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Temperature field of bed climate and thermal comfort assessment based on local thermal sensations

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ABSTRACT

Bed climate is an essential determinant in creating thermal comfort condition during sleep. This study explored the bed climate distribution and thermal sensations of different local body parts. The mean bed temperatures calculated from different measuring points were evaluated based on their sensitivity to the physiological parameter (mean skin temperature) and subjective quantification (thermal sensation vote). The results showed that the mean bed temperature around the middle part of the body (MBT_M) was most suitable for use in the study of sleeping thermal comfort. The bed climate was regularly distributed along with human body segments. To reach a whole body thermal comfort condition inside the bed climate, the deviations from thermal neutrality of different local body parts were obtained. In addition, the thermal comfort zone of indoor environment perceived on the face was wider than that on the covered body. People could be in thermal comfort state when they perceived cool on face, and the indoor temperature could be lower with a higher bedding thermal resistance.

1. Introduction

Sleep is influenced by the micro thermal environment around human body. When asleep, energy expenditure is reduced due to the supine position and lack of physical activity, and the core temperature is kept low [1–3]. The appropriate surrounding temperature yields an advantage for attaining and stabilizing the level of skin blood flow, and more importantly, maintaining physiological homeostasis through the thermoregulatory mechanisms [4–6].

Humans sleeping at high or low ambient temperatures exhibited different thermal sensations and sleep structures [7,8]. When people exposed to humid heat sleeping environment, increments in subjective discomfort and rectal temperature were observed [9,10], together with increased wakefulness and decreased slow wave sleep [11,12]. In order to avoid the excessive heat load during sleep, the design standards of air-conditioning and insulation values of bedding systems for sleeping environments were developed, especially in tropics and/or sub-tropics [13,14]. In cold environments, the wakefulness of people was increased, and the rapid eye movement sleep was decreased mainly due to the suppression of the thermoregulatory response, shivering, and body movements [15,16]. Besides, it is reported that cold environments were more disruptive to sleep than warm ones [17]. Both sleep and cold exposure affected cardiac autonomic activity [18], which may have a significant impact on health. Therefore, sufficient information about the thermal requirement of sleeping body under cold ambient environment should be obtained.

In most cases, people sleep with bed coverings, especially in cold environment. Although the indoor thermal requirements for sleeping might varied from season to season [19–21], appropriate usage of bed coverings might weaken the difference in sleep parameters among seasons. Besides, it was safe for the organism to fall asleep if the sleep-appetitive behaviors of lying down and covering up are fulfilled [22].

In general, the bed climate is naturally formed by the person sleeping inside or manipulated with devices. As for the former case, the bed climate is mainly affected by the body biological character, the ambient environment and the bedding system conditions. Different researchers carrying out experimental studies about the effect of bed climate on human sleep adopted different thermo-neutral bed temperature in the range of 26 °C–36 °C [23–27]. However, it has reached to an agreement that the bed temperature tends to be more steady with the varying ambient temperature. A pilot study about the bed climate reported that the temperature between the sheets of an occupied bed was generally between 27 °C and 29 °C within a few inches of the body [28]. Macpherson

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et al. reported that the bed temperature throughout the night was very consistent and never far from 28 °C in both summer and winter [29]. It was also found that the bed climate temperature varied from 28.6 °C to 30.9 °C while the ambient temperature varied from 16 °C to 25 °C [30]. In a study about the effects of different seasons on sleep and skin temperature in subjects' homes [31], it was indicated that subjects maintained a stable bed climate temperature of 32–34 °C in autumn and winter. According to an investigation about the infant's bed climate of different seasons (spring, summer, and autumn) in Japanese, the bed temperature at the back and foot of the bedding was about 36.0 °C among the three seasons without significant difference [32]. The non-conformance of the recommended bed temperatures above could be mainly attributed to the difference in physiological features of subjects, inconstancy of bed covering conditions, and more importantly, the diverse measuring points of bed climate. To prevent pressure ulcer, measuring points of the bed climate have been mainly focused at the back, pelvis, and foot of the bedding. However, research on the design of thermal comfort in the bed climate during sleep is limited.

For bed climate manipulated with assistant devices, a sleep-permissive condition is created by improving the thermal perception of human body. For example, mild bed warming (without affecting skin temperature) could promote the sleep onset in a cool environment, because the skin temperature of the distal and proximal parts were manipulated [33,34]. Therefore, the thermal requirement of local body part has great implication for the development of comfortable sleeping environment.

The purpose of this study is to investigate the temperature distribution of the bed climate and the thermal comfort condition of different body parts. A field measurement was conducted in a residential house in winter, where the thermal environment was more accurate to real-life than in our previous laboratory study [35]. The mean bed temperatures calculated from different measuring points were evaluated based on their sensitivity to the physiological parameter of mean skin temperature and subjective thermal assessment. The key findings of the current work is that, the local body parts were deviated from thermal neutrality to different extents in order to reach a thermal comfort condition for the overall covered body. In addition, the comfort zone of the ambient temperature perceived on the face was wider than that on the covered body with the thermal resistance applied in this experiment.

2. Materials and methods

2.1. Subjects

6 male and 6 female postgraduates (mean ± SEM of age: 23.4 ± 0.4 years, height: 165.3 ± 1.9 cm, weight: 55.8 ± 2.0) participated in this study. All the subjects had regular sleep-wake daily cycles and were in good physical condition. Moreover, subjects were required to refrain from vigorous activity and excitant food such as alcohol and caffeine drinks during the day before the experimental night. The experimental procedure and subjective questionnaires were detailed explained to the participants in advance.

2.2. Conditions

The experiment was performed in a residential house without heating system in a consecutive period of time in winter in Northwest China, as shown in Fig. 1 and Fig. 2. During this period, the outdoor meteorological parameter and indoor temperature varied in a small range for each experimental thermal condition. In addition, electric heating devices, such as air conditioner, were used to maintain the thermal conditions of the test room. When the thermal environment kept lower than expected, the air conditioner would be switched on with real time monitoring of the indoor thermal parameters.

The indoor operative temperature (t_o) was obtained according to the following equation:

$$t_o = \frac{h_c t_a + h_r t_{mrt}}{h_c + h_r} \quad (1)$$

where t_a is the indoor air temperature; h_r is the radiant heat transfer coefficient with a value of 4.7 W/(m^2·K) [36]. The convective heat transfer coefficient h_c was calculate by Equation (4) [37].

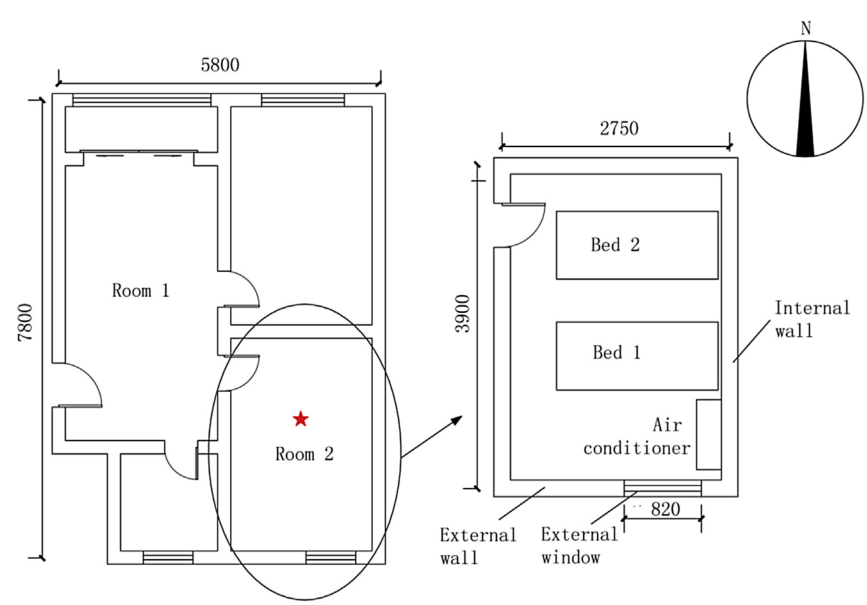

Fig. 1. Laboratory layout.