Proceedings of the 5th International Conference on Modern Medicine and Global Health
DOI: 10.54254/2753-8818/2027.37766

The Biological Mechanisms Behind Northern Elephant Seals' Extreme Sleep Deprivation During Long Marine Voyages

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Abstract. Northern elephant seals (Mirounga angustirostris), as lung-breathing mammals, have to voyage in the ocean while sleeping only about two hours per day. This creates an apparent conflict between their physiological needs of sleep and the ecological demands of feeding and surviving. This review synthesizes behavioral, physiological, cellular and comparative evidence to evaluate how such extreme sleep restriction may be tolerated for months. Direct electroencephalographic recordings show that elephant seals place short episodes of bilateral slow-wave sleep and rapid-eye-movement sleep within deep drift dives, preserving both major sleep states within a highly compressed sleep budget. Recent studies further suggest that sleep time can be reallocated according to elephant seals' current body conditions. At the cellular level, their endothelial cells can rapidly activate hypoxia-response and glutathione pathways, while comparative studies of hooded seals reveal an unusual neuronal hypoxia tolerance that may be shared as well in the elephant seals. Together, these findings support a layered-resilience model that elephant seals likely have used and provide a new perspective people can take when considering the lives of marine mammals.

Keywords: northern elephant seal, sleep ecology, slow-wave sleep, REM sleep, diving physiology

1. Introduction

As sleep is crucial in supporting neural plasticity, memory, metabolic regulation, and many other cellular maintenances, having enough sleep has the top priority for most mammals. Yet during sleep, the ability for a mammal to respond to external stimuli is also reduced. While such a trade-off is especially costly in an environment where the demand for traveling, feeding, avoiding predators, or even just breathing is high, northern elephant seals seem to provide an unusually powerful solution. Adults of northern elephant seals spend months foraging in the North Pacific, spending most of their time continuously diving for 8 months. During their journeys, they must keep a good balance between sleeping, acquiring energy, and survival.

Kendall-Bar et al. [1] proposed mechanisms that elephant seals used by analyzing their behavior and neurophysiology. Using a submersible system that combined electroencephalography (EEG), electrocardiography (ECG), and movement sensors, researchers recorded sleep states in freely

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diving seals. They then linked brain-state signatures to dive profiles and accelerometry from a much larger biologging dataset. Adult females were estimated to sleep approximately 2.2 hours per day at sea during the migrations, averaging about 217.7 days. Unlike dolphins or other ocean mammals that show unihemispheric slow-wave sleep (USWS), both cerebral hemispheres of elephant seals enter slow-wave sleep (SWS), and they drift spirally downwards during their rapid-eye-movement (REM) sleep.

These observations establish an interesting strategy, but they do not explain how such a state is maintained. Even though it is clear that elephant seals can successfully complete their navigations, how the sleep pressure is controlled at the molecular level, whether memory and attention remain unchanged across a whole migration, or whether there are delayed costs to synapses, immunity and waste clearance remains unknown. Therefore, this review synthesizes behavioral, physiological, cellular and comparative evidence to evaluate how such extreme sleep restriction may be tolerated for months.

2. Preservation of high-value sleep stages

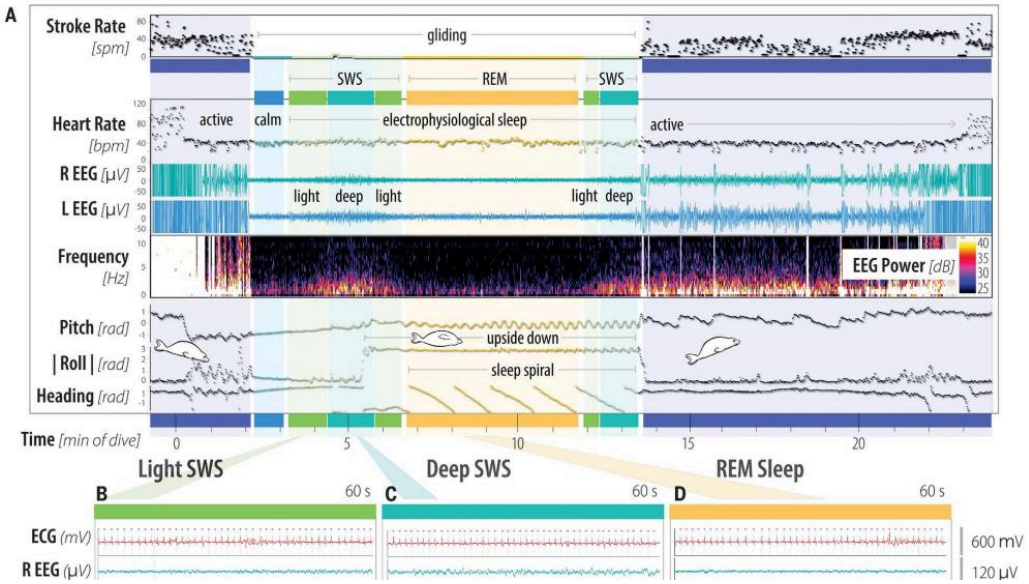

Figure 1. 3D drift dive sleep patterns. (A) A 23-min sleeping dive showing stroke rate [strokes per minute (spm)], heart rate [beats per minute (bpm)], left (L) EEG (mV), right (R) EEG (mV), L EEG spectrogram [power (dB) for frequency (Hz) over time], pitch (radians), roll (absolute value, radians) and heading (radians), and time (minutes of dive); (B) Raw EEG and ECG signals during the transition to light SWS; (C) deep SWS; and (D) REM [1]

The first mechanism is prioritization of sleep. While certain sleep stages play more important roles in maintaining bodily functions, ensuring the quality of these stages is often a fair trade-off, and elephant seals certainly take that deal. As shown in Figure 1, their sleep at sea is not a random collection of periods. EEG measurements show recognizable, bilateral SWS followed in some dives by REM sleep. In SWS, the animal begins a controlled drift, during REM sleep, postural control is reduced, and the seal will descend in a spiral, called a sleep spiral. Sleeping at depth can reduce exposure to surface predators, and the reduced need for oxygen also fits in the breath-hold cycle. Thus, the timing and location of sleep lower its ecological cost, while preserving important sleep

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stages like SWS and REM that cannot be abandoned entirely in order to maintain body functions [1].

On the other hand, preserved sleep stages do not necessarily mean that each minute of their sleep is more efficient and restorative than sleep in a terrestrial mammal. The available data do not yet show accelerated synaptic renormalization, enhanced metabolite clearance, or more efficient memory consolidation during the limited sleep elephant seals have. The interpretation from these data alone is narrower: that the high-value processes are preserved in elephant seals. The efficiency of those processes remains to be measured.

3. Flexibly gated sleep pressure

A second mechanism is flexible regulation of when sleep is expressed. In a simple homeostatic model, prolonged wakefulness produces steadily increasing sleep pressure until sleep becomes unavoidable. Elephant-seal behavior suggests that this pressure is integrated with energetic state and environmental risk. Adachi et al. [2] reported that seals in poorer body condition slept less and allocated more time to foraging. Results from Figure 2 suggest that as body condition improved, sleep duration increased while feeding effort declined. The result is a state-dependent time budget: an energy-deficient animal temporarily accepts less sleep to gain the resources that improve its later condition.

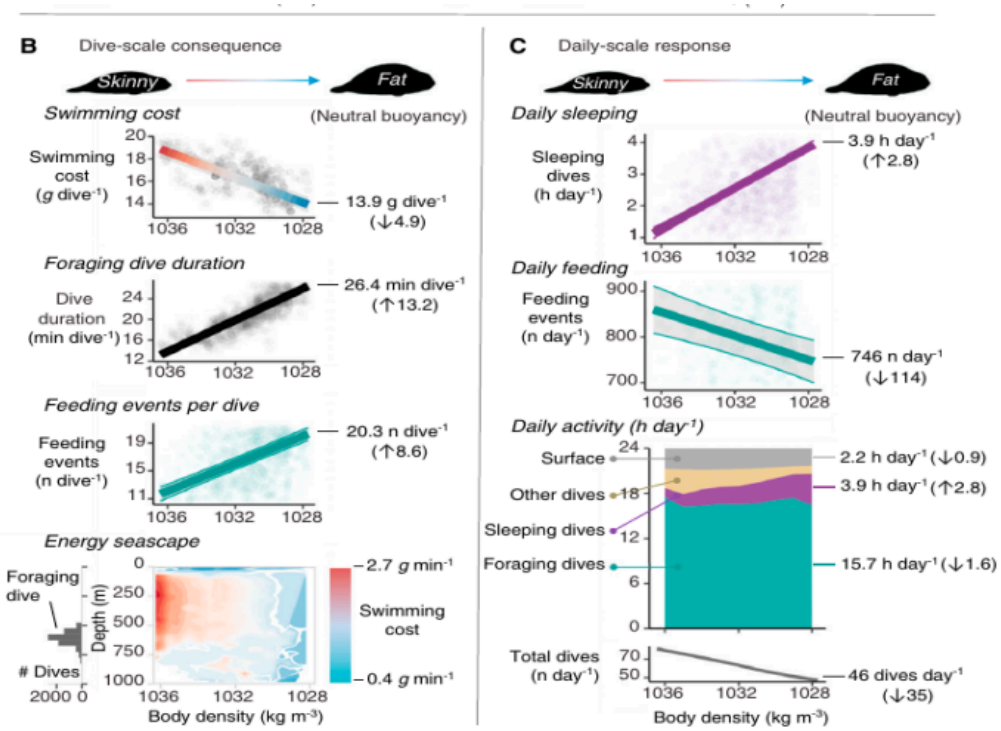

Figure 2. Relationships between body density (which is proportional to body fat percentage), sleeping behavior, foraging energetics, and daily-time activity budget. B. dive-scale consequence, C: daily-scale response [2]

This pattern should not be simply interpreted as the need for sleep being absent under certain circumstances. Instead, it indicates that sleep is flexible and gated. When the sleep pressure accumulates enough that it can no longer be ignored, the risk of hunger and predation can be permitted to meet the need for sleep, and vice versa. For example, a thin seal that preserves sleep at

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the expense of feeding may remain trapped in negative energy balance. A temporary reduction in sleep can therefore improve long-term survival even if it carries a physiological cost.

However, the molecular basis of this gating remains unknown. The field data do not identify how adenosine signaling, the circadian system, or other metabolic signals are altered during migration. The marked increase from approximately 2.2 hours at sea to 10.8 hours on land is consistent with ecological release from the marine time constraint, but it cannot by itself distinguish recovery sleep from a normal terrestrial sleep schedule.

4. Cellular protection during repeated physiological stress

The third mechanism is cellular protection. While available oxygen is limited in every dive, the cycle of hypoxia in the ocean followed by reoxygenation at the surface can create serious mitochondrial dysfunction in most terrestrial mammals. Elephant seals have the ability to repeatedly tolerate such arterial hypoxemia [3], suggesting that their tissues possess defenses against such stresses.

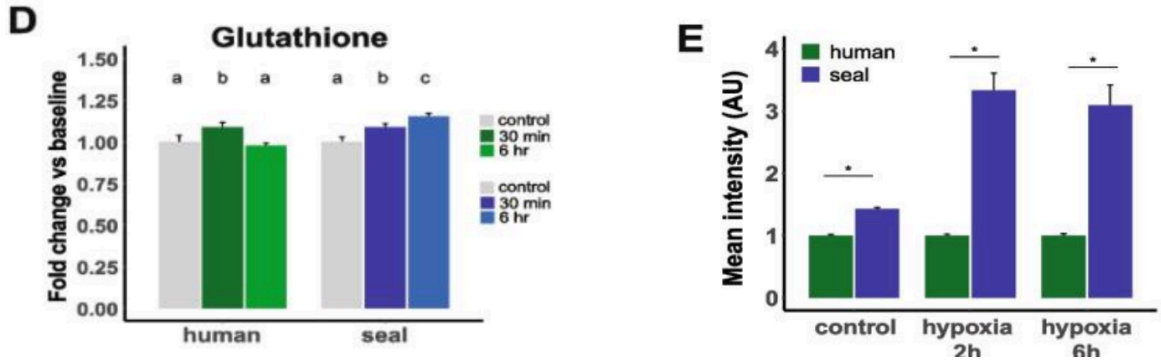

Figure 3. Concerted changes in gene expression in response to hypoxia exposure in seal cells: (D) glutathione, (E) ThiolTracker Violet fluorescence [4]

In the study by Allen et al. [4], they compared arterial endothelial cells derived from elephant seals with human endothelial cells under prolonged hypoxia. While glutathione is a major intracellular redox buffer and a cofactor for enzymes that remove peroxide waste from the liver, genes involved in glutathione synthesis were activated early in elephant seals. Figure 3 shows that the baseline glutathione content was about 1.4-fold higher in seal cells, and continued to increase and remained approximately threefold higher than in human cells during six hours of hypoxia.

Earlier in vivo work likewise showed two- to four-fold increases in glutathione during prolonged fasting in northern elephant seals, along with increased abundance of enzymes involved in glutathione synthesis [5]. Together, the studies suggest that elephant seals are prepared for this repeated cycle arising from diving. It is likely that elephant seals can also use this strong capacity to deal with prolonged wakefulness, as wakefulness can also increase oxidative stress, and being able to maintain high levels of glutathione will alleviate part of that burden.

5. Energy resilience of brain

A fourth potential explanation lies in the energy economy of the brain. Direct molecular experiments on the brains of migrating elephant seals are not presently available, so this part of the model relies heavily on other similar seal species. Hooded seals, as relatives of northern elephant seals, have their cortical neurons remain electrophysiologically active under severe hypoxia far longer than mouse

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neurons [6]. Hooded-seal brain tissue also shows greater glycogen availability and tolerance of low glucose and high lactate, indicating that they can maintain their neural function even when aerobic ATP production is reduced.

Hoff et al. [7] examined transcriptomic responses of hooded-seal cortical tissue slices under hypoxia and reoxygenation. Their study suggests that seal brains can remain active under severe hypoxia by downshifting parts of aerobic metabolism. The 4 mRNAs shown in Figure 4 are all encoded for the pyruvate dehydrogenase complex, which is required for oxygen-dependent mitochondrial metabolism. A drop in the expression of these mRNAs indicates a temporary shift toward anaerobic glycolysis in hooded seals, which is likely to be true as well in elephant seals.

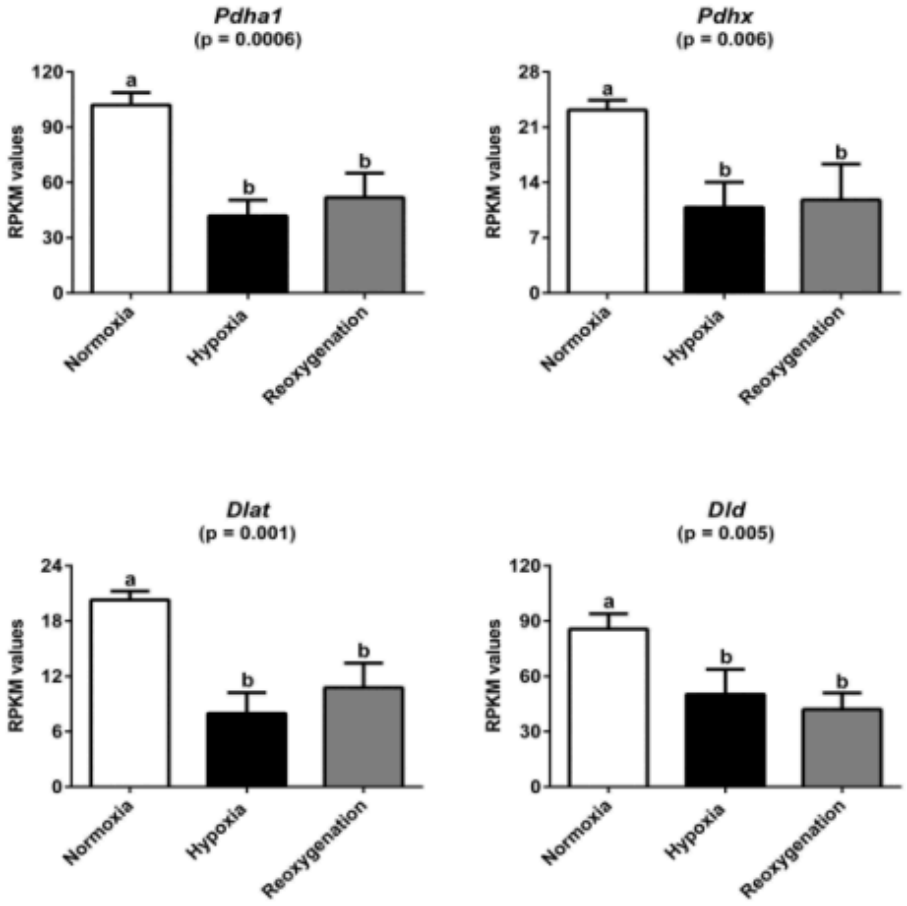

Figure 4. Expression levels of components of the pyruvate dehydrogenase (PDH) complex [7]

Behavioral evidence from northern fur seals offers additional evidence for the seal's high tolerance of prolonged wakefulness. In a study of three animals, 108 hours of total sleep deprivation did not worsen performance on visual tasks [8]. Although the small sample may not yield broad and solid conclusions, the results still suggest that seals' brains may not need as much sleep as humans' or other mammals'.

6. Conclusion

The most defensible conclusion is that northern elephant seals do not appear to solve their extreme sleep restriction dilemma through a single extraordinary mechanism. They achieve this through a layered-resilience model. They reduce the ecological cost of sleep by integrating it into deep dives.

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By preserving both SWS and REM within the compressed schedule, they seem to make the best use of their time. They have the ability to adjust sleep according to energetic condition in the short term, and possess diving adaptations that protect cells and conserve neural energy. Yet the central causal link remains open: no study has shown that these diving adaptations replace the long-term maintenance normally associated with sleep. To better test this model, more measurements that connect brain state to function across biologically meaningful timescales are still required. First, multi-day or multi-week EEG recordings should quantify slow-wave activity, sleep-stage sequence, microarousals, and changes in sleep intensity as migration progresses. Second, cognitive assays suitable for free-ranging animals are needed. Navigation accuracy, prey-capture performance, sensory discrimination, and memory proxies could reveal whether function is preserved uniformly or only in ecologically essential domains. As for now, although approximately two hours per day may not actually be universally sufficient sleep, it seems to be a good enough evolutionary compromise between sleeping, feeding, and staying safe.

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