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Intervention study of the effect of insulation retrofitting on home blood pressure in winter: a nationwide Smart Wellness Housing survey

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Objective: The WHO's Housing and health guidelines (2018) listed 'low indoor temperatures and insulation' as one of five priority areas, and indicated insulation retrofitting to help mitigate the effect of low indoor temperatures on health. However, there is still not enough evidence for the effect of insulation retrofitting based on an objective index.

Methods: We conducted a nonrandomized controlled trial comparing home blood pressure (HBP) between insulation retrofitting (942 households and 1578 participants) and noninsulation retrofitting groups (67 households and 107 participants). HBP and indoor temperature were measured for 2 weeks before and after the intervention in winter. To examine the influence of insulation retrofitting on HBP, we used multiple linear regression analysis.

Results: The analyses showed that indoor temperature in the morning rose by 1.4°C after insulation retrofitting, despite a slight decrease in outdoor temperature by 0.2°C. Insulation retrofitting significantly reduced morning home SBP (HSBP) by 3.1 mmHg [95% confidence interval (95% CI): 1.5–4.6], morning home DBP (HDBP) by 2.1 mmHg (95% CI: 1.1–3.2), evening HSBP by 1.8 mmHg (95% CI: 0.2–3.4) and evening HDBP by 1.5 mmHg (95% CI: 0.4–2.6). In addition, there was a dose–response relationship between indoor temperature and HBP, indicating the effectiveness of a significant improvement in the indoor thermal environment. Furthermore, there was heterogeneity in the effect of insulation retrofitting on morning HSBP in hypertensive patients compared with normotensive occupants (−7.7 versus −2.2 mmHg, *P* for interaction = 0.043).

Conclusion: Insulation retrofitting significantly reduced HBP and was more beneficial for reducing the morning HSBP of hypertensive patients.

Keywords: home blood pressure, housing, indoor temperature, insulation retrofitting, intervention

Abbreviations: ABPM, ambulatory BP monitoring; ANCOVA, analysis of covariance; BP, blood pressure; CI, confidence interval; CVDs, cardiovascular diseases; HBP, home blood pressure; HDBP, home DBP; HSBP, home SBP;

SWH, Smart Wellness Housing; Temp_{In}, indoor temperature; Temp_{Out}, outdoor temperature

INTRODUCTION

Hypertension is the main cause of cardiovascular diseases (CVDs) [1,2], the leading cause of death worldwide [3]. Because hypertension has almost no subjective symptoms, it is often referred to as a 'silent killer' [4]. In the current situation, large numbers of hypertensive patients are not aware of their hypertension and blood pressure (BP) is not well controlled by antihypertensive drugs [5]. This demonstrates the inadequacy of the high-risk strategy of using antihypertensive drugs alone. A need therefore exists for a population strategy that shifts the BP of the entire population in the appropriate direction.

Improving the home environment, which is independent of individual efforts and lifestyle habits, has attracted attention as a population strategy in recent years because people spend a large amount of time at home [6–8]. As evidence of such attention, the WHO issued the Housing and health guidelines [9] in 2018. One of the five priority

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areas listed in the guidelines is 'low indoor temperatures and insulation', with low indoor temperature named a factor for inducing vasoconstriction, which is a risk factor for hypertension, and retrofitting insulation in existing housing as one strategy to help mitigate the effect of low indoor temperatures on health. However, the evidence level that living in insulated homes is associated with improved health outcomes was assessed as moderate rather than high. The guidelines suggest the need to strengthen the evidence through objective health outcomes over self-reports by occupants, through intergroup comparisons of populations living in insulated versus noninsulated homes, and intragroup comparisons performed before and after intervention.

In Japan, the total existing housing stock was 61 million, with 52 million households in 2013, indicating an excess in housing stocks (vacancy rate: 13.5%) [10]. Although efficient use of existing housing stocks is needed, there are still many houses with low thermal insulation in Japan (an estimated 39% of existing houses are uninsulated) [11].

Therefore, this study used insulation retrofitting of existing housing stocks as an intervention. Insulation retrofitting is a method for improving the thermal insulation performance of a building's outer skin to make it difficult for heat to escape from the interior to the exterior. We aimed to elucidate the longitudinal changes in home BP (HBP) due to insulation retrofitting intervention by comparing HBP in the insulation retrofitting group and the noninsulation retrofitting group before and after intervention.

MATERIALS AND METHODS

The authors declare that the data supporting the findings of this study are provided within this article and its online-only Data Supplement. The study was conducted according to the principles of the Declaration of Helsinki. The study protocol and informed consent procedure were approved by the ethics committee of the Hattori Clinic Institutional Review Board (Approval No. S1410-J03). The study protocol was registered at the University Hospital Medical Information Network Clinical Trials Registry (UMIN000030601). All of the participants provided written informed consent to participate and to have their data published.

Study design

The study design of the Smart Wellness Housing (SWH) survey is reported elsewhere [12]. Participants were recruited by construction companies throughout all 47 prefectures of Japan. Inclusion criteria were intention to conduct insulation retrofitting, age over 20 years and pre-renovation house did not meet S (Supreme) standards of the 'Act on the Promotion of Dissemination of Long-Lasting Quality Housing' in Japan [13]. This survey was conducted as a nonrandomized controlled trial with groups defined according to participants' choice to conduct or not conduct insulation retrofitting, given that it is unethical to randomly divide houses into insulation and no insulation groups.

For the recruitment of households by construction companies, the Japan Sustainable Building Consortium, the main body governing the research project, submitted a request to conduct the investigation. Households that gave consent

were sent an investigation kit that included questionnaires, a thermos-hygrometer and an HBP meter. The participants started the 14-day baseline survey (investigation prior to insulation retrofitting) within 5 days of receiving the investigation kit. After completing the baseline survey, the participants' houses were retrofitted by the construction companies. After the insulation retrofitting, the participants completed the follow-up survey in the same manner as the baseline survey. Participants who completed the two surveys without conducting insulation retrofitting, despite being scheduled to do so, were included in the analysis as control group participants.

The surveys were conducted in the winter season (November–March) of FY 2014 to 2018. Given the need for a renovation period and the survey to be conducted in the winter season, there was at least a 1-year interval between the baseline and follow-up surveys.

Intervention

The intervention was the thermal insulation retrofitting of participants' homes. This included heat-insulation work such as that on the outer walls, floor and/or roof; replacement of single-glazed windows with double-glazed windows; and replacement of window frames. Subsidies of up to 1.2 million yen were provided for insulation retrofitting by the Project for Promotion of SWH. After completing the insulation retrofitting, construction companies submitted a Certificate of Conformance with Energy-Saving Standards to the Ministry of Land, Infrastructure, Transport and Tourism to indicate that the house met S standards (approximately equivalent to a long life high-quality newly built house) or A standards (lower than S standards but constant performance improvement is expected) [13].

Home blood pressure and other measurements

Methods for measuring HBP and other parameters are reported elsewhere [12]. Briefly, HBP was measured twice after getting out of bed in the morning and twice before getting into bed in the evening, in accordance with the Guidelines of the Japanese Society of Hypertension [14]. HBP was measured in the living room for 2 weeks using an automatic oscillometric device (HEM-7251G; Omron Healthcare Co., Ltd, Kyoto, Japan). The expected number of observations was 56 [= 14 days × 2 occasions/day (morning and evening) × 2 observations/occasion], giving 28 observations in the morning and evening, respectively. HBP data were automatically stored with indoor ambient temperature ($Temp_{in}$) data. Outdoor temperature ($Temp_{out}$) was obtained from the closest local meteorological observatory to each participant's house. A questionnaire survey was also conducted, which covered demographics, such as age, sex and weight; and lifestyle indicators, such as eating habits, smoking, alcohol consumption and health conditions, focusing on diseases associated with hypertension.

Statistical analysis

To examine the influence of insulation retrofitting on HBP, we used multiple linear regression analysis. The multiple linear regression model was developed to include changes in HBP of participants from the baseline survey (HBP at the

follow-up survey minus HBP at the baseline survey) as the dependent variable. Two models were developed: Model-1 included only the treatment condition (intervention vs. control) as an independent variable, while Model-2 included the treatment condition and changes in Temp_{In} from the baseline survey as independent variables. Moreover, adjustment was performed for the following variables: HBP at the baseline survey; change in age; change in BMI; and change in Temp_{Out} from the baseline survey. Change in age was included in the model to adjust for the interval between the baseline and follow-up surveys. Change in BMI was used as an index for changes in lifestyle habits before and after the intervention. Finally, change in Temp_{Out} was used to take account of differences in weather conditions and/or baseline and follow-up survey period.

Furthermore, to determine the populations that may most benefit from insulated housing, subgroup analyses were conducted by stratifying participants by age (≥ 65 or < 65 years), sex, BMI (≥ 25 or < 25 kg/m²), salt check sheet score [15] (≥ 14 or < 14 points), smoking status (current smoker), alcohol consumption (current drinker), physical activity (regular exercise) and self-reported hypertension. Heterogeneity in the effect of the intervention on HBP among subgroups was examined by including an intervention-by-subgroup interaction in the multiple linear regression model.

All *P* values were two-sided, and a two-sided *P* value less than 0.05 was considered statistically significant. All analyses were performed using SPSS Ver. 25 (SPSS Inc., Chicago, Illinois, USA).

RESULTS

Baseline characteristics in the intervention and control groups

Figure 1 shows the flow for the selection of valid samples. Of the 3775 participants (2095 households) who completed the baseline survey, 1954 participants completed two measurements. One thousand, six hundred and eighty-five participants were selected as providing valid samples after excluding those with insufficient data, participants aged

TABLE 1. Baseline characteristics of participants in the intervention and control groups

Characteristic	Intervention (<i>n</i> = 1578)	Control (<i>n</i> = 107)
Blood pressure		
Morning		
HSBP, mmHg (SD)	128.7 (16.8)	127.4 (16.3)
HDBP, mmHg (SD)	80.4 (10.3)	80.1 (10.2)
Evening		
HSBP, mmHg (SD)	122.0 (15.5)	122.1 (13.9)
HDBP, mmHg (SD)	73.9 (9.7)	74.1 (9.9)
Demographics		
Age, years (SD)	58 (13)	54 (14)
Men, <i>n</i> (%)	725 (46)	52 (49)
BMI, kg/m ² (SD)	22.7 (3.4)	23.1 (3.2)
Lifestyle		
Salt check sheet, points (SD)	12.8 (4.2)	14.1 (4.1)
Current smoker, <i>n</i> (%)	188 (13)	21 (21)
Current drinker, <i>n</i> (%)	832 (54)	54 (50)
Regular exercise, <i>n</i> (%)	468 (30)	38 (36)
Antihypertensive drugs, <i>n</i> (%)	388 (25)	16 (16)
Health condition		
Hypertension, <i>n</i> (%)	375 (25)	18 (17)
Diabetes mellitus, <i>n</i> (%)	100 (7)	6 (6)

HDBP, home DBP; HSBP, home SBP.

under 20 years and participants with changes in antihypertensive drug use from the baseline survey. Of these, 1578 participants (942 households) comprised the intervention (insulation retrofitting) group, while 107 participants (67 households) comprised the control (noninsulation retrofitting) group.

The baseline characteristics of participants in the intervention group and control group are summarized in Table 1. The average age was 58 years in the intervention group and 54 years in the control group. The proportion of men was nearly 50%, and the average BMI was about 23 kg/m² in each group. Although differences in HBP between the intervention group and control group were small, HBP at the baseline survey was adjusted in the subsequent multiple linear regression model to reflect the differences in baseline characteristics between the groups.

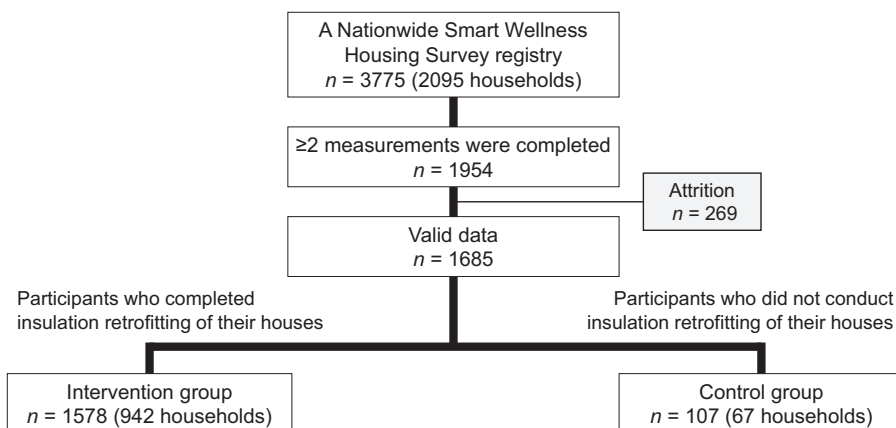


FIGURE 1 Study flow through the study. Reasons for attrition were as follows: (1) after removing error data, data were available from < 5 days either in the morning or evening; (2) unavailability of data from the living room or bedroom or changing room temperature; (3) unavailability of data from the questionnaire or diary; (4) mismatch between responses to a questionnaire and those provided in a diary; (5) under 20 years old; (6) mismatch between responses for birth date/sex in the questionnaire before and after insulation retrofitting; and (7) participants with changes in antihypertensive drug use conditions from the baseline survey.

TABLE 2. Indoor and outdoor temperature in the intervention and control groups

Temperature	Treatment						P for between-group comparison		
	Intervention (n = 1578)			Control (n = 107)			Before	After	Difference
	Before	After	Difference	Before	After	Difference			
Temp _{In} (°C)									
In the morning	14.5	15.9	1.4	15.4	16.6	1.2	0.012	0.028	0.599
In the evening	18.0	19.1	1.1	18.2	19.2	1.0	0.607	0.675	0.878
Temp _{Out} (°C)									
In the morning	3.2	3.0	-0.2	2.9	4.5	1.7	0.274	<0.001	<0.001
In the evening	4.6	4.5	-0.1	4.0	5.7	1.7	0.057	<0.001	<0.001

Temp_{In}, indoor ambient temperature; Temp_{Out}, outdoor temperature.**TABLE 3. Home blood pressure in the intervention and control groups**

Blood pressure	Treatment group						P for between-group comparison		
	Intervention (n = 1578)			Control (n = 107)			Before	After	Difference
	Before	After	Difference	Before	After	Difference			
Morning									
HSBP (mmHg)	128.7	128.1	-0.6	127.4	129.4	2.0	0.415	0.440	0.001
HDBP (mmHg)	80.4	80.5	0.1	80.1	82.0	1.9	0.756	0.150	0.001
Evening									
HSBP (mmHg)	122.0	121.3	-0.7	122.1	122.9	0.8	0.930	0.279	0.069
HDBP (mmHg)	73.9	73.8	-0.1	74.1	75.3	1.2	0.817	0.119	0.028

HDBP, home DBP; HSBP, home SBP.

Comparison of indoor temperature before and after intervention

We examined the influence of insulation retrofitting intervention on Temp_{In}. Temp_{In} before and after the intervention is summarized for the intervention group and control group in Table 2. In the control group, Temp_{Out} rose after the intervention, and Temp_{In} rose along with this change. In contrast, in the intervention group, Temp_{Out} decreased slightly, while Temp_{In} rose after the intervention. For example, the indoor temperature in the morning rose by 1.4°C after insulation retrofitting despite a slight decrease in outdoor temperature by 0.2°C. The rise in Temp_{In} against the decrease in Temp_{Out} is likely a direct effect of the insulation retrofitting intervention.

Comparison of home blood pressure before and after intervention

Table 3 summarizes HBP in the intervention and control groups before and after the intervention. Despite the presence of at least a 1-year interval between the baseline and follow-up surveys, morning and evening HSBP decreased and HDBP remained the same level in the intervention group. In contrast, both HSBP and HDBP increased in the control group.

Table 4 summarizes HBP in the groups classified by change in Temp_{In} from the baseline survey (intervention group only). There was a dose-response relationship between HBP and Temp_{In} such that a greater increase in indoor temperature was correlated with a greater decrease

TABLE 4. Home blood pressure by change in indoor temperature (intervention group only)

Blood pressure	Morning																	
	Change in morning Temp _{In} from the baseline survey															P for between-group comparison		
	<-3°C (n = 61)			-3°C to -1°C (n = 208)			-1°C to +1°C (n = 470)			+1°C to +3°C (n = 471)			≤+3°C (n = 368)					
	Before	After	Difference	Before	After	Difference	Before	After	Difference	Before	After	Difference	Before	After	Difference	Before	After	Difference
HSBP (mmHg)	125.9	130.2	+4.3	127.0	129.3	+2.3	127.6	128.3	+0.7	128.7	127.4	-1.3	131.7	127.7	-4.0	0.001	0.515	<0.001
HDBP (mmHg)	79.8	82.3	+2.5	79.7	81.5	+1.8	80.1	80.8	+0.8	80.0	79.9	-0.1	81.8	79.9	-1.9	0.072	0.116	<0.001
Blood pressure	Evening																	
	Change in evening Temp _{In} from the baseline survey															P for between-group comparison		
	<-3°C (n = 61)			-3°C to -1°C (n = 206)			-1°C to +1°C (n = 571)			+1°C to +3°C (n = 450)			+3°C ≤ (n = 290)					
	Before	After	Difference	Before	After	Difference	Before	After	Difference	Before	After	Difference	Before	After	Difference	Before	After	Difference
HSBP (mmHg)	119.1	122.3	+3.1	121.4	123.4	+2.0	120.9	120.9	-0.0	122.2	121.3	-0.9	123.3	120.3	-3.0	0.003	0.220	<0.001
HDBP (mmHg)	72.9	74.2	+1.2	74.0	75.1	+1.0	73.4	73.8	+0.4	73.6	73.5	-0.2	74.5	73.3	-1.3	0.053	0.232	<0.001

HDBP, home DBP; HSBP, home SBP; Temp_{In}, indoor temperature.

TABLE 5. Effect of intervention and change in indoor temperature on home blood pressure in the morning and evening

Predictor	Unadjusted			Model-1 ^a			Model-2 ^b		
	β	95% CI	P	β	95% CI	P	β	95% CI	P
Change in morning HSBP from the baseline survey (mmHg)									
Intervention versus control	-2.6	-4.3 to -1.0	0.001	-3.1	-4.6 to -1.5	<0.001	-2.7	-4.2 to -1.1	0.001
Change in Temp _{in} (°C)	-	-	-	-	-	-	-0.64	-0.78 to -0.49	<0.001
Change in morning HDBP from the baseline survey (mmHg)									
Intervention versus control	-1.8	-2.9 to -0.7	0.001	-2.1	-3.2 to -1.1	<0.001	-1.9	-3.0 to -0.9	<0.001
Change in Temp _{in} (°C)	-	-	-	-	-	-	-0.29	-0.39 to -0.19	<0.001
Change in evening HSBP from the baseline survey (mmHg)									
Intervention versus control	-1.5	-3.2 to 0.1	0.069	-1.8	-3.4 to -0.2	0.029	-1.6	-3.1 to -0.0	0.046
Change in Temp _{in} (°C)	-	-	-	-	-	-	-0.73	-0.88 to -0.57	<0.001
Change in evening HDBP from the baseline survey (mmHg)									
Intervention versus control	-1.3	-2.4 to -0.1	0.028	-1.5	-2.6 to -0.4	0.006	-1.4	-2.5 to -0.3	0.010
Change in Temp _{in} (°C)	-	-	-	-	-	-	-0.34	-0.44 to -0.23	<0.001

CI, confidence interval; HDBP, home DBP; HSBP, home SBP.

^aModel-1 included the treatment condition (intervention versus control) as a predictor, and was adjusted for HSBP/HDBP at the baseline survey, change in age, change in BMI and change in outdoor temperature from baseline.

^bModel-2 included the treatment condition (intervention versus control) and change in indoor temperature as predictors, and was adjusted for HSBP/HDBP at the baseline survey, change in age, change in BMI and change in outdoor temperature from baseline.

in HBP. For example, morning HSBP decreased by 4.0 mmHg in participants who experienced an increase in morning indoor temperature by 3°C or more. As baseline HBP levels progressively increased across the five groups in Table 4, we performed an analysis of covariance (ANCOVA) and confirmed a dose–response relationship after adjusting for baseline HBP levels (see Table S1, Supplemental Digital Content, which shows results of the ANCOVA, <http://links.lww.com/HJH/B381>).

Longitudinal changes in home blood pressure due to insulation retrofitting intervention

The effect of insulation retrofitting on HBP is summarized in Table 5. The multiple linear regression model (Model-1) showed that insulation retrofitting significantly reduced morning HSBP by 3.1 mmHg [95% confidence interval (95% CI): 1.5–4.6; $P < 0.001$] and morning HDBP by 2.1 mmHg (95% CI: 1.1–3.2; $P < 0.001$). The model also showed that insulation retrofitting reduced evening HSBP by 1.8 mmHg (95% CI: 0.2–3.4; $P = 0.029$) and evening HDBP by 1.5 mmHg (95% CI: 0.4–2.6; $P = 0.006$). In Model-2, changes in Temp_{in} from the baseline survey were significant ($P < 0.001$) for all HBP indices (HSBP and HDBP in the morning and evening), indicating the presence of a dose–response relationship between indoor temperature and HBP, and the effectiveness of a significant improvement in the indoor thermal environment.

Heterogeneity in the effect of insulation retrofitting on home blood pressure in subgroups

Given evidence indicating that CVDs occur frequently in the morning [16–19] and that SBP provides important prognostic information about CVDs [1,20,21], we focused on HSBP in the morning. The effects of insulation retrofitting of houses on morning HSBP in various subgroups of participants are shown in Fig. 2. Significant effects of insulation retrofitting were confirmed in almost all subgroups, but were more beneficial in subgroups at high risk

of CVDs. The effect of insulation retrofitting was greater in self-reported hypertensive patients (–7.7 mmHg; 95% CI: –12.1 to –3.3; $P < 0.001$) than normotensive occupants (–2.2 mmHg; 95% CI: –3.8 to –0.5; $P = 0.012$) (P for interaction = 0.043), even after adjusting for HBP level in the baseline survey.

DISCUSSION

Summary of findings

This study analysed the effect of insulation retrofitting of houses on HBP by comparing HBP in an insulation retrofitting group (942 households and 1578 participants) and noninsulation retrofitting group (67 households and 107 participants) before and after intervention. The analyses showed that indoor temperature in the morning rose by 1.4°C after insulation retrofitting, despite a slight decrease in outdoor temperature by 0.2°C; insulation retrofitting significantly reduced morning HSBP by 3.1 mmHg (95% CI: 1.5–4.6), morning HDBP by 2.1 mmHg (95% CI: 1.1–3.2), evening HSBP by 1.8 mmHg (95% CI: 0.2–3.4) and evening HDBP by 1.5 mmHg (95% CI: 0.4–2.6); there was a dose–response relationship between indoor temperature and HBP; there was heterogeneity in the effect of insulation retrofitting on HSBP in the morning in self-reported hypertensive patients compared with normotensive occupants (–7.7 vs. –2.2 mmHg), despite adjustment for HBP level in the baseline survey.

A reduction in morning HBP is expected to lead to a reduction in future cardiovascular events, because higher morning HBP is independently and closely associated with cardiovascular prognosis in prospective studies [22–25].

Previous longitudinal studies on housing and blood pressure

In recent years, there has been an abundance of research on the relationship between the thermal environment inside houses and BP of occupants [12,26–29]. However, much of this research has used cross-sectional methods, while evidence based on longitudinal studies remains limited.

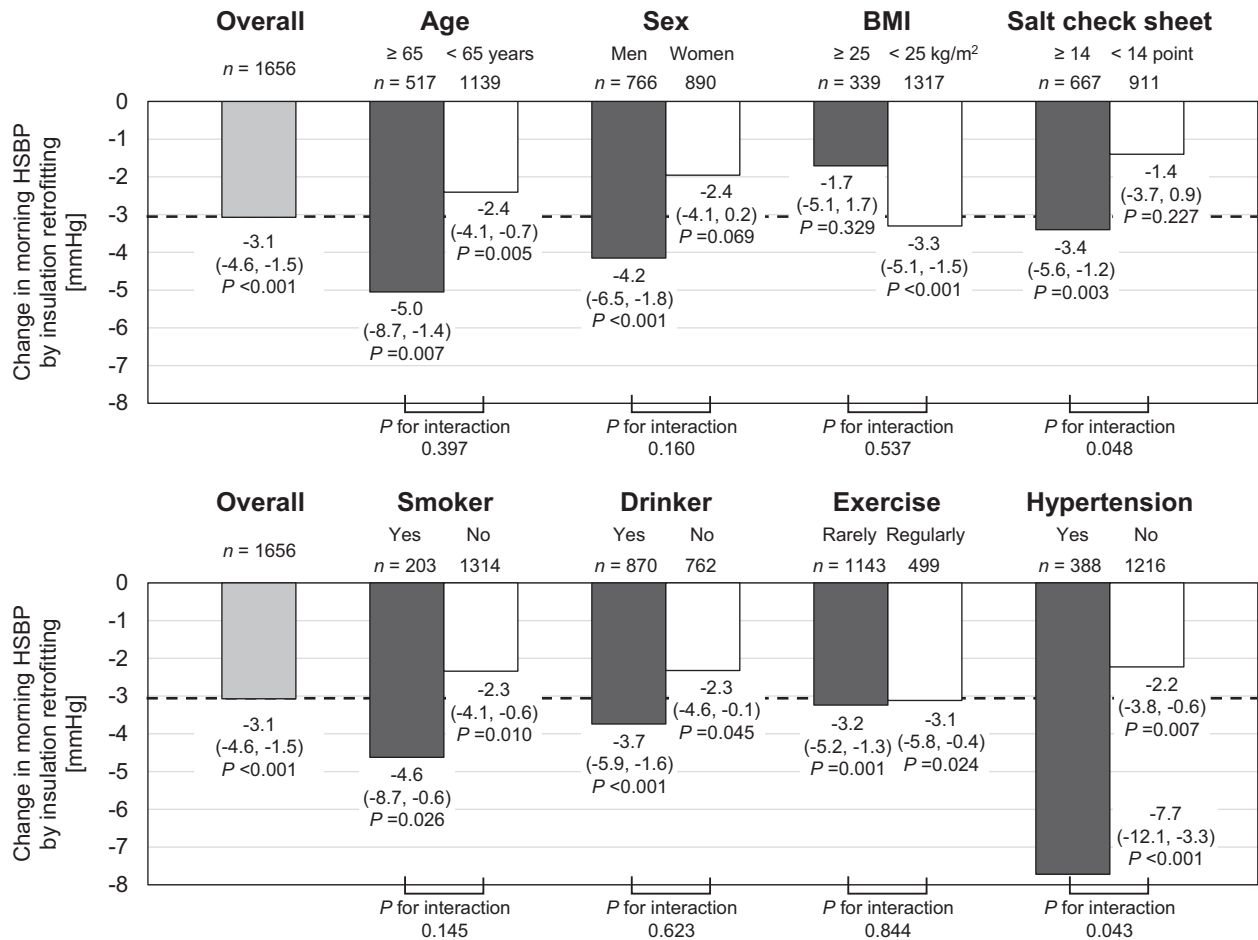


FIGURE 2 Change in morning home SBP following insulation retrofitting by subgroup. Black bars indicate subgroups at high risk of cardiovascular diseases and white bars indicate subgroups at low risk of cardiovascular diseases. Models were adjusted for HSBP/HDBP at the baseline survey, change in age, change in BMI and change in outdoor temperature from baseline.

In Scotland, Walker *et al.* [30] examined this relationship in a programme that built new central heating systems in the households of elderly individuals with inadequate or irreparable central heating facilities. They conducted a prospective control study that compared the diagnosis of heart diseases and hypertension in a central heating-introduced group (1281 households) and control group (1084 households). They found that the odds ratio for receiving a diagnosis of hypertension was 0.77 (95% CI: 0.61–0.97) for the central heating-introduced group, thereby confirming the positive effect of using central heating. However, given that the diagnosis of hypertension was based on self-reports using a questionnaire, this result was not based on objective data.

In contrast, two randomized controlled trials by Saeki *et al.* [31,32] are examples of studies based on objective data. One was an interventional study in which participants were randomly assigned to conduct measurements in either a laboratory set to 12°C or one set to 22°C. The other was an interventional study conducted in participants' actual living environments, where a doctor instructed the participants to turn on their heating to a set room temperature of 24°C one hour before getting out of bed. Both studies reported a significant decrease in SBP in the group with the higher

temperature setting at the time of waking. These studies focused on the way heating is used and recommended studies focusing on insulation retrofitting in the future.

An example of a study that used insulation retrofitting as an intervention was one conducted by Lloyd *et al.* [33], which examined the improvement in BP through provision of home renovation packages in Scotland. A housing renovation package was developed and included double-skinning the outer walls, introduction of insulation material, doubling glass on windows and introduction of gas central heating systems, which were conducted in the interventional study. Two blocks (36 houses) were chosen as the intervention group, while two other blocks were chosen as the control group. The intervention group alone showed significant improvements in BP. However, because the size of the final analysis sample was very small, with only 27 participants in the intervention group and nine participants in the control group, it is difficult to conclude that the results are universally applicable.

Building on the results of these studies, our study examined the effect of insulation retrofitting on HBP, with 1578 participants in the intervention group and 107 participants in the control group across Japan. We expect that the finding that HBP decreased due to home insulation

retrofitting in the present study will be useful in health policy for developing a population strategy to prevent CVDs.

Potential of insulation retrofitting as a population and high-risk strategy

Health Japan 21 (the second term) [34] is a policy established to prevent CVDs in Japan. This policy estimates that a 4 mmHg decrease in average SBP of Japanese aged 40–89 years (men: 138→134 mmHg, women: 133→129 mmHg) will lead to a corresponding decrease of approximately 14 000 deaths a year due to CVDs (approximately 9300 deaths a year due to cerebrovascular disease and approximately 4700 deaths a year due to ischemic heart disease) in Japan. The present results showed that insulation retrofitting led to a 3.1 mmHg decrease in HSBP at the time of waking. Therefore, insulation retrofitting of houses may be an effective population strategy for reducing HBP. Furthermore, the present results indicated that there was heterogeneity in the effect of insulation retrofitting, namely, hypertensive patients who are at high risk of CVDs might benefit much more from insulated housing than normotensive occupants at low risk of CVDs. Therefore, in addition to a population strategy, insulation retrofitting of houses may also be an effective high-risk strategy.

Strengths and limitations

There were three main strengths of this study. First, we conducted an intervention study and performed a longitudinal analysis of data from before and after the intervention, enabling robust examination of the longitudinal changes in HBP due to insulation retrofitting intervention. Second, measurement of objective variables such as HBP and indoor temperature was conducted at multiple time points, which may have reduced biases such as observational and social desirable response bias. Third, as the interval between the baseline and follow-up surveys was relatively short (more than 95% of participants had completed the follow-up survey within 2 years of the baseline survey), it is unlikely that participants changed lifestyle habits such as diet, smoking, drinking and exercise. The impact of changes in lifestyle on the results is therefore expected to be small.

This study had five main limitations. First, because this survey was conducted on households who had the intention of conducting insulation retrofitting, the results may not be applicable to other populations. For example, participants might be biased towards wealthy households, given that average household expenditure on renovation was about \$11 000 (see Table S2, Supplemental Digital Content, which shows cost information on home renovation, <http://links.lww.com/HJH/B381>). However, the present analysis was based on HBP and indoor temperature, which were objectively measured, so our findings may have generalizability. Second, because this survey was conducted as a nonrandomized controlled trial, there were differences in baseline characteristics and weather conditions in the intervention compared with control group. However, the intervention and control groups were chosen from the same population (participants who had the intention of conducting insulation retrofitting), and we adjusted

for those differences in the multiple linear regression model. In addition, as indoor temperature in the morning was slightly higher in the control group than the intervention group (Table 2), we also conducted an additional analysis in which the model was adjusted for indoor temperature at the baseline survey. Results were closely similar with the present result, indicating that the effect of the difference in indoor temperature between groups was small (see Table S3, Supplemental Digital Content, which shows the multiple linear regression model adjusted for indoor temperature at baseline, <http://links.lww.com/HJH/B381>). Third, this real-world survey could not control for changes in the use of heating with the intervention. As summarized from Table 4, some households showed a rise in indoor temperature of 3°C or more, while others showed a decrease in indoor temperature after insulation retrofitting. This was likely because we could not control the use of heating; accordingly, the frequency of heating may have decreased due to insulation retrofitting. The heating intervention study by Saeki *et al.* [32] in participants' actual living environments showed that SBP at the time of waking decreased by 4.4 mmHg. Therefore, an intervention that combines insulation and heating is expected to further increase indoor temperatures, and consequently reduce HBP. Fourth, the mechanism underlying the changes in HBP due to insulation retrofitting is unclear based on the present analysis. Although the coefficients for insulation retrofitting were slightly weakened when changes in indoor temperature were added to the model as an independent variable, only this variable could not account for a decrease in HBP by insulation retrofitting. One possible reason for this is that the frequency of heating may have changed due to insulation retrofitting, as described above. In addition, because indoor temperature at the time of HBP measurement was included in the model, it may be necessary to also add an index that reflects the variability in indoor temperature over time to the model. Moreover, it was necessary to account for near-floor air temperature or floor surface temperature due to the concentration of cutaneous thermoreceptors on the feet [35]. Further verification is required to clearly explain the mechanism. Finally, we could not investigate time-series BP data, although BP varies from hour to hour and from season to season. To determine whether the effect of insulation retrofitting is temporary, 24-h ambulatory BP monitoring (ABPM) is necessary to examine the effects based on other BP parameters, such as average daytime BP. We considered that night-time BP (which is also obtained from ABPM) is worthy of attention because it is a significant independent risk factor for future cardiovascular events [36]. As temperature in the bed is important for the verification of night-time BP and housing environment, future studies should investigate temperature in bed in addition to indoor temperature. Furthermore, hot temperatures in summer are associated with nocturnal hypertension [37] and seasonal variation in BP has attracted attention in recent years [38]. Given that heat loss through windows and walls is reduced in insulated homes, the indoor thermal environment in summer can be poor (hot) without proper cooling. Therefore, it is necessary to verify the effects of insulation retrofitting on BP throughout the year.

In conclusion, the results of this article demonstrate the short-term HBP-lowering effects of insulation retrofitting. Further studies are needed to determine whether there are long-term effects of insulation retrofitting using a cohort follow-up study of houses with high insulation performance and low insulation performance. We hypothesize that continuing to live in a cold house causes a vicious cycle, as prolonged hypertension can cause arteriosclerosis, which can result in further hypertension. Therefore, we believe that the long-term effects of living in highly insulated houses are truly valuable. The planned long-term cohort study (see Figure S1, Supplemental Digital Content, which provides an overview of the nationwide SWH survey in Japan, <http://links.lww.com/HJH/B381>) on the insulation retrofitting group and noninsulation retrofitting group aims to examine whether living in a warm house has a temporary or long-term effect on decreasing BP.

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Conflicts of interest

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