A personalized sleep quality assessment mechanism based on sleep pattern analysis

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Abstract

Most sleep management systems lack reliable assessment of sleep quality and receive single information source only. In this paper, we proposed a sleep quality assessment mechanism based on the physiological sleep pattern with scenarios of multiple data sources. This mechanism provides an intuitive personalized sleep quotient which encourages users to have long-term usage of sleep management service. It further helps users to understand their sleep patterns and adjust sleep habits. In addition, sleep medical professionals can strengthen the diagnostic judgment with this assessment mechanism.

Keywords — Sleep management service; Quality assessment, Sleep stage; Sleep quotient.

1. Introduction

Human being spend nearly one-third of lifetime sleeping. Sleep makes profound impact on people's lives. As the rapid development of sleep medicine in last thirty years, sleep physiology researchers found that sleep is highly related to the brain and body functions. Adequate sleep is the premise of good health. However, more and more people have sleep problems because of work stress, fast-paced life, changes in lifestyle, etc. An investigation of Taiwan Society of Sleep Medicine shows the prevalence of chronic insomnia in 2006 was 11.5%, and doubled to 21.8% in 2009. Because of the complexity of sleep disorders involving many physiological and psychological factors, patients suffering from sleep disorders may visit sleep laboratories multiple times for diagnosis and treatment. Sleep clinic is expensive to operate due to lack of experienced sleep technologists and high-price instruments. In addition, most people may feel discomfort of falling asleep in an unfamiliar environment, resulting in lower availability of test results. High medical expenses as well as poor measurement results are the major obstacles to the development of sleep clinic[1-3].

There are also service providers develop health-related applications with technological assistance (such as Internet and embedded computers) to help the medical industry. These medical and health services and applications are expected not only support lifelong health records management, but also provide real-time analysis to mine the hidden information and predict future illness. These systems and applications can help users to build up their heath profile. When visiting a doctor, users can share recorded health information with medical professionals. The quality of treatment and diagnosis will be enhanced. As sleep medicine receive increasing attention, many sleep related services and instruments have been proposed and developed. Although these services provide fundamental sleep data recording, they are still far away from the goal of self-management. Only few services provide simple sleep pattern analysis to show the details of sleep. The analysis result generated from incomplete data and imprecise analysis lead users to have wrong perception of their sleep. The suggestion of sleep adjustment will not be helpful to users. Our research proposes a sleep quality assessment mechanism based on physiological significances of each sleep stage. This assessment mechanism will provide users an intuitive sleep quotient for sleep quality, and thus attract users to prolong the use of sleep management services.

This paper includes five sections to describe the design and implementation of the proposed sleep quality assessment mechanism. Next section introduces the background of sleep pattern, such as the structure of sleep cycle. In the third section, we introduce the sleep assessment mechanism which quantifies the quality of sleep into a numeric value called Sleep Quotient (SQ). The higher the value of the SQ reflects the better quality of sleep, and vice versa. SQ offers

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users an intuitive insight into their sleep through the sleep pattern analysis. Fifth section discusses the meaning of assessment mechanism and verifies the correctness of the schemes with real users' data. With the sleep quotient, users can quickly and intuitively understand the meaning of their sleep behavior, and adjust their lifestyle accordingly. Finally, we summarize the research and discuss further work.

2. Sleep

Sleep is an essential relaxed state of most animals including mammal, birds and even invertebrates. Humans replenish the physical and psychic energy quickly during sleep. Sleep involves both brain and body functions. Sleep not only restores energy and physical strength, but also strengthens cognitive abilities including judgment, memory and logic reasoning. Sleep enhances physiological regulation like immune system and metabolic regulation. Lacking of sleep will make people feel somnolent in daytime, and may cause many physiological and psychological problems. If drivers do not have enough sleep, they may be too slow to respond to when a sudden event. Recent research shows that sleep deprivation in rats will result in death in three or four weeks. These facts show how important sleep is.

Since sleep accounted for one third of human's life, it have a great impact on our livings. Adequate and regular sleep is necessary for survival and staying healthy. Everyone should put more attention on maintaining good sleep. Evaluation of sleep should not just on total sleep time; the quality of sleep must also be taken into account. Realizing the overall structure of sleep is helpful on designing a proper sleep quality evaluation mechanism.

When people fall asleep, their sleep pattern repeats in cycles. A sleep cycle can be divided into the two phases namely Rapid Eyes Movement (REM) sleep and Non-Rapid Eyes Movement (NREM) sleep. The American Academy of Sleep Medicine (AASM) defines three stages of the NREM sleep based on different physiological measures such as the brain waves. Each NREM stage shows its own physiological, neurological, and psychological features.

- Stage1 (N1): When people fall asleep gradually, they feel very relax. The ratio of the alpha waves (7 ~ 13Hz) will be reduced slowly in the brain over time, and theta wave (4 ~ 6Hz) began to appear and slowly increase its proportion. In this stage, sleepers may not feel that they fall asleep, and can easily be awakened to the surrounding environment.
- Stage2 (N2): In this stage, sleepers' brain wave is very similar to Stage N1 except the increasing proportion of theta waves. Spindles wave and K-complexes wave appear in sleeper's EEG measures. People will dream in this stage occasionally. They will have no eye movement and are still vulnerable to be awakened because of the interference of the surrounding environment. N1 and N2 are collectively referred to as "light sleep".
- Stage3 (N3): N3 stage is also called Slow-Wave Sleep (SWS) or deep sleep. At this stage, the possibility of dreaming is higher than other two stages of the NREM sleep. Sleepers' body will be completely relaxed and difficult to be awakened. This is an important stage for energy restoration.
- REM sleep: Criteria for REM sleep is rapid eye movement as well as low muscle tone (REM Atonia), low-voltage brain waves. In REM sleep, the activity of brain is quite similar to wakefulness. Most memorable dreaming occurs in this stage. In humans, people often turn over or change positions during this stage. Some researchers believe that we stabilize procedural memory and spatial memory during REM sleep [1], but others have found that lack of REM sleep does not cause significant impairment of memory.

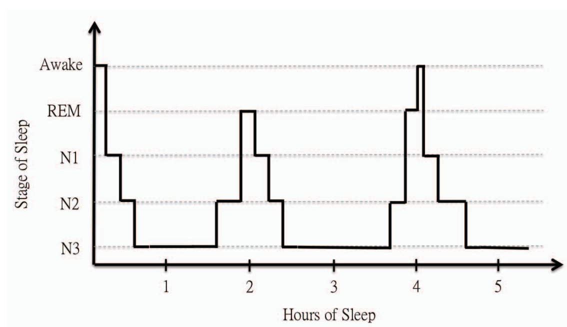

Fig. 1 Sleep Stage of Normal Adult

The change of sleep structure is significant in human's life: there are more in REM and deep sleep in infancy; with the growth and development, sleep structure formed a regular sleep cycle gradually, and REM sleep reduced in elders[2, 3]. An average sleep cycle of normal adult is 90 to 110 minutes[4]. As shown in the Figure 1, the order of sleep stage sequence of a cycle is N1→N2→N3→N3→N2→REM, and it will usually repeat 4 to 5 cycles during entire sleep process until waking up. People get deeper mental relaxation and recuperate physiological power in deep sleep and REM sleep. The proportion of deep sleep and REM sleep in total sleep time is more appropriate to reflect sleep quality.

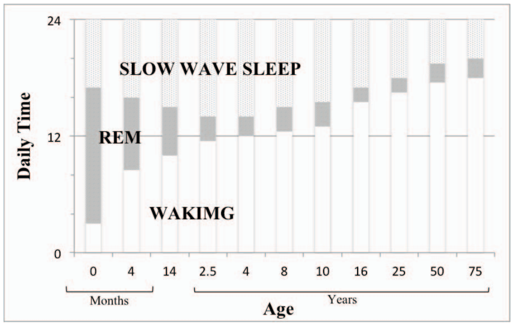

Fig. 2 Structure of Sleep Cycle with Ages

As the progressing of Sleep Medicine, the whole process and behavior during sleep can be monitored by instruments. The advancement of technology makes sleep measurements instruments smaller and lighter. Home-monitored devices such as Bio-alarm clocks[5], sleep manager (e.g. Zeo[6]) also becomes more common. In addition, many sleep related applications on smartphones (e.g. iPhone or Android) are developed. These devices provide diverse selections for people and provide more objective data to users.

3. Sleep quality evaluation mechanism

Data collection is a critical factor in personal sleep management services when design the sleep quality assessment mechanism. An ideal sleep service should integrate multiple data input from different sources such as individual medical information (e.g. hospital medical records) in order to provide complete and accurate personal sleep summary and medical history. The common data sources for sleep monitory can be classified into two categories: subjective and objective. Most of the subjective information, including self-estimated declarative description or quantitative values, is gathered from sleep diary or sleep questionnaires. Although the subjective data is widely used for long time, it is hard to deduce a credible sleep quality assessment result due to its inaccuracy and ambiguity. Objective data may be well-define values or meaningful results including physiological signals detected by medical equipment or home-monitoring devices, such as brain waves, body tremble and other sleep-related indicators (e.g. REM sleep duration, awakening times). The major objective data source includes patient-entered information, care providers' record, home-monitored devices data, medical equipment data, or the medical records.

3.1. Formula with sleep cycle identifier devices

Since the advancement of technology, many of the original bulky instruments become lightweight and more accurate. Today, lightweight sleep devices, including mobile devices detecting body movement using acceleration sensors, home monitoring equipment (the Zeo, etc.) or other sleep-related instruments, are used to monitor physiological characteristics of sleep stages. These objective parameters about their own sleep cycle can be used to generate an evaluation quotient as an index for present the quality of sleep.

Users using sleep devices to monitor sleep state can collect the information of sleep pattern. The quality of sleep depends on the percentage and long of REM sleep and deep sleep according to sleep physiology as the deeper understanding of sleep. The design of sleep quality assessment mechanism follows the principle of this physiological characteristic. Zeo Inc. has already developed an evaluation method to help their users to understand the quality of sleep every night, called ZQ[6]. ZQ has been already considered the impact of sleep physiology. ZQ is defined as followed:

$$\mathrm{ZQ} = \{(\mathrm{TST}\times 1 + \mathrm{DST}\times 1.5 + \mathrm{RST}\times 0.5) - (\mathrm{TIW}\times 0.5 + \frac{\mathrm{ATS}}{15})\}\times 8.5 \quad \text{-------}(1)$$

ZQ quantifies the sleep quality as a numeric value. It has taken both positive factors improving sleep quality and negative factors deteriorating quality into account. ZQ weights the three positive factors with different proportion of weighted values: total sleep duration (TST), the total length of deep sleep (DST) and the total REM sleep time (RST). Then, ZQ deducts the two harmful parameters for sleep: the total awaken time (TIW) and awakening times (ATS). Eventually, the final ZQ value are produced after multiplied an optimal average sleep time of 8.5. For example, a user has an eight hours sleep one night. This user also learn that his total deep sleep time is 1.5 hours and total length of REM sleep is 1 hour from the measurement of the instrument; he awakes 3 times during the entire process of sleep and the total time of awakening is 15 minutes. Based on this assessment formula calculation, ZQ value of this user is 89.

Zeo provides a relative credible sleep quality analysis than most devices; nevertheless, ZQ has an obvious bias: it depends excessively on the optimal average sleep time. ZQ ignores the fact that people's sleep structures are not same. It only uses an idealized average value to assess the sleep quality for all users. If a person is a short sleeper in natural, that user will get a lower ZQ because his total sleep time is less than optimal average sleep time. These miscalculated evaluations quotients will reduce the confidence of ZQ. In order to solve the bias of the assessment formula of ZQ, we add a new parameter, the personalized optimal sleep time α_p. We multiply the formula by optimal average sleep time α_{avg} (ZQ assumes α_{avg} is 8.5) and divide by α_p. All factors, TST, DST, the RST and TIW, are multiplied by their own weighted value $\mathcal{W}_{TST}$, $\mathcal{W}_{DST}$, $\mathcal{W}_{RST}$ and $\mathcal{W}_{TIW}$. Zeo has already analyzed mass sleep information from their database DOZER, and set each weight value a specific proportion. In our sleep quality assessment model, we adopt this proportion: $\mathcal{W}_{TST}:\mathcal{W}_{DST}:\mathcal{W}_{RST}:\mathcal{W}_{TIW} = 1:1.5:0.5:0.5$. So we rewrite the assessment formula as follows:

$$\mathrm{SQ_{obj}} = \{(TST\times\mathcal{W}_{TST} + DST\times\mathcal{W}_{DST} + RST\times\mathcal{W}_{RST}) - (TIW\times\mathcal{W}_{TIW} + \frac{ATS}{\alpha_{ats}})\}\times\alpha_{avg}\times\frac{\alpha_{avg}}{\alpha_p}$$

Finally, we can express this mechanism after simplification as follow:

$$\mathrm{SQ_{obj}} = \{(TST\times\mathcal{W}_{TST} + DST\times\mathcal{W}_{DST} + RST\times\mathcal{W}_{RST}) - (TIW\times\mathcal{W}_{TIW} + \frac{ATS}{\alpha_{ats}})\}\times\alpha_p \text{ ----- (2)}$$

where
$$\begin{cases} \mathcal{W}_{TST} = (\frac{\alpha_{avg}}{\alpha_p})^2 \\ \mathcal{W}_{DST} = (\frac{\alpha_{avg}}{\alpha_p})^2\times 1.5, \\ \mathcal{W}_{RST} = \mathcal{W}_{TIW} = (\frac{\alpha_{avg}}{\alpha_p})^2\times 0.5 \end{cases}$$

3.2. Formula without sleep cycle identifier devices

User are difficult to learn their objective data such as sleep cycle and other information when only adoption subjective input to record their sleep. Sleep diary is currently the most widely used subjective sleep information gathering tool, which mainly used to help users to record the vast majority of information can be subjectively aware during sleep. It includes sleep related information; self sleep hygiene, and several daytime mood estimates. Sleep diary is not only used in the academic field, physicians also use it in sleep clinic to get the insight of patient's lifestyle or assess treatment effectiveness.

Compared the data from sleep diary with the sleep quality assessment quotient from objective data (formula (2)), subjective data lacks two parameters: RST and DST. Therefore, users only recording to subjective data cannot get their sleep quotient directly through the analysis of, sleep pattern. However, we can solve this problem from some statistical information. The Zeo Company has analyzed average users of all ages sleep information from their sleep database DOZER[7, 8] (see Table 1 and Table 2). Combining statistical information from DOZER and the sleep quality estimated parameter from sleep diary (sq); we can estimate the approximate RST and DST parameters.

$$\mathrm{RST_{avg}} \cong \mathrm{TST}\times\mathcal{P}_{\mathrm{age}}\times\frac{\mathrm{sq}}{\mathrm{sq_{max}}} \text{ ----- (i)}$$
$$\mathrm{DST_{avg}} \cong \mathrm{TST}\times\mathcal{P}_{\mathrm{age}}\times\frac{\mathrm{sq}}{\mathrm{sq_{max}}} \text{ ----- (ii)}$$

After bringing (i) (ii) into the formula (2), we can get the sleep quotient with subjective data:

$$\mathrm{SQ_{sub}} = \left\{ TST\times\mathcal{W}_{TST} + \left(\begin{array}{c} TST\times\mathcal{P}_{age}\times\frac{sq}{\mathrm{sq_{max}}}\times\mathcal{W}_{DST} + \\ TST\times\mathcal{P}_{age}\times\frac{sq}{\mathrm{sq_{max}}}\times\mathcal{W}_{RST} \end{array} \right) - \left(TIW\times\mathcal{W}_{TIW} + \frac{ATS}{\alpha_{ats}}\right) \right\}\times\alpha_p \text{ ----- (3)}$$

4. Discussion

With different data sources scenarios and formulas, users will get different sleep quotients. In this section we apply four different ages, genders and sleep architectures recorders' information into ZQ formula and our sleep quality assessment mechanism, and then compare the results and discuss.

(1) Analysis of User A

Table 1. User A's one week sleep record

	Mon	Tue	Wen	The	Fri	Sat	Sun
	User A, 25 years old female, α_p=9						
TST	7.33	6.72	6.07	4.4	6.43	5.73	4.72
RST	1.76	1.62	1.32	1.2	2.48	2.72	0.83
DST	1.85	1.78	2.57	2.25	1.03	0.02	0.53
TIW	0.12	0.05	0	0.62	0.03	0.02	0.53
ATS	4	1	0	2	1	1	2
Sq	5	3	5	2	4	4	2

(except AST and sq, the unit of others fields are all hour in this table)

In Figure 4, we can find that the diagram of $\mathrm{SQ_{obj}}$ is close to the diagram of ZQ. According to Table 1, the personalized optimal sleep time α_p of User A is very similar to optimal sleep time α_{avg}. The parameter α_p of User A is slightly larger than α_{avg}, and then makes $\mathrm{SQ_{obj}}$ will be smaller than the ZQ. It reflects that sleep qualities this user gets are not as good as ZQ shown. The excessive overestimated quotients may be reduced to a more reasonable range to present the quality.

However, the quotient of $\mathrm{SQ_{sub}}$ is far smaller than the ZQ and $\mathrm{SQ_{obj}}$ results. After the observation of user's sleep information, it can be found that the proportion of total deep sleep time (33%) is much higher than the average range (15%). This results the former gap the between $\mathrm{SQ_{sub}}$ and other two quotients.

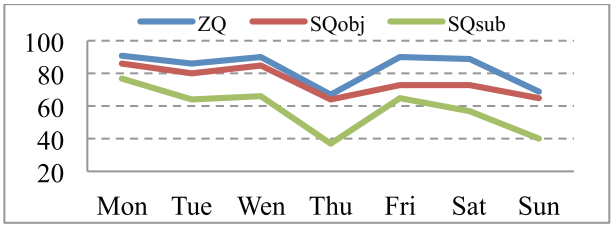

Fig 4. User A sleep quotient diagram

（2） Analysis of User B

Table 2. User B's one week sleep record

	Mon	Tue	Wen	Thu	Fri	Sat	Sun
	User B, 54 years old male, α_p=7						
TST	6.47	6.33	7.86	6.75	7.25	7.00	6.86
RST	1.80	1.63	2.40	2.40	2.35	2.43	2.48
DST	0.6	0.66	0.83	0.67	0.68	0.50	0.48
TIW	0.17	0.17	0.18	0.15	0.05	0.07	0.07
ATS	6	5	3	6	3	4	3
Sq	4	5	3	3	5	4	5
TST	6.78	7.20	6.83	6.45	6.90	7.32	6.80
RST	2.07	2.28	2.52	2.20	2.28	2.82	2.20
DST	0.43	0.75	0.77	0.70	0.58	0.55	0.67
TIW	0.25	0.15	0.02	0.12	0.03	0.03	0.07
ATS	7	6	2	4	2	2	4
Sq	2	5	4	4	3	3	4

（except AST and sq, the unit of others fields are all hour in this table）

As shown in Figure 5 and Figure 6, the personalized optimal sleep time α_p of User B is smaller than the optimal sleep time α_{avg}. User B only requires shorter rest time to restore energy, so the smaller ZQ scores convert to larger values. SQ_{obj} is larger than ZQ value. It shows this user has a better quality of sleep than other same age users.

SQ_{sub} is slightly larger than ZQ. Its reason for the differences can be found through observation of the raw data. The total REM sleep duration of User B (33%) is higher than the general average (22.7%). Therefore the sleep quotient value from subjective data is among formula 2 and ZQ value.

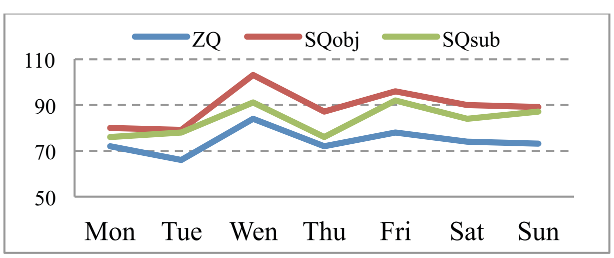

Fig 5. User B first week sleep quotient diagram

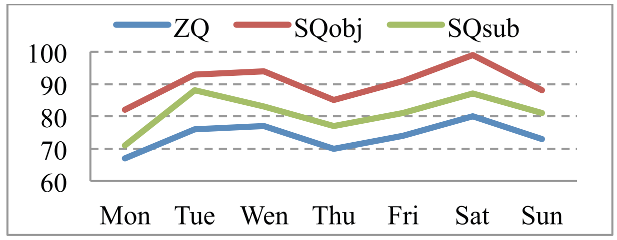

Fig 6. User B last week sleep quotient diagram

（3） Analysis of User C

Table 3. User C's one week sleep record

	Mon	Tue	Wen	The	Fri	Sat	Sun
	User C, 25 years old male, α_p=8						
TST	4.47	7.42	5.72	8.75	4.62	6.13	1.57
RST	1.43	2.12	1.78	2.38	1.28	1.38	0.23
DST	0.75	0.87	1.32	1.23	0.78	1.05	0.60
TIW	0.08	0	0.47	0.20	0.65	0.02	0
ATS	2	0	2	3	5	1	0
Sq	4	2	4	1	3	3	3

（except AST and sq, the unit of others fields are all hour in this table）

According to the data in Table 3, User C's α_p is slight smaller than optimal sleep time α_{avg}. We can find the diagram of SQ_{obj} is very close to the diagram of ZQ; his ZQ is almost equals to SQ_{obj} values. Besides, with the observation of User B's raw data, his total deep sleep duration (20%) is slightly higher than the general average percentage (14%). Therefore SQ_{sub} is lower than SQ_{obj} and ZQ.

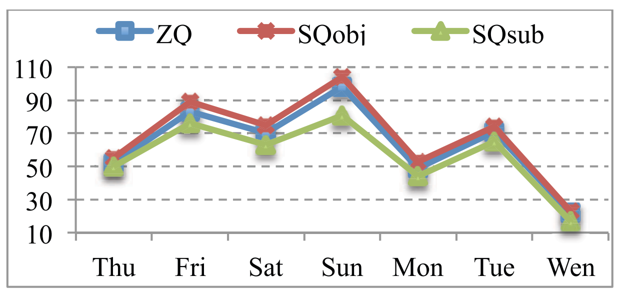

Fig 7. User C sleep quotient diagram

（4） Analysis of User D

Table 4. User D's one week sleep record

	Mon	Tue	Wen	The	Fri	Sat	Sun
	User C, 25 years old male, α_p=8						
TST	5.52	3.30	1.05	3.10	6.88	1.60	5.83
RST	1.48	0.45	0.30	1.90	1.78	0.13	1.46
DST	0.43	0.75	0.77	0.70	0.58	0.55	1.08
TIW	0.25	0.15	0.02	0.12	0.03	0.03	0.15
ATS	7	6	2	4	2	2	3
Sq	3	3	3	3	3	2	4

（except AST and sq, the unit of others fields are all hour in this table）

User D's sleep structure is very similar to User C, so his sleep quotient diagram is seems to resemble. (See Figure 8) The personalized optimal sleep time α_p of User D is very close to α_{avg}. User D's ZQ is consequently almost equals to SQ_{obj}. We can find the diagram of SQ_{obj} is very close to the diagram of ZQ. User B's total deep sleep duration (20%) is slightly higher than the general average percentage (14%), and his total REM sleep duration (27%) is also slightly higher than the general average percentage (24%). Therefore, SQ_{sub} estimated by the statistical average information is slightly lower than SQ_{obj} and ZQ.

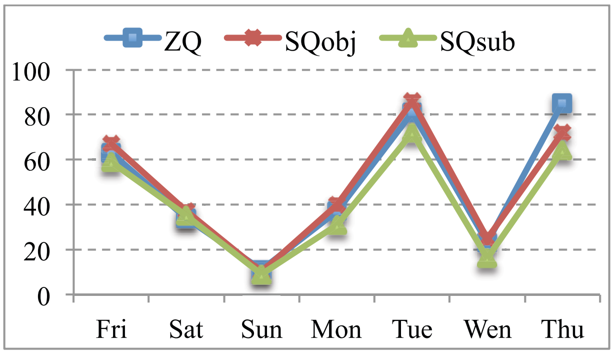

Fig 8. User D sleep quotient diagram

Through the validation of sleep information of four users, this sleep quality assessment mechanism solve the problem of over-reliance on via α_{avg} joining the parameter of personalized optimal total sleep time, α_p. At the same time, we consider multiple data scenarios into account. Users without sleep-monitoring devices can also have a more credible sleep quality assessment quotient.

5. Conclusion

Due to the rising of sleep medicine and personal health management services, sleep management services become increasingly popular. Most sleep services ignore the principle of sleep physiology and assess the quality of sleep with the total sleep time only, which resulting in poor quality assessment. In addition, multiple data sources scenarios should be considered when designing a sleep quality assessment mechanism. Sleep-related data are classified into subjective data and objective data.

Combined with the physiological impact of each sleep stage and data gathering scenarios, we propose an enhanced sleep quality assessment mechanism to provide a more intuitive and credible reference for users and subsequent researchers. With the popularity of home-monitored sleep device, integration of subjective and objective data further cut down the cost of sleep management and quality assessment. The comprehensive evaluation results may encourage users to use sleep management system and maintain their sleep profile. Sleep profiles provided additional reference information for sleep disorders diagnosis and treatment, and reduce health care costs.

The sleep quotient, SQ, proposed in this research is based on human's sleep architecture for personalized sleep quality assessment mechanism. Although the SQ-based assessment is verified with real data, current experiment cases are small. More users are expected in the future. The sleep quality assessment mechanism can be refined continuously through mining more sleep information from users with various profiles. With constant refinement of the sleep quotient mechanism, sleep services can provide more valuable sleep information to researcher in sleep science.

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