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Effects of Ondol Sleep Environment on the Thermo-physiological Response of the Human Body

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온돌 수면환경이 인체의 온열생리반응에 미치는 영향

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Abstract : The purpose of this study was to investigate actual sleeping environments in Ondol rooms depending on the season. The experiment was performed on five healthy women. The bedroom environments using Ondol were measured in five cases (three apartments and two houses). The environments in bedroom, bedding temperature, skin temperature and thermal sensation were measured continuously through the seven days for each season in real life. This data of sleeping environments were analyzed in the view of seasonal variations and housing types. Annual average bedroom temperatures: 26.2~31.0°C in apartments, 15.7~33.6°C in houses. Annual average bedroom humidity: 48.3~82.1% RH in apartments, 64.9~87.0% RH in houses. During sleeping, temperatures of contact surfaces like sheets and under quilts ranged between 30.5°C and 34.1°C regardless of season or housing type. Annual average rectal temperature was 36.8°C with no significant difference in season or housing type. In the point of thermal sensation, neutral temperature of the bedroom was 25.9°C in apartments and 20.3°C in houses. It was concluded that in spite of thermal environmental variations according to the seasons, skin, bedding and bedroom temperatures in apartments were better and more stable than those of houses. It is regarded that while houses are brick structured, apartments are steel-frame structured. Due to better insulation and air tightness, apartments were affected less from outdoor temperature and maintained higher room temperature than houses.

Key words : ondol, bedding temperature, thermal sensation, seasonal variation, housing type.

1. Introduction

In 84.9% of bedrooms in Korea, the bedding is laid on the Ondol floor (Jung and Sung, 1997). In this system, the floor is heated and then the heat is transferred from the floor to the entire room by the radiation and convection heat transfer mechanism. It is well-known that Ondol is a popular heating system which is quite effective in view of heating efficiency, and thus it is very comfortable and pleasant for the human body (Robert, 1985; Isoda *et al.*, 1986; Shon,1986). However, the problem is that there is a significant difference between the floor and the room temperatures due to the construction quality. Therefore, residents in an Ondol system can be affected significantly by room temperature and floor temperature according to their living patterns (Yoon and Choi, 1990). Though many researches about the Ondol system has been performed since 1980, most of it was focused on examining the response of the human body under the artificial climate chamber (Lee and Kweon, 1997, 1993; Yoon and Choi, 1990; Shon, 1986; Isoda, 1986). Only some of the research has been performed regarding the physiological response of the human body under the real bedroom temperature during daily life. But to define a systematical thermal environmental standard, it is needed to show the thermal environmental features by measuring the physical thermal environmental aspects and psychological and physiological reactions of the residents. To understand the real sleeping environments in Ondol rooms, bedding and room temperatures were measured, and physiological reactions during sleeping time were checked in real life surroundings. This data of sleeping environments was analyzed in the view of seasonal variations

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and housing types.

2. Materials and Methods

2.1. Subjects and clothing

The experiment was performed on five healthy women living in Taegu city. The mean (S.D.) physical characteristics of the subjects were at an age of 27.2 (3.63) years, height of 162 (1.41) cm, weight of 48.4 (2.19) kg, BSA of 1.44 (0.03) m^2 and a Rohrel of index of 113.80 (4.90).

Pajamas with one hundred percent cotton which are suitable for each season were used as the sleeping wear for the experiment. Constitution of clothes were brassiere, briefs and sleeping wear. Total weight of the clothing was 254 g in spring, 204 g in summer, 254 g in autumn and 456 g in winter respectively.

2.2. Experimental housing and bedding

The bedroom environments using Ondol were measured in five cases (three apartments and two houses located in Taegu city). The properties of the experimental housing are shown in Table 1. Among the variable factors of bedroom environment, floor temperature, room temperature and humidity were set up as conditions for this experiment. Accordingly, to reduce the effects of radiant heat from outdoors, the windows were not opened. As for whether or not to use a specific heating and cooling system, the experimental houses were heated as a whole using Ondol in winter, while partial cooling fans were used in summer. The most common types of bedding in Korean housing were used for the experiment considering the most representative seasonal climate conditions, as summarized in Table 2.

2.3. Procedure

The tests were performed four times for a week long period, which were in January, April, July and October. Those months were selected to verify the effect of seasonal change of temperatures, based on the last 30-year statistical results of the Monthly Weather Reports of Taegu city. The skin, rectal, bedding and bedroom temperature were measured consecutively during seven days for each season.

2.4. Measurements

The skin, rectal, bedding and bedroom temperature were measured with thermometers (Micro Data Logger, LT-8A, Nikkiso-Ysi Co., Japan). The humidity of the bedrooms were measured using a hydrometer (Thermo Recorder, TR-72, Hans System, Korea).

Table 1. Properties of experimental housing

Housing	Apartment			House	
	A	B	C	D	E
Floor-height	12	12	15	1	2
Location	nedangdong	susungdong	woelsungdong	samduckdong	sinarmdong
Structure	steel-flame structure	steel-flame structure	steel-flame structure	brick structure	brick structure
Living space(m^2)	141.9	115.5	107.3	99.0	115.5
Heating system	control heating	central heating	contral heating	individual heating	individual heating

Table 2. Specification of bedding

Season	Type	Material (cover/pad)	Size (cm)	Weight (g)
Spring	quilt	contton 100%/PET100%	170×200	2800
	sheet	contton 100%/PET100%(quilting)	140×200	1400
	mattress	contton 100%/contton100%	120×200	4000
Summer	quit	hemp 100%	170×200	800
	sheet	cotton 100%/PET 100%(quilting)	140×200	1260
	mattress	cotton 100%/PET 100%	120×200	4000
Autumn	quilt	cotton100%/PET100%	170×200	2800
	Sheet	cotton100%/PET100%(quilting)	140×200	1400
	mattress	cotton100%/cotton	120×200	4000
Winter	quilt	cotton100%/PET100%	170×200	3900
	sheet	cotton100%/PET100%(quilting)	140×200	1400
	mattress	cotton100%/cotton100%	120×200	4000

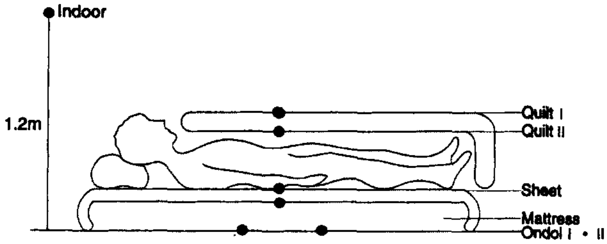

Fig. 1. Indicates measuring points of bed temperature.

Temperature and humidity in the bedrooms were measured every five minutes. To understand the vertical variation of the bedroom, the temperature for six different heights were measured for every five minutes (10 cm, 40 cm, 80 cm, 120 cm, 180 cm and 250 cm) from the floor.

Skin temperatures were measured on seven points of the subjects: forehead, abdomen, forearm, hand, thigh, leg and instep for every two minutes. Mean skin temperature (Tsk) was calculated by using Hardy and Dubois's equation (Hardy *et al.*, 1938). As a reference, rectal and skin temperatures on the chest, back and surrounding temperatures were also measured.

Bedding temperatures were measured every five minutes. Bedding was unchanged during the period. The total of the seven points of temperatures were measured. The locations of the thermometer sensors for measurement are shown in Fig. 1.

The subjects were asked to describe their thermal sensations of the face, hand, foot and entire body (+4 : very hot, +3 : hot, +2 : warm, +1 : slightly warm, 0 : neither cool nor warm, -1 : slightly cool, -2 : cool, -3 : cold, -4 : very cold) just before sleep and just after sleep. The heating and cooling systems, the hardware specification, operation time and period, and location were all reported.

2.5. Statistics method

Measured data were processed by SAS to get an average and standard deviation. Any correlation among subjects, bedding, housing types, seasons and time were verified with ANOVA.

3. Results

3.1. Temperature and humidity in bedroom

The time-history of the bedroom temperature for apartment and house depending on the seasons is shown in Fig. 2. Yearly variations of the temperature were 26.2~31.0°C in apartments, and 15.7~33.6°C in houses. The variation of the temperature for the house showed larger than that for the apartment. Houses had a higher temperature than apartment in summer (1.9°C) and had a lower temperature in spring

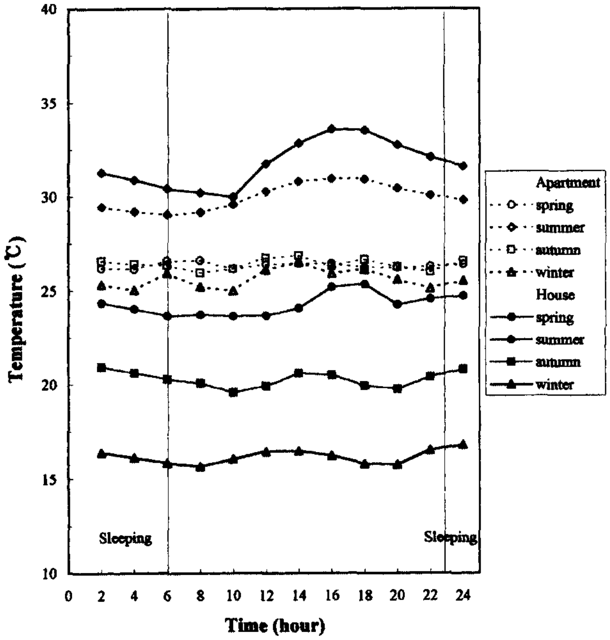

Fig. 2. Seasonal changes of bedroom temperature for 24 hours.

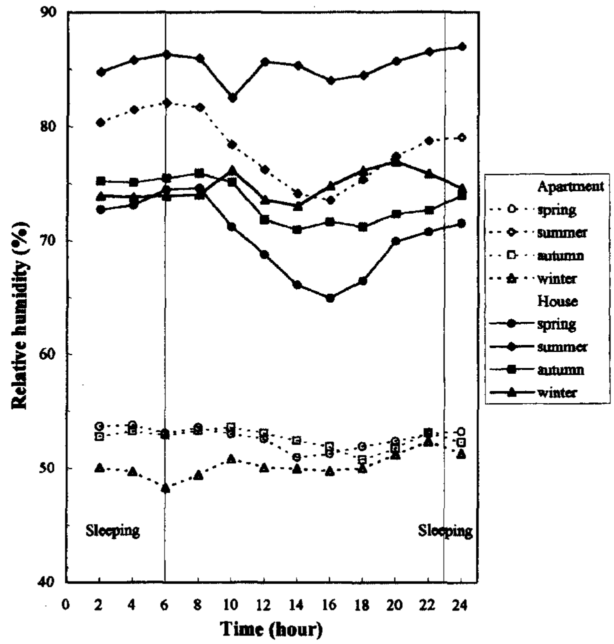

Fig. 3. Seasonal changes of relative humidity in bedroom for 24 hours.

(2.1°C), autumn (6.1°C) and winter (9.5°C). That means the climate of houses were more significantly affected by outside weather change than apartment.

The time-history of the bedroom humidity for both housing types depending on the seasons is shown in Fig. 3 . Annual variation of bedroom humidity ranged from 48.3%

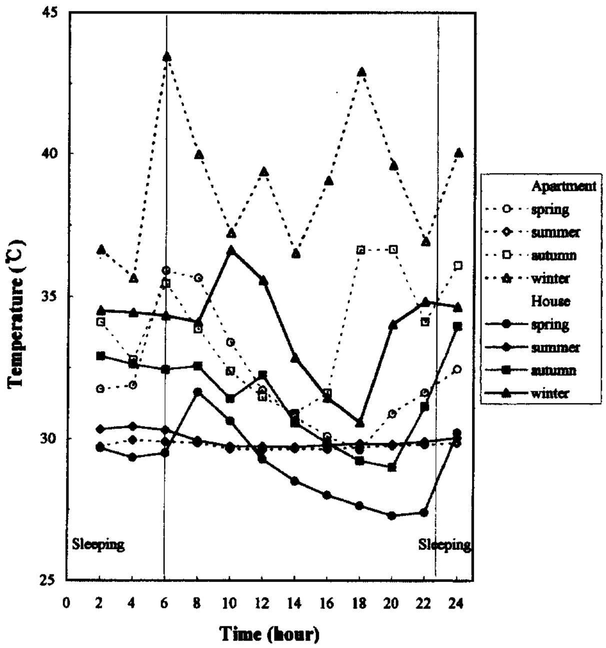

Fig. 4. Seasonal changes of ondol temperature in bedroom 24 hours.

RH to 82.1% RH in the apartments and from 64.9% RH to 87.0% RH in houses. Humidity in the house was much higher than in the apartment, except for the humidity in the apartment in summer.

3.2. Temperature in bedding

The time-history of Ondol temperature under the mattress in the bedroom for both housing types depending on the seasons is shown in Fig. 4. The variations of Ondol temperatures under the mattress were in the range of 29.7°C to 38.9°C for the apartment and from 29.1°C to 33.9°C for the house. Especially in winter, the variation was as large as 7.8°C for the apartment than it was as 6.1°C for the house. Depending on the types of housing, there were significant differences in spring ($p<0.001$), autumn ($p<0.01$) and winter ($p<0.001$), but no significant differences in summer. Cycle of temperature curve was coincident with the cycle of heating periods: 4-6 o'clock, 10-12 o'clock and 16-18 o'clock in winter apartments which were operated with a central heating system. The temperature difference between day and night was more clear in the houses than in the apartments, and the temperature increased around sleeping time for both types.

The results for average bed temperature, its standard deviation, and average temperature difference between housing types before and during sleeping time were summarized in Table 3 for each season. Before sleeping time,

Table 3. Average bed temperatures before and during sleep (unit:°C)

Before sleep

Location	Type	Spring	Summer	Autumn	Winter
Quilt	A	29.1±2.39	29.8±3.88	29.4±2.33	30.7±2.33
	H	27.0±2.95 (***)	31.2±1.69 (***)	27.1±3.67 (***)	25.9±3.97 (***)
Sheet	A	29.8±2.68	29.4±4.44	29.9±2.86	32.1±2.73
	H	27.2±3.09 (***)	31.4±2.50 (***)	27.6±3.87 (***)	27.2±4.88 (***)
Mattress	A	29.6±2.85	30.2±1.43	30.5±2.78	33.2±2.77
	H	27.3±2.82 (***)	30.6±2.22 (***)	28.3±3.83 (***)	27.7±4.45 (***)
Ondol	A	31.7±2.85	29.7±0.71	33.5±3.42	38.7±3.32
	H	28.8±2.59	29.8±2.30 (***)	30.6±2.26 (***)	33.8±5.15 (***)

During sleep

Location	Type	Spring	Summer	Autumn	Winter
Quilt	A	31.6±2.24	30.5±4.12	32.0±2.20	32.3±1.99
	H	30.6±3.23	31.5±1.45	32.6±2.04	31.0±2.36 (*)
Sheet	A	33.0±2.47	31.7±1.82	33.8±2.39	34.1±3.03
	H	31.0±3.17 (***)	33.0±2.06 (***)	32.5±3.70	32.5±3.70
Mattress	A	33.2±2.92	31.7±1.55	33.9±2.36	35.5±3.19
	H	30.3±3.09 (***)	23.3±1.81 (*)	33.9±2.54	32.9±4.30 (***)
Ondol	A	33.0±3.12	29.8±0.76	34.5±3.26	38.9±4.04
	H	29.6±2.21 (***)	30.2±2.07	32.9±1.83 (**)	34.4±3.49 (***)

Values are mean±S.D.

A : Apartment, H : House

*$p<0.05$, **$p<0.01$, ***$p<0.001$

temperature of contact surfaces such as on the sheets and under quilts were 29.1~32.1°C in apartments and 25.9~31.4°C in houses. During sleeping time, those were 30.5~34.1°C in apartments and 30.6~33.0°C in houses.

3.3. Physiological responses

The time-history of rectal temperatures and mean skin temperature during sleep on the seasons is shown Fig. 5. There was no significant difference in the rectal temperature

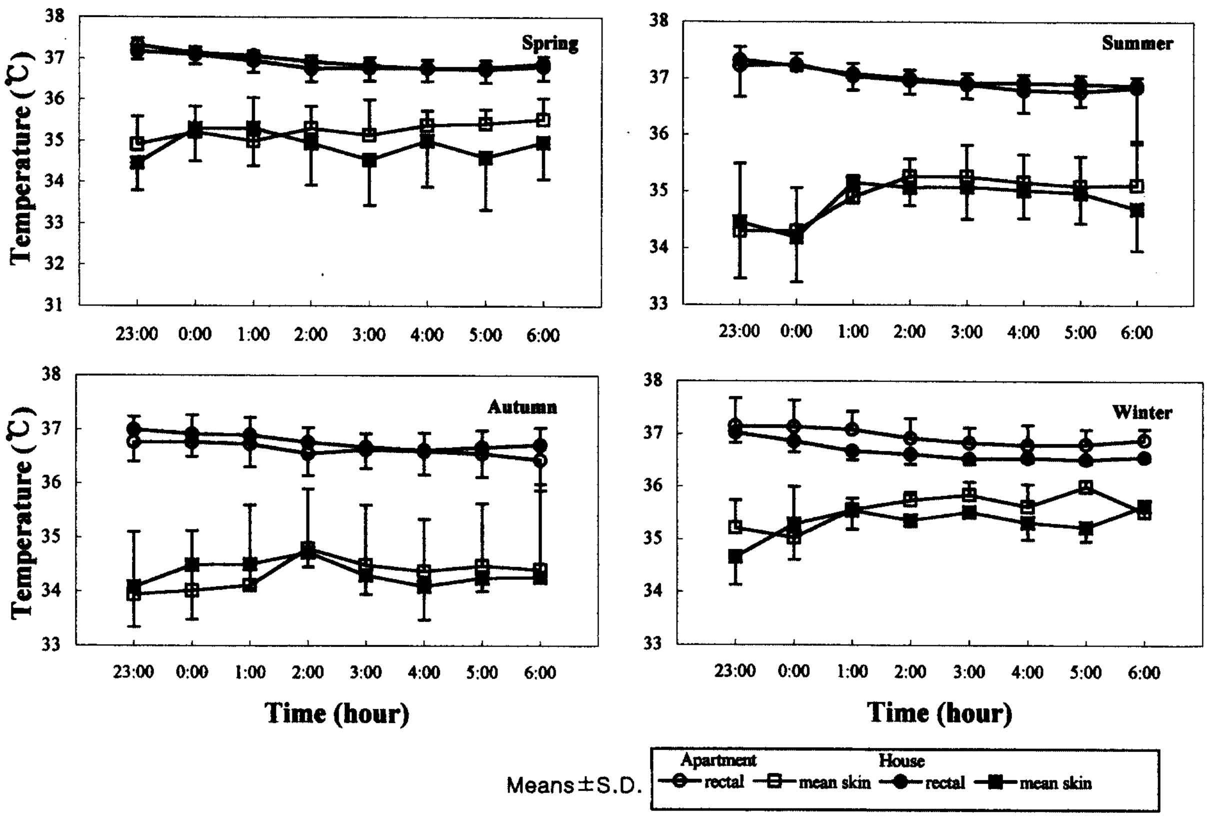

Fig. 5. Seasonal changes in rectal temperature and mean skin temperature during sleep.

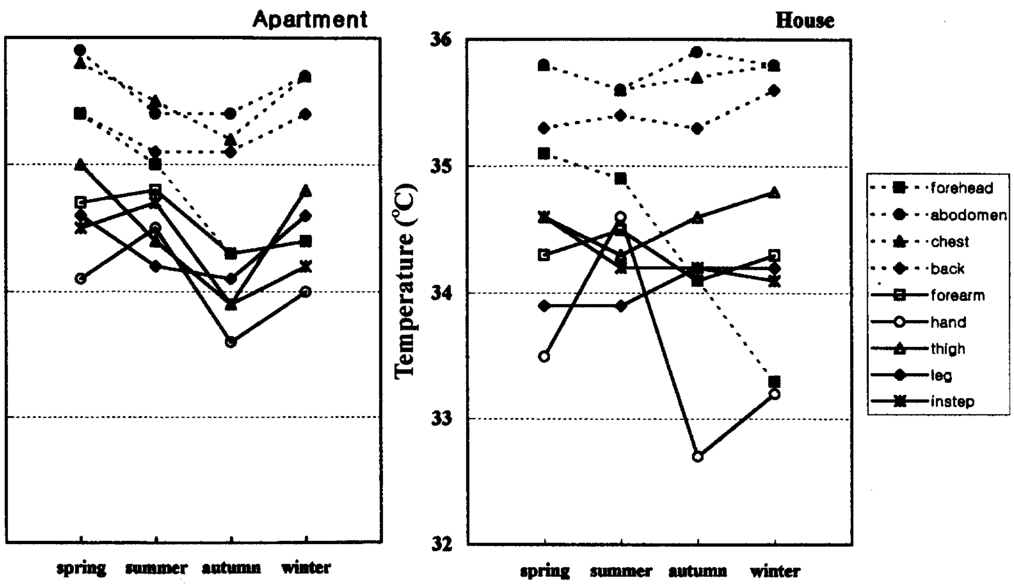

Fig. 6. Seasonal changes in skin temperature during sleep.

regardless of the housing types or seasonal variation, and average temperature was 36.8°C. Mean skin temperatures were 35.1°C, 34.8°C, 34.3°C and 35.4°C for spring, summer, autumn and winter respectively. The significant difference of the temperature in season was shown ($p<0.001$), however the temperature variation with the time was not.

Seasonal difference of skin temperature on nine body parts during sleep is shown in Fig. 6. Though skin temperature on forehead showed no significant difference depending on housing types, the seasonal difference was clear as 35.3°C in spring, 35.0°C in summer, 34.2°C in autumn and 33.9°C in winter ($p<0.001$). Annual average abdomen and chest skin temperature was 35.6°C in apartments and 35.8°C in houses. The chests skin temperature in summer and the abdomens skin temperature in both summer and autumn showed a significant difference between housing types ($p<0.001$). The hand and insteps skin temperatures showed a significant difference regardless of seasons ($p<0.001$) and especially the hands skin temperature of houses showed a larger variation in the range of 32.7°C~34.6°C throughout the four seasons.

3.4. Vertical temperature

The vertical temperature difference of the bedroom for 24 hours depending on the seasons is shown in Fig. 7. There were as shown significant differences depending on the types of housing and the seasons ($p<0.001$). In apartments, vertical temperature differences were 0.3°C in spring, 0.5°C in summer, 0.6°C in autumn and 0.5°C in winter. In houses, it was 0.8°C in spring, 0.6°C in summer, 0.3°C in autumn and 0.6°C in winter. In summer, the reason for the significant difference ($p<0.001$) in the time-history of the temperature is because the room temperature without heating is largely affected by the radiation heat from outdoors. On the other hand, it showed almost no significant difference in its time-history throughout the other seasons, since the floor was heated several times a day and the heating effect lasted all day long.

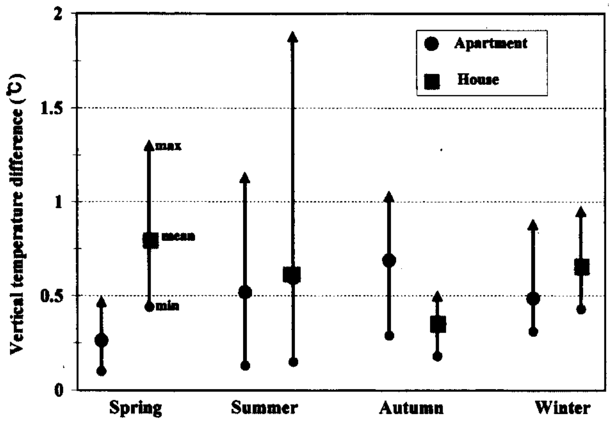

Fig. 7. Vartical temperature difference of bedroom for 24 hours. The temperature is measured at 6 different heights 10 cm, 40 cm, 80 cm, 120 cm, 160 cm and 200 cm from the floor.

3.5. Thermal sensation

The relationship between thermal sensation and bed-

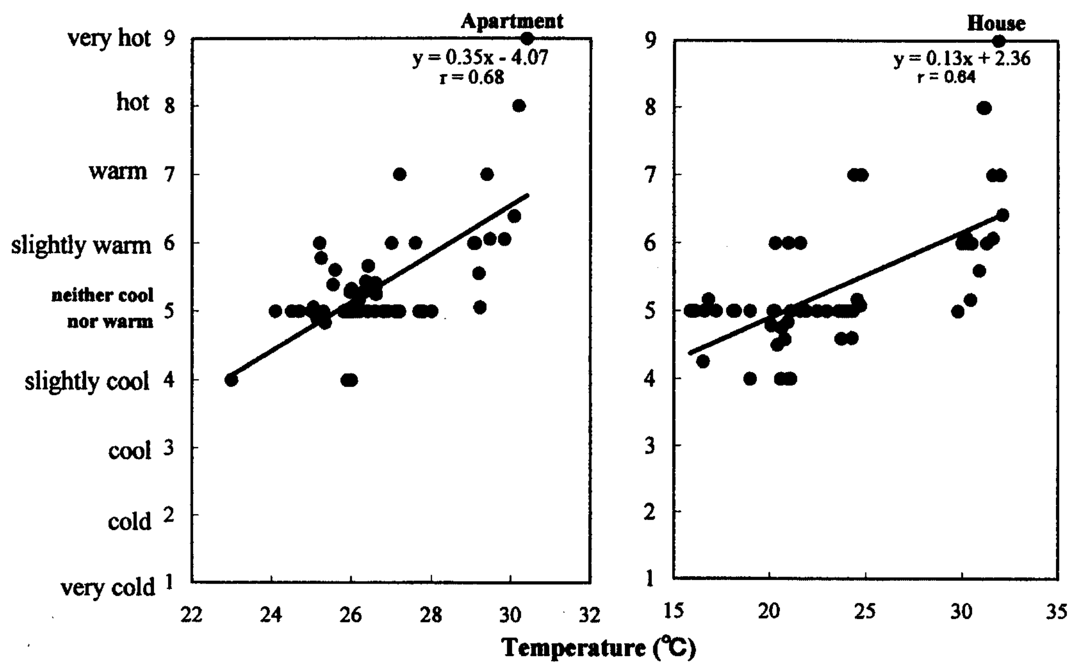

Fig. 8. Relationship between thermal sensation and bedroom temperature.

room temperature was presented in Fig. 8. The neutral points of bedroom temperature were 25.9℃ in apartments and 20.3℃ in houses. Thermal sensations of the apartments residents were 5.6℃ higher than that of house residents. When we assume that comfort zone ranges from the point feeling slightly cool to the point feeling slightly warm, the comfort temperature zone in apartments ranged 23.6~28.8℃, and that of houses ranged 12.6~28.0℃. This shows that house residents are adapted to a much wider temperature distribution.

4. Discussion

Seasonal differences of room temperature were lower in apartments (4.8℃) than in houses (17.9℃)(Fig. 2, Fig. 3). As insulation and air tightness were better in apartments than in houses, the effects of outdoor temperature were not as strong on room temperature and humidity. Except the high bedroom temperature and humidity in summer, the bedroom temperature and humidity in apartments in spring, autumn and winter showed an even distribution. It is regarded that the effects of outdoor temperature naturally increase without any kinds of artificial heating in summer. Though, the effects of outdoor temperature have been much less in apartments than in houses.

Temperature difference between room and Ondol floor temperature under mattress was larger than any other season in winter; 13.5℃ in apartments and 18.1℃ in houses (Fig. 2, Fig. 4). The temperature difference occurs between floor temperature and room temperature because of inherent structural characteristics of Ondol type buildings which is based on the low temperature radiation heating system from the floor (Yoon and Choi, 1990). Therefore, Korean people have a distinctive and unique thermal sensation of the body contacting the warm floor.

Bed temperature in autumn and winter showed higher in the order of Ondol floor, mattress and sheets (Table 3). This is because the bed temperature is more significantly affected by the heated floor than the body temperature. It is considered that the bedding temperature becomes lower than the floor temperature because of the heat transfer rate differences of mattress and sheets. However, in summer, the bed temperature showed higher in the order of sheets, mattress and Ondol floor. This can be explained by those temperatures not being affected by Ondol since it is not heated during summer, and the heat from the body is radiated through the mattress by conduction heat transfer (Kweon *et al.*, 1992).

The temperature of sheets, which contact body during sleep, were 33.0℃ in spring, 31.7℃ in summer, 33.8℃ in autumn and 34.1℃ in winter in apartments and 31.0℃, 33.0℃, 32.5℃ and 32.5℃ in houses respectively. Regardless of housing types and seasons, they showed a comfortable temperature zone. This agrees to the result of previous research on bedding temperature in Ondol rooms during sleep (Lee and Kweon, 1997; Kweon and Lee, 1993; Kweon *et al.*, 1992). However, Komatsuzaki *et al.* (1998) reported that bed temperatures were 30℃ in spring, 32℃ in summer, 28℃ in autumn and winter. Candas *et al.* (1979) reported that inside the bed the temperature was 29.6℃ with an ambient temperature of 19℃ and 22℃. It is considered that the higher bed temperatures in Ondol rooms were caused by the radiation heating system from the floor which affects the bedding temperature.

It is reported that the mean skin temperature for sound sleep is 34.5~35.6℃ (Ogino *et al.*, 1987). In this research, mean skin temperatures ranged between 34.3℃ and 35.4℃ regardless of housing types per a comfort zone (Fig. 5). The mean skin temperature in winter was 0.6℃ higher than in summer. The research by Kweon (1993) also showed a similar result (0.4℃). The reason is that the temperature for Ondol and bedding is higher in winter than those of in summer.

The time-history of skin temperature for body parts during sleeping time showed a rise in one to two hours after falling asleep regardless of seasons and body parts, and there was no significant temperature difference after that. The skin temperature after an equivalent state showed narrow variation between 34~36℃ in spring and summer, and showed a wider variation between 32~36℃ in autumn and winter (Fig. 6). The skin temperature difference was larger in winter houses than any other seasons (30.6~36.2℃). In summer apartments, the difference was smaller than any other seasons (34.2~35.5℃). It is considered that the temperature difference between room and Ondol floor is as small as 0.5℃ in summer apartments and as large as 18.1℃ in winter houses, since skin temperature was affected by room temperature and Ondol floor temperature.

As for the apartment type, the skin temperature showed significant difference in season for all 9 body parts, but only three parts (forehead, hand and instep skin temperature) showed significant difference according to the seasons than as for the housing types. It is caused by a larger variation of Ondol temperature for the apartment that will affect the bed and skin temperatures significantly, since the yearly-averaged Ondol temperature variation over the seasons was 9.1℃ for the apartment, and 4.8℃ for the house. Therefore, skin temperatures were directly affected by bed temperature which is caused by room and floor temperature.

Annual average vertical temperature differences ranged from 0.1℃ to 1.1℃ in apartments and from 0.2℃ to 1.

9°C in houses, hence the difference for apartments was less than the difference for houses (Fig. 7). This phenomena is caused by the room temperature and Ondol temperature in apartments being higher than in houses due to better insulation and other factors like the locations of windows and doors that seem to adapt to the better thermal environments in apartments.

The ambient temperature of the sleeping room is very important in the organization of human sleep (Muzet *et al.*, 1984). The room temperature between 18°C and 21°C must be considered as a neutral environment among five ambient conditions; 15°C, 18°C, 21°C, 24°C and 27°C (Lee *et al.*, 1991). This explanation is also supported by the investigations of Macpherson (1973) and Humphreys (1979) who proposed a thermal comfort zone for the bed room temperature. Subjective thermal sensation about bedroom environments showed significant difference according to the housing type ($p<0.001$), so the neutral temperature of bedroom was 25.9°C in apartments, 20.3°C in houses (Fig. 8). It is supposed to be related with the fact that bedroom temperature in apartments in winter was 9.1°C higher than that of houses and floor temperature was 4.5°C higher than that of houses. Also it can be said that the residents were adapted to the thermal environments of their own housing.

In this research, sleeping environments in Ondol rooms were defined and understood according to the seasons and housing types. As a result, in spite of thermal environmental variations according to the seasons, skin, bedding and bedrooms temperatures in apartments were better and more stable than those of houses. But in the view point of energy saving and health, it should be reconsidered to set up a more comfortable living temperature for more effective heating.

5. Conclusion

The purpose of this study was to investigate actual sleeping environments in Ondol rooms depending on the season. The experiment was performed on five healthy women living in Korea. The bedroom environments using Ondol were measured in five cases (three apartments and two houses located in Taegu city). The most common type of bedding in Korean housing were used for the experiment considering the most representative seasonal climate condition. The environments in bedroom, bedding temperature, skin temperature and thermal sensation were measured continuously through the seven days for each season in real life. This data of sleeping environments was analyzed in the view of seasonal variations and housing types. The main results are as follows: 1) Annual average bedroom temperatures: 26.2~31.0°C in apartments, 15.7~33.6°C in houses. Annually averaged bedroom humidity: 48.3~82.1% RH in apartments, 64.9~87.0% RH in houses. Annual average Ondol temperature under mattress: 29.7~38.9°C in apartments, 29.1~33.9°C in houses. 2) During sleep, temperatures of contact surfaces like sheets and under quilts ranged between 30.5°C and 34.1°C regardless of season or housing type. 3) Annual average rectal temperature was 36.8°C with no significant difference in season or housing type. Mean skin temperature was 35.1°C in spring, 34.8°C in summer, 34.3°C in autumn and 35.3°C in winter. There was a significant difference according to seasons but no significant difference between housing types. 4) In the point of thermal sensation, neutral temperature of the bedroom was 25.9°C in apartments and 20.3°C in houses. It was concluded that in spite of thermal environmental variations according to the seasons, skin, bedding and bedroom temperatures in apartments were better and more stable than those of houses. It is regarded that while houses are brick structured, apartments are steel-frame structured. Due to better insulation and air tightness, apartments were affected less from outdoor temperature and maintained higher room temperature than houses.

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국문요약 : 한국의 침실양식은 84.9%가 요와 이불을 사용하여 온돌의 방바닥에 누워 자는 형식이다. 이에 본 연구는 온돌난방 주택에서의 수면환경의 실태를 파악하기 위하여 온돌침실의 온열환경, 침상기후, 수면시 생리반응를 각 가정의 일상생활중에서 직접 측정하여 계절별, 주택형태별에 따른 수면환경의 차이를 분석하였다. 그 결과, 계절 및 주택형태별에 따른 수면환경의 큰 온도차이에도 불구하고 수면 중 인체와 접촉하는 이불 밑과 요 시트의 침상온도는 계절과 주택형태에 관계없이 연평균 30.5~34.1℃로 쾌적한 침상 내 온도를 나타내었을 뿐만 아니라 수면 중 직장온도도 연평균 36.8℃로 계절 및 주택형태에 따른 유의한 차이는 인정되지 않았다. 그러나 침실환경에 대한 주관적 온열감각은 주택형태에 따라 유의한 차이를 나타내어 침실의 온열 중성점이 아파트 25.9℃, 단독주택 20.3℃로 아파트가 단독주택보다 5.6℃ 높게 나타났다. 이는 건물의 구조가 주택은 조적조의 구조인 반면 아파트는 철근콘크리트의 구조로 우수한 단열력을 가지므로 외기온의 영향을 받기 어려워 높은 실내온도를 유지하였기 때문이다. 뿐만 아니라 거주자들이 주택 내 환경에 적응되어진 결과라고도 할 수 있겠으나 아파트 거주자의 측면에서는 온열환경에 대한 에너지 절약, 건강 유지 등의 관점에서 보다 효율적인 난방을 위한 쾌적한 생활온도 설정을 재고할 필요가 있다고 하겠다.

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