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Appropriate indoor operative temperature and bedding micro climate temperature that satisfies the requirements of sleep thermal comfort

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ABSTRACT

The thermal comfort theories in workplaces during the day are well studied, but research on the thermal comfort of sleeping environments at night is limited. The bedding micro climate has a greater impact on thermal comfort for subjects with bedding covers during the sleeping period compared with the indoor thermal environment. To investigate the effect of the bedding micro climate on sleep quality and thermal comfort during sleep under different indoor operative temperature and to obtain the appropriate indoor operative temperature and bedding micro climate temperature that satisfies sleep thermal comfort, the mean skin temperature (MST) and bedding temperature (BT) of each subject during the sleep period were measured in this experiment. The thermal sensation vote (TSV) and thermal comfort vote (TCV) of pre-sleep, post-sleep and bed micro climate were investigated simultaneously. The results indicated that the thermal neutral temperature of pre-sleep and post-sleep TSV was 18.3 °C. The subjects' comfortable temperature ranges of pre-sleep and post-sleep TCV were 15.8 °C–20.6 °C and 15.8–18.3 °C, respectively. The operative temperature of 15.8 °C was thermally neutral and comfortable during sleep. A BT of 30 °C –30.8 °C was considered a comfortable temperature range during the sleep period, and the corresponding indoor operative temperature was 14.5 °C–17.5 °C. The subjects' TSV of bedding micro climate was neutral when the mean bedding temperature (MBT) was 30.4 °C.

1. Introduction

To date, thermal comfort in workplaces during the day has been well studied [1–3]. Examples of studies of thermal comfort in the literature include the establishment of models [4–6], experiments involving climate chambers [7] and field surveys [8,9], establishment of thermal comfort standards and evaluation methods [10,11], and the development of hybrid models [12]. However, research on thermal comfort for sleeping environments at night is limited. Human beings spend approximately one-third of their life sleeping. Sleep quality directly affects people's work efficiency and mental state. Higher or lower indoor temperature does not fully address sleep thermal comfort. Compared with the indoor operative temperature, the bedding micro climate has a greater effect on sleep thermal comfort with a body-covering quilt.

Yu Hibino et al. studied the thermal physiological response to local heating and cooling during sleep [13]. Hisako Fujii researched fatigue and sleep under large summer temperature differences [14]. Pan DM et al. numerically studied the microclimate around a sleeping person in a space installed with a displacement ventilation system [15]. They also studied the Performance evaluation of an air conditioning system with different heights of supply outlet applied to a sleeping environment [16,17]. Lan Li et al. proposed a bedside personalized ventilation system and found it could be used as a potential ventilation strategy to improve indoor air quality and thermal comfort in bedroom [18,19]. They also proposed the method for evaluation of sleep quality in thermal environment and observed significant effect of low indoor temperature on sleep quality of 8 human subjects in winter [20,21]. S.C. Sekhar studied thermal comfort and IAQ characteristics of naturally and mechanically ventilated and air-conditioned bedrooms in a hot and humid climate [22].

Different researchers carrying out experimental studies on the effects of high and low ambient temperatures on human sleep stages adopted different thermoneutral temperature in sleep in the range of 20 °C–32 °C [23–30]. Okamoto-Mizuno investigated the thermal sensations of subjects' different skin points both before sleep and on waking for each season, but the indoor temperature was not controlled [31]. Noel Djongyang et al. investigated sleep thermal comfort in the sub-Saharan Africa region. The results

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obtained indicated that the suitable monthly total insulation values for bedding systems in the dry-tropical regions range between 0.81 clo and 0.94 clo. The thermoneutral operative temperature ranges from 29 °C to 32 °C, while the thermoneutral air temperature ranges from 27 °C to 30 °C [32]. Kim DG and Kum JS determined that the appropriate indoor temperature was 24 °C–26 °C during sleep and that the highest temperature should not exceed 28.1 °C [33,34]. Li Pan [35] investigated the subjects' thermal sensation of pre-sleep and post-sleep by the method of subjective survey, considering the temperatures of 23 °C, 26 °C and 30 °C in the summer and 17 °C, 23 °C and 30 °C in the winter. The results indicated that the indoor environment TSV of post-sleep was lower than that of pre-sleep when the indoor temperature was the same. Li Pan proposed that the comfortable indoor temperature was 23 °C in winter and 26 °C in summer during the sleep period. However, the influence of bedding micro climate on human thermal sensation was not considered in the experiment.

With the necessity of reducing energy consumption, several authors interested to thermal comfort in indoor environments in the past decades [36]. The required lower indoor operative temperature is beneficial to reduce the heating system output and save energy. Chris Leung et al. found via numerical calculation that the operative temperature can be reduced to 15 °C to maintain sleep thermal comfort. A calculation of the peak heating day with the building characteristics was performed with reduced heating set points during sleep; up to 10% of the heating energy was found to be reduced [37].

When a person sleeps with a covering quilt, the bedding system insulates the human body from the indoor thermal environment. Therefore, sleep quality and sleep thermal comfort are more affected by the bedding micro climate compared with the indoor thermal environment [38,39]. If the indoor temperature is lower, then sleep thermal comfort can be satisfied by changing the thermal resistance of the clothes and quilts. Frederick et al. [40] studied the effect of the bedding system on sleep thermal sensation. The results indicated that the comfortable indoor temperature range was 21.2 °C–32.2 °C without bedding covers during sleep. The lower limit of the comfortable indoor temperature range was below 20 °C with bedding covers. In addition, they indicated that the bedding micro climate temperature was best when the human body MST was between 34.7 °C–35.6 °C.

Li Lan [41] investigated the effect of air temperature on sleep quality with subjective assessments and physiological measurements in summer. The results were obtained: the subjective sleep quality was lower at 23 °C or 30 °C compared with 26 °C. The subjects felt thermally neutral at 23 °C, slightly warm at 26 °C and warm at 30 °C in waking state, while they perceived it to be uncomfortably cool at 23 °C, slightly cool at 26 °C and warm at 30 °C for sleep. However, the bed climate was not investigated. Zhongping Lin [8] reported a theoretical study on thermal comfort for sleeping environments. A comfort equation applicable to sleeping thermal environments was derived by introducing appropriate modifications to Fanger's comfort model. Based on the derived comfort equation for sleeping environments, the relationship between the thermoneutral temperature and the total insulation value provided by a bedding system has been established. The comfort charts with different comfort lines have also been developed, and can be used for determining thermally neutral environmental conditions under a given bedding system. However, in the study of indoor thermal environment, particularly the thermal comfort assessment during sleep, performing a thermal comfort subjective survey was more practical than analyzing the results from a thermal comfort model [41]. A thermal comfort subjective survey can evaluate the thermal environment in a more accurate and reliable manner by considering the physiological adaptability and psychological satisfaction of the subjects. Subjectives' assessment is more reliable for evaluating the thermal environment than polysomnography records because it reflects human physiological adaption and psychological satisfaction with the surrounding thermal conditions. Therefore, a survey is a significant tool for the research of sleep thermal comfort.

In summary, the aim of this paper is to investigate the effect of the bedding micro climate on sleep quality and sleep thermal comfort under 5 indoor operative temperatures in winter. The appropriate bedding micro climate temperature and indoor operative temperature that satisfies the requirements of sleep thermal comfort were obtained. The most important result is that, when the indoor operative temperature and the bedding insulation value changes, as long as the bed temperature is appropriate can meet the demand of thermal comfort for sleep. In other words, it is a effective method to meet sleep thermal comfort by increasing bedding insulation value when the indoor temperature decrease. The results also have practical implications in achieving energy saving in residential buildings, where the indoor temperatures are usually kept to be unnecessarily high with air conditioner in winter. A higher indoor temperature may increase the energy consumption and reduce the sleep thermal comfort of human beings. Moreover, a lower temperature does not improve sleep thermal comfort. In this paper, the MST of subjects and BT during sleep were measured in the experiment. In addition, the TSV and TCV of the pre-sleep and post-sleep states and the bed micro climate were investigated. The methodology used in this research and the results and discussion are included in the following sections.

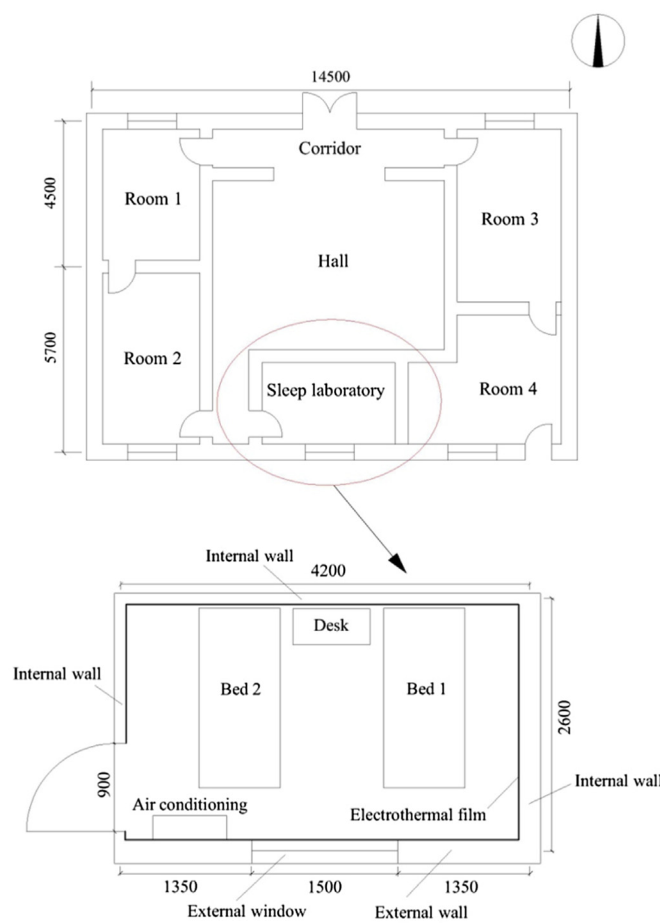

Fig. 1. The schematic of the climatic chamber.