian sleep. For instance, great frigatebirds can sleep during long flights. Their sleep time during flight is much less than when they sleep on land. Moreover, they can keep their trip by asymmetric and even single-hemisphere sleep when they have to fly over the ocean for several days [13]. In recent years, many new characteristics and regulating mechanisms of sleep have been found in birds.

After a long flight, birds can regulate their sleep time by the homeostatic mechanism [13]. Nevertheless, the asymmetric sleep cannot compensate for the need for sleep for birds. Sjoerd et al. used high-density EEG recording to study the sleep of European jackdaws. They found that during the period of increasing sleep pressure and the beginning of sleep, birds have a lower proportion of asymmetric sleep, which indicates a balanced regulation between the necessity of alertness of surroundings and the need for sleep [14].

This trade-off mechanism is also embodied in clearing waste in the brain. In mammalian sleep, cerebrospinal fluid (CSF) is necessary to remove the toxic proteins accumulated during wakefulness. Meanwhile, Gianina et al. found that, compared with wakefulness, the flow of CSF of pigeons increases during the NREM sleep stage, which is quite similar to that of mammals. On the contrary, CSF flow will rapidly reduce when pigeons are in REM sleep. The switch of CSF flow demonstrates the presence of the trade-off regulation of pigeons between the extensive brain activation in REM and the waste clearance in NREM [15].

6. Sleep of non-avian reptiles (examples of lizards)

Non-avian reptiles are crucial in evolution because they share common ancestors with mammals and birds [4]. Therefore, sleep research in non-avian reptiles can provide significant clues for interpreting sleep's function and evolutionary origins. Among various non-avian reptile species, lizards are widely used to investigate the sleep of ectotherms, which show a distinct position during sleep, such as lying down, closing eyes and being static. According to recent research, two sleep states similar to REM and NREM, respectively, in mammals and birds have been found in lizards,

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which can be proved from the perspective of electrophysiology, such as local field potentials (LFP) [16]. This process makes further research on the sleeping structure of lizards even more meaningful.

The ectothermic characteristic of lizards has a significant impact on their sleep patterns. Nitzan et al. discovered that there are frequent transitions between rapid eye movement-like (REM-like) sleep state and slow wave sleep-like (SWS-like) state in rough-tail rock agama (Laudakia vulgaris), which was found by recording LFP from their dorsal ventricular ridge (DVR). The frequency of this periodic switch is significantly affected by temperature: an increase in temperature leads to an increase in the changing frequency, and a reduction in temperature results in a decrease in frequency. Interestingly, during the REM-like state, both the breathing rate and the amplitude of lizards are rising, which is different from that of mammals [17]. This study suggests that the two-state sleep is likely present in vertebrates. Additionally, the regulatory mechanisms related to this type of two-state sleep perform an evident difference. Lorenz and colleagues, through the electrophysiological recording of Pogona, found a continuous competitive relationship between two brain hemispheres during REM-like sleep, which fails to be detected in SWS-like sleep [18]. On the other hand, because the discovery of two-state sleep was based on the DVR LFP signal, this electrophysiology characteristic exists independently of the cortex. However, the cortex still plays certain regulatory roles in the sleeping process. Sena et al. discovered that the two-stage sleep of Pogona has a homeostatic regulatory mechanism similar to the compensation of sleep after sleep deprivation in mammals and birds. After a restriction of sleep, Pogona exhibited a significant rebound of LFP. Still, these enhanced signals would disappear with the cortical resection surgery, indicating a homeostatic mechanism and the effect of cortical regulation in two-state sleep [19].

7. Discussion

In biological evolution, sleep is a behavior that appeared relatively late. This review discusses the new progress of species that are of critical significance for researching the evolutionary origin and regulatory mechanisms of sleep. Among different species, the characteristics and patterns of sleep have tremendous differences. Even between mammals and birds, there are many changes in sleep regulation because of the huge differences in behaviors and habits. The causes for these differences are diverse, including sunlight and temperature, and exist between different species and individuals. Although it is challenging to clarify completely, comparing and analyzing the distinctions and potential factors play a crucial role in researching the evolutionary origin of sleep. To thoroughly understand the functions and regulatory mechanisms of sleep, it is necessary to analyse and compare the sleep patterns of different animals in-depth. The sleep functions and regulatory mechanisms of mammals, birds and non-avian reptiles share some homologous parts at certain levels with those of humans; thus, investigating their sleep can help humans comprehend the principles of sleep and apply them to relevant therapeutic areas. Finally, even though human beings have achieved many results in sleep research so far, there is still a vast space for further study about sleep's regulatory mechanisms and evolutionary origins. Therefore, enhancing the comprehension of sleep in extensive species regarding sleep characteristics, functions, and mechanisms is of great significance.

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