INTRODUCTION

The need for sleep

Normal human sleep

Normal human sleep comprises two main types – non-rapid eye movement sleep (non-REM) and rapid eye movement sleep (REM).[1] Non-REM and REM sleep serve many physiologic functions and play many important roles for maintenance and restoration of the brain and body.[2, 3] Non-REM sleep is divided into three stages, representing a continuum from 'light' sleep in stages 1 and 2, through to 'deep' sleep in stage 3, or slow-wave sleep (Supplementary Figure 1).[4] Under the original classification system,[5] non-REM sleep was divided into four stages, with two stages of slow-wave sleep, i.e., stages 3 and 4. However, in the more recent, modified classification system,[4] non-REM sleep is divided into three stages, with the original stages 3 and 4 combined into a single stage of slow-wave sleep, i.e., stage 3.

Characteristics of sleep

The different sleep stages are distinguished from wake and from each other by characteristic patterns of brain activity, eye movements, and muscle tone, as assessed in the laboratory with polysomnography, electroencephalogram, electrooculogram and electromyogram measurements. However, from a behavioural perspective, sleep is defined as a reversible, naturally recurring state characterised by closed eyes, recumbent body position, reduced body movement, reduced responsiveness to external stimuli and a reduced breathing rate.[3] During non-REM sleep, the brain is relatively inactive, although it is actively regulating vital functions, and the body is movable.[1] In contrast, during REM sleep, the brain is highly activated, while the body is essentially paralysed.[1] It was originally thought that REM sleep was the only stage in which dreaming occurs, but it is now known that dreaming also occurs in non-REM sleep, albeit about half as often compared to REM sleep.[6]

Composition of sleep

The composition of normal sleep changes across the life cycle. In early-primary children, sleep is relatively long – at least 9–10 hours – and composed of a high proportion of slow-wave sleep; whereas in the elderly, sleep is relatively short – only 5.5–6.5 hours – and comprised of very little slow-wave sleep.[7] At the ages most relevant to aspiring and established elite athletes, an 8–9-hour sleep for an adolescent (aged 15 years) contains approximately 57% light sleep, 22% deep sleep, and 21% REM sleep; and a 7–8-hour sleep for a young adult (aged 30 years) contains approximately 61% light sleep, 16% deep sleep, and 23% REM sleep.[7]

Sleep and cognitive health

Until the late 1990s it was thought that chronic sleep loss led to increased sleepiness but had relatively little effect on cognitive function due to an adaptive response.[8] However, between 1997 and 2003, three seminal laboratory-based studies provided compelling evidence to refute this position. In these studies, sleep was restricted to (a) 5 hours each night for seven nights,[9] (b) 3, 5, 7, or 9 hours each night for seven nights,[10] and (c) 4, 6, or 8 hours each night for fourteen nights.[11] Together, these studies demonstrated that chronic sleep loss does impair cognitive function, particularly in sustained attention and response speed, and that the degree of impairment increases as the sleep dose decreases.

The repetition, or practice, of a task is a critical component of learning. Nevertheless, several studies have now shown that learning can also occur in the absence of practice, and that this process of practice-independent learning is enhanced by sleep.[12-14] In one of the early studies on this topic,[15] participants learnt a basic motor task (sequential finger-tapping) in the evening, then had a night of normal sleep or total sleep deprivation. In both cases, performance on the task improved when retested in the morning (increased speed and fewer errors) but the improvement was ~30% greater after a night of sleep compared to a night of wakefulness. Most importantly, it is now suggested that "it is practice, with sleep, that ultimately leads to perfection".[12]

With regards mental well-being, poor sleep increases discomfort, impairs mood, and reduces the capacity to cope with stressors. When sleep is deliberately restricted to 4 hours each night over 12 nights, optimism and sociability are reduced, while bodily discomfort is elevated due to increased back pain, stomach pain and general body pain.[16] During 1–2 nights of total sleep deprivation, mood is substantially impaired such that feelings of depression, anger, frustration, tension, anxiety and paranoia all increase.[17-19]

Sleep and physical heath

Human growth hormone is essential for the reproduction and regeneration of cells. The secretion of growth hormone is influenced by both the circadian system and the sleep/wake system. Under normal circumstances, these two systems work in concert, such that very little growth hormone is secreted during daytime wakefulness, and the majority of growth hormone is secreted at night, during non-REM, slow-wave sleep.[20] Sleep also plays an important role in the defence against inflammatory challenges, particularly for those at increased risk of infection.[21] At a molecular level, a week of short sleep (5.7 hours sleep each night), upregulated the expression of genes related to tumours, chronic inflammation, and stress and downregulated the expression of genes related to immune function.[22] At a broader level, when a vaccine is given before a night of total sleep deprivation, or during a week of severe sleep restriction (4 hours sleep each night), the antibody response is reduced by about 50%.[23, 24] Furthermore, when people were exposed to a 'cold' virus, those who averaged < 7 hours of sleep each night in the preceding two weeks were three times more likely to develop a cold than those who averaged > 8 hours of sleep each night.[25]

It was previously argued that a moderate level of sleep loss, i.e., 2 hours below the optimal dose of ~8 hours each night, does not have serious consequences for human physiology.[26] However, this view is changing as evidence of the consequences of chronic sleep loss, particularly for the cardiometabolic system, grows. For example, when sleep is restricted to ~4–5 hours each night, the capacity to process glucose is impaired,[27, 28] hunger is stimulated,[29, 30] and vascular inflammation is increased.[31, 32] Furthermore, the epidemiological data indicate that these types of effects may eventually lead to adverse health outcomes. For example, habitual sleep durations of 5–6 hours each night, independent of other lifestyle factors, are associated with higher rates of type 2 diabetes,[33] obesity,[34] cardiovascular disease[35] and respiratory infection.[25] Perhaps for these reasons, many studies have shown that habitual short sleep duration is associated with increased mortality risk.[36]

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Measuring sleep

With the increasing popularity of measuring sleep within both medical and consumer fields, unsurprisingly, the number of sleep measurement tools is rapidly increasing (Table 1). Some of the more common measurements regarding sleep include: sleep architecture (sleep staging), sleep duration, measured or estimated sleep efficiency (quality), sleep onset latency (SOL: time taken to fall asleep) and wake after sleep onset (WASO). Tools to measure sleep can be divided into several primary categories including: polysomnography, activity monitoring (including research grade and consumer wearables), smartphone applications and nearable devices (designed to be placed on or near the bed, hence 'nearable'), sleep diaries and questionnaires. A brief description of each of these categories is included below and has been comprehensively reviewed elsewhere.[37]

Polysomnography

Polysomnography is considered the gold standard of sleep monitoring and typically includes an assessment of eye movement, brain activity, heart rate, muscle activity, oxygen saturation, breathing rate and body movement.[38] Polysomnography allows for the determination of REM and non-REM. As polysomnography can be an expensive, obtrusive and complex technique, it is typically utilised for the assessment of sleep disorders or in research studies. In addition to traditional polysomnography, there are an increasing number of commercial devices that use modified versions of polysomnography to record at-home sleep.[39] These are different from true ambulatory polysomnography units in that they do not collect the full montage of signals, typically employing a small number of electrodes (1–2 in most cases, often as part of a portable headband). These devices have shown utility at collecting objective sleep data, but in most cases they are preliminary and are not as well-validated as in-lab recordings. In the case of athletes, who may not be able to come into a laboratory, these may be a viable alternative.

Activity monitoring

Activity monitors are wearable devices that record movement,[40] with most utilising a 3-axis accelerometer to determine sleep/wake based on a specific algorithm.[41] Currently, there are generally two classifications of devices – those that are considered "research-grade" and those that are considered "commercially-available." "Research-grade" devices have been subject to rigorous validation, and often have become scientifically accepted as a measurement of habitual sleep duration, timing, and continuity.[42] Research-grade activity monitors have been validated against polysomnography,[43] the algorithms utilised to quantify sleep and wakefulness are reported and, importantly, several of these devices have been validated in an athlete population.[44, 45] These devices are useful for longitudinal monitoring and are popular devices in both research and practice.[40]

Both research-grade and commercially-available activity monitors typically overestimate sleep duration relative to polysomnography (and underestimate relative to recall and sleep diary), underestimate awakenings and WASO relative to polysomnography (and overestimate relative to recall and sleep diary), and generally underestimate sleep latency relative to both polysomnography and sleep diary.[42] These discrepancies are larger in the case of sleep disorders, including insomnia. Further, these devices typically perform poorer in those individuals with fragmented sleep (higher amounts of wakefulness), as the deficiency in these devices is related to their ability to detect wakefulness.[40] These discrepancies may not always reflect inaccuracy; rather it may be the case that different methodologies for measuring sleep capture different aspects of sleep-wake regulation. Despite these discrepancies, activity monitoring is considered to be a valid and reliable method for evaluating sleep-wake rhythms in free living settings.[46] Recent reviews of commercially-available devices suggest that they can be useful for monitoring sleep,[41, 47, 48] including in athlete populations,[49] but this depends on the quality of the data supporting each device.[43, 50, 51]

Nearables and smartphone applications

One subset of nearable devices is placed on the mattress and measures movement and other physiologic signals of the individual lying on the bed (typically using ballistocardiography).[52, 53] Currently, validation of available devices is sparse, little is known about the algorithms used, and these devices are not very accurate for measuring sleep.[54] Another type of nearable device sits at the bedside and detects movement and physiologic signals of the individual lying on the bed. Similarly, this technology shows promise for detecting sleep and wake,[55] but there is still a relative lack of supporting validation for available devices.

Consumer-targeted smartphone applications (apps) use motion detection, audio and/or video recording as well as questionnaires[56] for sleep assessment and self-management.[57] In general, smartphone apps are poor at determining sleep stages and sleep parameters[41] and researchers have little room to influence or access raw data.[58] Readers are directed elsewhere for a comprehensive review of current smartphone applications for sleep assessment and self-management.[57]

Sleep diaries

Sleep diaries can be a simple and cost-effective means of assessing sleep and typically include: bed and wake time, lights-out time, daytime napping, ratings of sleepiness and alertness, caffeine and alcohol intake, exercise and light emitting device use[59] for a duration of at least one week. One example is the consensus sleep diary that resulted from the collaboration of a team of sleep experts.[60] Limitations of sleep diaries include recall bias and response expectation.

Sleep questionnaires

Questionnaires are often utilised for screening purposes or an initial assessment of sleep due to their ease of administration and low cost. Common questionnaires in insomnia research include: the Pittsburgh Sleep Quality Index (PSQI) to assess sleep quality,[61] the Sleep Hygiene Index to assess sleep hygiene,[62] the Leeds Sleep Evaluation Questionnaire to assess various aspects of sleep and early morning behaviour[63] and the Epworth Sleepiness Scale[64] to assess daytime sleepiness. However, these questionnaires have not been validated for athletes. Athlete specific questionnaires include the Athlete Sleep Screening Questionnaire[65, 66] and the Athlete Sleep Behaviour Questionnaire.[67] Similar to sleep diaries, while questionnaires may be time and cost effective, response biases may exist.

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In summary, there are increasing options for scientists and athletes to monitor sleep, with some devices (primarily consumer sleep technology) having some limitations in their assessment of sleep and wakefulness. Consideration should be given to whether or not the devices are validated, and an assessment is required as to the usefulness and appropriateness of utilising unvalidated technology. Some devices may provide some basic level of sleep awareness and education; however, individuals should be cognisant of the limitations of available means of monitoring sleep. Table 1 provides current information on sleep monitoring tools with respect to their validation for detecting sleep.

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Figure Legend

Supplementary Figure 1. Examples of sleep stages (hypnograms) in healthy, young adults spending 9 hours in bed – showing wake, rapid eye movement sleep (REM), and the three stages of non-rapid eye movement sleep (non-REM), i.e., N1, N2, and N3. Panel A shows a normal sleep – it has alternating periods of non-REM and REM, most deep sleep (N3) occurs in the first third of the night, and most REM occurs in the last third of the night. Panels B, C, and D show sleep with longer than normal periods of wake at the start, middle, and end, respectively.

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