

# Seasonal variation in blood pressure reactivity to stress tests in young adults

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## Research Article

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# Abstract

## Background

Blood pressure (BP) reactivity is the BP rise to a given stimulus from baseline values, and is a strong predictor of hypertension and subsequent cardiovascular events. Blood pressure exhibits seasonal variations. However, the effect of seasonal variations on BP reactivity to stress is not well understood. This study aimed to explore the effect of seasonal variation on BP reactivity due to the cold pressor test (CPT) and handgrip test (HGT) among healthy young adults in Nepal.

## Methods

A prospective pretest–posttest study was conducted among 45 healthy students (55.6% female) with a mean age of  $21.62 \pm 2.93$  years. Blood pressure at baseline, during and after CPT and HGT interventions were measured as per protocol, during winter (December 2023) and summer (July 2024), and the BP reactivity was compared between two seasons using analytical statistics. The significance level was set at 5%.

## Results

Baseline mean BP were lower in summer than in winter season (SBP:  $107.71 \pm 12.17$  vs  $120.78 \pm 11.31$ ,  $p = 0.001$ ; DBP:  $71.49 \pm 8.74$  vs  $77.60 \pm 8.83$ ,  $p = 0.001$ ; paired t-test). During CPT, there was a significantly higher rise of BP in summer compared to the rise in winter (SBP:  $25.27 \pm 11.56$  vs  $13.84 \pm 11.17$ ,  $p < 0.001$ ; DBP:  $25.53 \pm 10.14$  vs  $13.51 \pm 7.15$ ,  $p < 0.001$ ; paired t-test). Similarly, HGT also raised BP higher in summer than winter (SBP:  $35.07 \pm 17.11$  vs  $25.47 \pm 14.81$ ,  $p = 0.008$ ; DBP:  $30.96 \pm 12.12$  vs  $24.16 \pm 11.64$ ,  $p = 0.009$ ; paired t-test); and this was confirmed in linear regression analysis ( $p < 0.01$ ). Independent effect of season on BP reactivity was confirmed by multiple linear regression analysis ( $p < 0.05$ ).

## Conclusion

Baseline BP is lower in summer compared to winter; but the BP reactivity to CPT and HGT is heightened in summer compared to winter, indicating seasonal modulation of cardiovascular stress responses, which may have implications for cardiovascular risk and adaptability to environmental changes.

## Introduction

Blood pressure (BP) is a dynamic physiological parameter that exhibits continuous fluctuations across time spans ranging from seconds to years (Parati et al. 2018). These fluctuations result from complex interactions among hemodynamic factors, neuronal reflexes, and hormonal, behavioural, and environmental stimuli that aim to maintain BP homeostasis (Rosei et al. 2020). Although often overlooked, environmental factors also importantly contribute to BP variations, as they influence physiological mechanisms involved in BP regulation, particularly through seasonal temperature changes (Cuspidi et al. 2012). Blood pressure increases during winter compared to summer, which has been observed in clinical settings, home BP monitoring and 24-hour ambulatory BP assessments (Modesti 2013; Iwahori et al. 2018; Goyal et al. 2019). This seasonal increase in BP is associated

with cardiovascular events, as it parallels with the well-established rise in the incidence of cardiovascular diseases during winter (Narita and Kario 2023).

Blood pressure rise to a given stimulus in relation to baseline values has been referred to as BP reactivity (Gauche et al. 2017). Evidence suggests that individuals exhibiting abnormal BP reactivity in response to physical or psychological stressors are at increased risk of developing hypertension and subsequent cardiovascular events independent of resting BP. (Dalve et al. 2025; Mariano et al. 2023; Flaa et al. 2008). It is a critical indicator of risk of hypertension (Dalve et al. 2025). The cold pressor test (CPT) and handgrip test (HGT) are well-established sympatho-excitatory stress tests used to evaluate cardiac autonomic function and to assess BP reactivity across different settings (Dillon et al. 2020). However, there is paucity of data available about the specific effects of season in stressor-induced cardiovascular responses. Thus, this study aims to assess seasonal differences in baseline systolic and diastolic BP and to determine variations in blood pressure responses to the CPT and HGT between summer and winter in young adults. This study attempts to answer the questions: What is the baseline as well as stressor-induced blood pressure in summer and winter season? Does the differential increase in stress response depend on baseline BP or does season has independent effect?

## **Materials and methods**

### **Study design and setting**

This prospective pretest-posttest prospective study was conducted among 45 healthy adults aged 17–30 years at the Department of Physiology, Karnali Academy of Health Sciences, Jumla, Nepal. Karnali Academy of Health Sciences (KAHS) is situated in the mountainous Karnali Province of northwestern Nepal at an altitude of approximately 2,300 m above sea level. The climate here varies from a warm temperate to an alpine climate with four distinct seasons: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). Data were collected at two time points representing contrasting seasonal conditions: winter (December 2023) and summer (July 2024) (Fig. 1).

### **Study population and sampling**

The study population consisted of undergraduate students enrolled in different programs during the 2023–2024 academic year. A purposive sampling technique was used for data collection. Sample size was calculated using the formula:  $n = 2[(Z_{\alpha/2} + Z_{\beta})^2 \times SD^2] / (\text{mean difference})^2$  at the power of 80%, 5% error, 95% confidence with a mean diastolic blood pressure difference of 8 mm Hg and standard deviation of 13 between summer and winter (Kimura et al. 2010). Allowing a non-response rate of 10% on follow-up visits, minimum sample size required for the study was 45. All consenting apparently healthy students were included. While participants with a history of any cardiovascular, neurological disorder or disabilities and Raynaud phenomenon, those under any medications affecting autonomic functions (such as beta blockers, muscarinic antagonists etc), and non-consenting students were excluded.

## **Ethical considerations**

### **Ethical approval**

was obtained from the Institutional Review Committee of KAHS (Ref. 079/80/22) and Nepal Health Research Council (Ref. No.2566, (31 March 2023). Informed written consent was obtained from all participants for their voluntary participation.

## Experimental procedures

The procedures were done in the summer as well as in winter season by following up of the same subjects. All participants were studied in the early afternoon, after abstaining from food and caffeine for at least 4 hours, and exercise and alcohol for at least 12 hours. Basic demographic information of participants, including age, sex, address, course and year of study were obtained by questionnaire. Health history and general physical examination was taken to rule out obvious diseases as per the exclusion criteria. In the autonomic function lab, room temperature was recorded by digital room thermometer (OMSONS Co., India). Humidity could not be recorded due to unavailability of the facility. All testing was conducted in the laboratory under ambient environmental conditions reflective of the natural seasonal temperature variation, with room temperature recorded at each session ( $22.5 \pm 3.35^{\circ}\text{C}$  in summer and  $10.32 \pm 5.63^{\circ}\text{C}$  in winter). This approach was deliberately chosen to preserve the ecological validity of seasonal exposure, as artificially maintaining a thermoneutral environment year-round would have eliminated the natural seasonal stimulus (both chronic acclimatization and acute thermal conditions) that is fundamental to the research question. While this design does not isolate acute cold stress from chronic seasonal adaptation, it reflects real-world conditions relevant to seasonal cardiovascular physiology.

## Blood Pressure Measurement

The participants were allowed to sit comfortably in a chair and were informed about the tests and the procedures. Baseline blood pressure was measured before the intervention using a digital automated blood pressure monitor (Dr. Morepen, BP-02, Morepen Laboratories Ltd., New Delhi, India). The BP was measured after the participant had been in a sitting position for 5 minutes. Three readings were taken at least 1 min apart. The mean of the last two readings was used as the final measurement. All measurements were made by the research team, including two physiologists. The same instrument sets were used throughout the study. After blood pressure measurement, participants then underwent two sympathoexcitatory stimuli: CPT followed by HGT maneuvers with 30 min of rest in between.

### Cold Pressor Test (Zygmunt and Stanczyk 2010)

First, the sphygmomanometer cuff was tied around the left arm to measure blood pressure. Then each participant was asked to immerse their right hand just above the wrist, in a bath of ice-water for 1 minute. The ice-water mixture temperature was monitored using a digital thermometer and was maintained at  $4\text{--}8^{\circ}\text{C}$  throughout the procedure for consistency. BP was measured three times: at 1 minute during hand immersion in the ice-water bath, and at 2 and 4 minutes post-immersion. The peak value was noted. The BP response to CPT was calculated by subtracting the baseline values from the peak values.

### Handgrip Test (Zygmunt and Stanczyk 2010)

After 30 min of rest, each participant was asked to grip the handgrip dynamometer (Labycare; S.K. Scientific and Surgicals, India) with maximal isometric force of the dominant hand. It was repeated three times, each 2 minutes

apart. The maximum value of the three readings was taken as the maximal voluntary contraction (MVC). Next, the participant was instructed to sustain the grip on the dynamometer at one third of the MVC for 4 minutes, or until exhaustion, whichever was early. During this procedure BP at the end of 1st, 2nd, 3rd and 4th minutes were recorded on the contralateral arm. If a subject couldn't perform for 4 minutes fully, last BP was taken before the release as the final measurement. The recovery BP was taken at 2 and 4 minutes after the release of the grip. Peak BP was noted. The BP response was calculated by subtracting the baseline BP from the peak BP.

## Data analysis

All the collected data were coded and entered in a spreadsheet program. Statistical package for social sciences version 16 (IBM® SPSS® v16) was used for statistical calculation. Descriptive statistics was used to calculate frequency, percentage mean and standard deviation. As data were parametric, comparative analysis was done using paired t-test and multiple linear regression analysis. A p-value of < 0.05 was taken as statistically significant.

## Results

A total of 45 health sciences students participated in the study, including female (n = 25, 55.6%) and male (n = 20, 44.4%) with the mean age  $21.62 \pm 2.93$  yrs. Blood pressure before and after the intervention (CPT and HGT) in winter and summer season is illustrated in Table 1. The result shows that the baseline systolic and diastolic BP are significantly higher in winter season compared to the summer season. Similarly, there is a statistically significant difference in the mean maximum DBP after the CPT intervention during winter and summer season, but not in other parameters.

Table 1

Seasonal comparison of baseline parameters and pressor responses in the participants (N = 45) (paired t-test)

| Variables              | Summer (Mean $\pm$ SD) | Winter (Mean $\pm$ SD) | Difference (winter - summer) | p value |
|------------------------|------------------------|------------------------|------------------------------|---------|
| Baseline SBP           | 107.71 $\pm$ 12.17     | 120.78 $\pm$ 11.31     | 13.07 $\pm$ 14.98            | 0.001*  |
| Baseline DBP           | 71.49 $\pm$ 8.74       | 77.60 $\pm$ 8.83       | 6.11 $\pm$ 10.75             | 0.001*  |
| Maximum SBP during CPT | 132.98 $\pm$ 12.92     | 134.62 $\pm$ 13.83     | 1.64 $\pm$ 16.67             | 0.512   |
| Maximum DBP during CPT | 97.02 $\pm$ 9.15       | 91.11 $\pm$ 9.88       | -5.91 $\pm$ 11.43            | 0.001*  |
| Maximum SBP during HGT | 142.78 $\pm$ 21.03     | 146.24 $\pm$ 18.66     | 3.47 $\pm$ 25.09             | 0.359   |
| Maximum DBP during HGT | 102.44 $\pm$ 14.34     | 101.76 $\pm$ 12.98     | -0.69 $\pm$ 18.16            | 0.800   |
| MVC during HGT (Kg)    | 28.96 $\pm$ 10.73      | 28.69 $\pm$ 11.61      | 0.27 $\pm$ 8.88              | 0.841   |

\* significant value at 99% confidence level.

SBP, Systolic Blood Pressure; DBP, Diastolic Blood Pressure; SD, Standard Deviation; CPT, Cold Pressor Test; HGT, Handgrip Test; MVC, Maximum Voluntary Contraction. All pressures are in mm of mercury column.

Following CPT and HGT intervention, there was a statistically significant rise in systolic and diastolic BP in summer compared to winter as illustrated in Fig. 2.

As a secondary analysis, sex-based comparison was done in the parameters (Table 2). In our participants, females showed significantly higher rise in SBP during CPT in summer, but not in winter, and none in DBP. During HGT, males showed significantly higher rise in both SBP and DBP in winter and only in DBP in summer.

Table 2  
Sex-based comparison of pressor responses to sympathetic stress tests (N = 45) (Student t-test)

| Parameters                                                                                                                                                                                                                                                                               | Mean $\pm$ SD Female | Mean $\pm$ SD Male | t-value | Effect Size (Cohen's d) | p-value |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|--------------------|---------|-------------------------|---------|
| Baseline SBP (overall)                                                                                                                                                                                                                                                                   | 113.76 $\pm$ 13.01   | 114.83 $\pm$ 14.0  | -0.38   | -0.08                   | 0.707   |
| Baseline DBP (overall)                                                                                                                                                                                                                                                                   | 74.69 $\pm$ 8.33     | 74.37 $\pm$ 10.37  | 0.17    | 0.04                    | 0.868   |
| Baseline SBP in winter                                                                                                                                                                                                                                                                   | 119.28 $\pm$ 11.90   | 122.65 $\pm$ 10.53 | -0.99   | -0.30                   | 0.326   |
| Baseline SBP in summer                                                                                                                                                                                                                                                                   | 104.76 $\pm$ 10.53   | 111.4 $\pm$ 13.3   | -1.87   | -0.56                   | 0.068   |
| Baseline DBP in winter                                                                                                                                                                                                                                                                   | 78.4 $\pm$ 8.64      | 76.6 $\pm$ 9.18    | 0.68    | 0.20                    | 0.503   |
| Baseline DBP in summer                                                                                                                                                                                                                                                                   | 71.4 $\pm$ 7.22      | 71.6 $\pm$ 10.53   | -0.08   | -0.02                   | 0.940   |
| $\Delta$ SBP_CPT winter                                                                                                                                                                                                                                                                  | 16.04 $\pm$ 11.81    | 11.1 $\pm$ 9.92    | 1.50    | 0.45                    | 0.142   |
| $\Delta$ SBP_CPT summer                                                                                                                                                                                                                                                                  | 28.92 $\pm$ 12.35    | 20.7 $\pm$ 8.79    | 2.51    | 0.75                    | 0.016*  |
| $\Delta$ DBP_CPT winter                                                                                                                                                                                                                                                                  | 15.04 $\pm$ 6.19     | 11.6 $\pm$ 7.95    | 1.63    | 0.49                    | 0.11    |
| $\Delta$ DBP_CPT summer                                                                                                                                                                                                                                                                  | 26.88 $\pm$ 10.39    | 23.85 $\pm$ 9.81   | 1.00    | 0.30                    | 0.325   |
| $\Delta$ SBP_HGT winter                                                                                                                                                                                                                                                                  | 19.96 $\pm$ 12.15    | 32.35 $\pm$ 15.22  | -3.04   | -0.91                   | 0.004*  |
| $\Delta$ SBP_HGT summer                                                                                                                                                                                                                                                                  | 31.68 $\pm$ 14.16    | 39.3 $\pm$ 19.78   | -1.51   | -0.45                   | 0.14    |
| $\Delta$ DBP_HGT winter                                                                                                                                                                                                                                                                  | 20.32 $\pm$ 7.88     | 28.95 $\pm$ 13.86  | -2.63   | -0.79                   | 0.012*  |
| $\Delta$ DBP_HGT summer                                                                                                                                                                                                                                                                  | 26.96 $\pm$ 11.06    | 35.95 $\pm$ 11.77  | -2.63   | -0.79                   | 0.012*  |
| * significant difference at 95% confidence                                                                                                                                                                                                                                               |                      |                    |         |                         |         |
| $\Delta$ SBP_CPT, change in systolic BP during Cold Pressor Test; $\Delta$ SBP_HGT, change in systolic BP during Handgrip test; $\Delta$ DBP_CPT, change in diastolic BP during Cold Pressor Test; $\Delta$ DBP_HGT, change in diastolic BP during Handgrip test. BP Values in mm of Hg. |                      |                    |         |                         |         |

To evaluate the relation between stress response with baseline BP, Pearson correlation analysis was done. The correlation matrix shows that baseline SBP correlated significantly with baseline DBP ( $r = 0.638$ ,  $p < 0.001$ ). The stress-induced rise in systolic and diastolic BP was significantly negatively correlated with baseline systolic and diastolic BP, respectively, except for rise in SBP in HGT. Rise in SBP and in DBP also correlated with each other in each test (Table 3). Age showed no significant correlation with any variables.

Table 3  
Pearson correlation matrix of age, baseline BP and stress-induced pressor responses (N = 45)

| Correlations                                                      |                     | Baseline DBP | Baseline SBP | $\Delta$ DBP_CPT | $\Delta$ SBP_CPT | $\Delta$ DBP_HGT | $\Delta$ SBP_HGT |
|-------------------------------------------------------------------|---------------------|--------------|--------------|------------------|------------------|------------------|------------------|
| Baseline SBP                                                      | Pearson Correlation | .638**       | 1            |                  |                  |                  |                  |
|                                                                   | Sig. (2-tailed)     | <0.001       |              |                  |                  |                  |                  |
| $\Delta$ DBP_CPT                                                  | Pearson Correlation | – .508**     | – .386**     | 1                |                  |                  |                  |
|                                                                   | Sig. (2-tailed)     | <0.001       | <0.001       |                  |                  |                  |                  |
| $\Delta$ SBP_CPT                                                  | Pearson Correlation | -0.175       | – .478**     | .614**           | 1                |                  |                  |
|                                                                   | Sig. (2-tailed)     | 0.1          | <0.001       | <0.001           |                  |                  |                  |
| $\Delta$ DBP_HGT                                                  | Pearson Correlation | – .228*      | -0.029       | .227*            | 0.11             | 1                |                  |
|                                                                   | Sig. (2-tailed)     | 0.031        | 0.787        | 0.031            | 0.303            |                  |                  |
| $\Delta$ SBP_HGT                                                  | Pearson Correlation | -0.067       | -0.14        | 0.191            | .286**           | 0.709**          | 1                |
|                                                                   | Sig. (2-tailed)     | 0.528        | 0.189        | 0.072            | 0.006            | < 0.001          |                  |
| Age                                                               | Pearson Correlation | 0.14         | 0.09         | 0.01             | -0.02            | -0.19            | -0.19            |
|                                                                   | Sig. (2-tailed)     | 0.2          | 0.42         | 0.94             | 0.89             | 0.07             | 0.07             |
| * significant at 95% confidence; ** significant at 99% confidence |                     |              |              |                  |                  |                  |                  |

A simple linear regression analysis was performed to determine the relationship between blood pressure and season (Table 4). It showed that season significantly predicted the pressor response for all four outcomes ( $p < 0.01$  for all). Winter shows consistently lower response (less rise in BP) compared to summer (B ranging from 7.62 to 10.61 mmHg). Alongside, baseline SBP and DBP also had significant negative relation with the pressure response, except for SBP rise in HGT. The standardized coefficients for season were relatively consistent across all four outcomes ( $\beta = 0.28$ – $0.50$ ), suggesting a robust seasonal effect on pressor reactivity of any type. In contrast, the effect of baseline SBP was highly variable – strongly predicting  $\Delta$ SBP\_CPT ( $\beta = -0.46$ ) but not  $\Delta$ SBP\_HGT ( $\beta \approx 0$ ), indicating that the influence of resting vascular tone depends on the nature of the stressor.

Table 4  
Multiple linear regression predicting pressor responses during CPT and HGT

| Dependent Variables                                                                | Predictor    | B     | SE   | $\beta$ | t     | p         | R <sup>2</sup> |
|------------------------------------------------------------------------------------|--------------|-------|------|---------|-------|-----------|----------------|
| $\Delta$ SBP_CPT                                                                   | Baseline SBP | -0.44 | 0.12 | -0.46   | -3.71 | < 0.001** | 0.35           |
|                                                                                    | Baseline DBP | 0.31  | 0.16 | 0.23    | 1.96  | 0.053     |                |
|                                                                                    | Age          | -0.29 | 0.44 | -0.07   | -0.67 | 0.506     |                |
|                                                                                    | Sex          | -4.43 | 2.48 | -0.18   | -1.78 | 0.078     |                |
|                                                                                    | Season       | 7.62  | 2.55 | 0.30    | 2.99  | 0.004**   |                |
| $\Delta$ SBP_HGT                                                                   | Baseline SBP | -0.05 | 0.18 | -0.04   | -0.29 | 0.77      | 0.14           |
|                                                                                    | Baseline DBP | 0.13  | 0.24 | 0.07    | 0.55  | 0.584     |                |
|                                                                                    | Age          | -0.71 | 0.67 | -0.12   | -1.07 | 0.288     |                |
|                                                                                    | Sex          | 4.69  | 3.75 | 0.14    | 1.25  | 0.215     |                |
|                                                                                    | Season       | 9.41  | 3.86 | 0.28    | 2.44  | 0.017*    |                |
| $\Delta$ DBP_CPT                                                                   | Baseline SBP | 0.12  | 0.09 | 0.15    | 1.41  | 0.161     | 0.5            |
|                                                                                    | Baseline DBP | -0.51 | 0.12 | -0.44   | -4.38 | < 0.001** |                |
|                                                                                    | Age          | -0.10 | 0.32 | -0.03   | -0.29 | 0.768     |                |
|                                                                                    | Sex          | -5.22 | 1.82 | -0.25   | -2.87 | 0.005**   |                |
|                                                                                    | Season       | 10.61 | 1.87 | 0.50    | 5.69  | < 0.001** |                |
| $\Delta$ DBP_HGT                                                                   | Baseline SBP | 0.31  | 0.13 | 0.33    | 2.45  | 0.016*    | 0.22           |
|                                                                                    | Baseline DBP | -0.42 | 0.17 | -0.32   | -2.52 | 0.014*    |                |
|                                                                                    | Age          | -0.36 | 0.47 | -0.08   | -0.77 | 0.446     |                |
|                                                                                    | Sex          | 4.49  | 2.65 | 0.18    | 1.69  | 0.094     |                |
|                                                                                    | Season       | 8.03  | 2.72 | 0.33    | 2.95  | 0.004**   |                |
| * significant at 95% confidence; ** significant at 99% confidence.                 |              |       |      |         |       |           |                |
| Sex was coded with female as reference; Season was coded with winter as reference. |              |       |      |         |       |           |                |

As stress response showed to be correlated with baseline BP as well as season, we wanted to assess whether season exerted an effect independent of baseline blood pressure. For this, we conducted a multiple linear regression (analysis of covariance (ANCOVA)) with season as a fixed factor and baseline SBP, baseline DBP, age and sex as covariates (Table 5). Season remained a significant predictor across all four outcomes ( $p < 0.05$  for all), confirming its additional influence beyond baseline BP. Partial  $\eta^2$  values showed that season explained significant variance in pressor responses, with the strongest effect on  $\Delta$ DBP\_CPT (27.8%), suggesting that cold-induced diastolic reactivity is particularly sensitive to seasonal variation. Model  $R^2$  ranged from 0.14 to 0.50, indicating moderate overall explanatory power for CPT responses but weaker fit for HGT responses. Baseline SBP strongly predicted rise in SBP by CPT ( $p < 0.001$ ) but not the same by HGT ( $p = 0.770$ ), while baseline DBP predicted rise in DBP in both tests ( $p < 0.001$  and  $p = 0.014$ , respectively). In addition, sex was a significant

predictor of rise in DBP by CPT, with females showing greater rise than males ( $B = -5.22$ ,  $p = 0.005$ ; partial  $\eta^2 = 0.057$ ). No sex differences were observed for  $\Delta SBP\_CPT$ ,  $\Delta SBP\_HGT$ , or  $\Delta DBP\_HGT$  ( $p > 0.05$  for all). Age was not significant in any model ( $p > 0.05$ ).

Table 5

Analysis of covariance (ANCOVA) for the independent effect of season on pressor response adjusting for baseline blood pressure, age and sex

| Dependent Variables | Season<br>$\eta^2$ , $p$ | Baseline SBP<br>$\eta^2$ , $p$ | Baseline DBP<br>$\eta^2$ , $p$ | Age<br>$\eta^2$ , $p$ | Sex<br>$\eta^2$ , $p$ | R <sup>2</sup> |
|---------------------|--------------------------|--------------------------------|--------------------------------|-----------------------|-----------------------|----------------|
| $\Delta SBP\_CPT$   | 0.096, 0.004             | 0.141, < 0.001                 | 0.044, 0.053                   | 0.004, 0.506          | 0.028, 0.078          | 0.35           |
| $\Delta SBP\_HGT$   | 0.066, 0.017             | 0.001, 0.770                   | 0.004, 0.584                   | 0.012, 0.288          | 0.017, 0.215          | 0.14           |
| $\Delta DBP\_CPT$   | 0.278, < .001            | 0.023, 0.161                   | 0.186, < .001                  | 0.001, 0.768          | 0.057, 0.005          | 0.5            |
| $\Delta DBP\_HGT$   | 0.094, 0.004             | 0.067, 0.016                   | 0.07, 0.014                    | 0.005, 0.446          | 0.026, 0.094          | 0.22           |

## Discussion

The purpose of this study was to characterize seasonal variations in baseline and BP responses to the CPT and HGT in young adults. This study provides novel and potentially important data that baseline systolic and diastolic BP were significantly higher in winter compared to summer and the BP responses to both CPT and HGT were more pronounced during the summer. These results suggest a complex interplay between seasonal environmental factors and cardiovascular autonomic mechanisms.

In the present study, mean systolic blood pressure (SBP) was 13 mmHg higher and diastolic blood pressure (DBP) was 6 mmHg higher in winter than in summer. A similar seasonal pattern has been reported in previous studies. For instance, a meta-analysis reported that both systolic and diastolic BP are higher in colder seasons compared to warmer ones, with differences averaging 3.42 mm Hg for systolic BP and 2.86 mm Hg for diastolic BP (Kuzmenko et al. 2022). Another study on normotensive women aged 18–40 years in urban India reported increases of 11 mmHg in SBP and 7 mmHg in DBP from summer to winter (Sinha et al. 2010), while another study from North India observed a seasonal difference of 9/6 mmHg (SBP/DBP) with higher reading in winter (Goyal et al. 2018). The increase in BP observed in the present study was somewhat larger than that reported in these and several other investigations and meta-analyses (Kollias et al. 2020; Tu et al. 2013; Imai et al. 1996). This discrepancy may be related to differences in subject characteristics, climatic conditions, environmental exposures, geographic location, or methodological approaches used to assess BP, which are shown to be significant factors (Brennan et al. 1982; Kollias et al. 2020). For instance, the availability of indoor temperature control at home or in the workplace (which generates a larger gradient between outdoor and indoor temperatures while reducing seasonal changes in living ambient temperature) has been shown to attenuate the increase in BP from summer to winter significantly (Cuspidi et al. 2012). Importantly, in the present study, measurements were conducted in a setting without strict thermoneutral temperature control, reflecting the typical environmental conditions of our region where heating and cooling systems are not routinely used. As a result, participants were likely exposed to ambient temperature variations similar to those experienced in daily life at home. This may have

amplified the observed BP differences compared with studies conducted under optimum temperature conditions. Although thermoneutral environment minimizes temperature-related variability, it may also mask the physiologically relevant cardiovascular responses to environmental temperature exposure (Heller et al. 1978). Therefore, our findings may provide a more realistic estimate of seasonal BP variation in everyday settings. Several environmental and behavioural factors contributed to the winter and summer differences in BP. In winter, exposure to cold temperature is associated with increased sympathetic tone and an increase in noradrenaline level in urine and blood. It also causes vasoconstriction, endothelial dysfunction, activation of renin-angiotensin-aldosterone system via multiple mechanisms; collectively contributing to an increase in blood pressure (Rosenthal 2004; Fares 2013; Handler 2011). In addition, winter has been associated with increased energy intake, which may indirectly contribute to elevated blood pressure through weight gain (Fujihira et al. 2023; Visscher and Seidell 2004). Cold exposure has also been reported to enhance salt intake (Saeki 2015). Meanwhile, sweating tends to decrease during winter. Considering the role of sodium in blood pressure regulation and the greater salt sensitivity observed in Asian populations, we believed that such seasonal change could also increase BP level in winter compared to summer (Park et al. 2020; Sarzani et al. 2014). Our results show that cardiovascular response to stress is increased on the face of lower baseline blood pressure. Our data is insufficient to draw any conclusion about this while doing the intraseasonal analysis, but previous evidence has shown that individuals with lower baseline sympathetic tone exhibit greater BP reactivity to cold pressor testing (Youssef et al. 2018). A notable finding of the present study is that BP responses to CPT and HGT were greater during summer, which is beyond the effect of different baseline BP across seasons. In both linear and multiple regression models, season remained a significant independent predictor of all pressor responses after adjusting for covariates ( $p < 0.05$  for all). The standardized coefficients ( $\beta$ ) for season were relatively consistent across outcomes, suggesting a stable effect size. The proportion of variance explained by season (partial  $\eta^2$ ) were variable, with the largest value observed for the diastolic response to CPT. However, as we did not directly compare these effect sizes statistically, this difference should be interpreted descriptively and warrants further investigation. This suggests that baseline blood pressure and stress-induced cardiovascular reactivity may not follow parallel seasonal patterns, and that seasonal modulation of sympathetic reactivity operates through mechanisms beyond resting vascular tone. One possible mechanism of increased cardiovascular reactivity at lower sympathetic tone in summer is that winter-associated elevation in resting sympathetic tone may reduce the relative capacity for further sympathetic drive during stress testing, reflecting a lower pressor response than summer. However, this hypothesis remains speculative because sympathetic activity was not directly assessed. These shifts in reactivity may have clinical implications, particularly in individuals at risk for stress-induced hypertensive episodes. It means that both baseline tone and reactive responses needs to be considered when examining cardiovascular and autonomic function, as they may be influenced by distinct physiological mechanisms and adaptive processes. It also opens avenues for considering seasonal factors in cardiovascular risk stratification.

Taken together, these findings indicate that resting and reactive cardiovascular responses may be regulated through partially distinct physiological mechanisms. Baseline BP elevation in winter is likely driven by a high sympathetic tone for thermoregulation (such as peripheral vasoconstriction); while heightened stress reactivity in summer may reflect adaptive phasic sympathetic response to environmental changes. Hormonal factors (cortisol, vasopressin, and other stress-related mediators) are important mediators of such stress response which fluctuate with seasonal variations in response to daylight, temperature, and humidity, influencing both baseline and reactive cardiovascular autonomic responses (Tsigos et al. 2020). Variation in those mediators would have been important parameter to describe the mechanism, which was not done in this study owing to the limited facility. Future studies might focus on the mechanisms of such responses.

Seasonal BP variability may also be influenced by sex related biological differences, although existing evidence remains inconsistent. Stergiou et al. (2015) observed a greater decline in blood pressure in summer among females compared with males, whereas a large population-based study from Taiwan demonstrated a more pronounced seasonal BP variation in men. In the present study, as a secondary analysis, we found that females showed a greater reduction in both systolic and diastolic BP from winter to summer than males; however, these differences did not reach statistical significance. We also observed sex related differences in BP reactivity to sympathetic stressors, although these were not uniform across tests. Females demonstrated a greater SBP response to CPT during summer, whereas males exhibited a larger BP response to HGT during winter in our sample. Previous studies have reported attenuated cardiovascular and sympathetic responses to isometric handgrip exercise in females as was demonstrated in our samples (Ettinger et al. 1996), while others have found comparable sympathetic activation between males and females during HGT (Jones et al. 1996) and CPT testing (Jarvis et al. 2011). Though we have found some significant differences between male and female of our participants, it was not enough to take any conclusion in this line. Further research can be designed to specifically study the gender difference, including the changes in menstrual cycle, which has not been accounted for in this study.

A major strength of this study is its repeated-measures design, in which the same participants were assessed during both summer and winter. In addition, the study examined not only resting BP but also BP reactivity to sympathetic stressors, providing a broader assessment of cardiovascular autonomic regulation. There are limitations in our study. The potential confounding variables such as physical activity levels, dietary patterns, BMI, humidity, sun exposure, daily outdoor temperature were not quantified and may influence BP and sympathetic responses. In addition, only single event of stress test and measurement risks including diurnal variation as confounder, for which we have tried to take the measurements at around noon for all the cases. Also, small sample size and single center would limit its generalisability. Future longitudinal studies across all four seasons, incorporating ambulatory BP monitoring, core temperature, and sympathetic biomarkers, are needed to confirm these findings and clarify the mechanisms underlying seasonal and sex-specific vascular reactivity.

## **Conclusions**

This study demonstrates that in healthy young adults, baseline BP is higher during winter, whereas BP responses to stressors are more pronounced in summer. These findings highlight a seasonal modulation of both resting and reactive cardiovascular regulation. The elevation in BP reactivity during summer, despite lower baseline BP, has implications for risk assessment, performance, and management of stress-related cardiovascular conditions. Further research is warranted to explore the underlying mechanisms and clinical relevance of these seasonal variations.

## **Declarations**

## **Ethics approval:**

Ethical approval was obtained from the Institutional Review Committee of Karnali Academy of Health Sciences, Jumla (Ref. 079/80/22) and the Nepal Health Research Council (Ref. No. 2566) prior to the study.

## **Consent to participate:**

Informed written consent was obtained from all individual participants for their voluntary participation.

### **Conflicts of interest:**

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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## **Author Contribution**

Author contributions: D.B.P.: conceptualization, data collection, analysis, supervision, resources, validation, writing original draft, review and editing.

J.P.J.: conceptualization, data collection, methodology, software, resources, analysis, validation, writing original draft, review and editing.

B.T.: analysis, resources, validation, visualization, review and editing.

All authors read and approved the final manuscript.

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## **Data Availability**

The relevant data of this study are available from the corresponding author upon reasonable request.

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## Figures

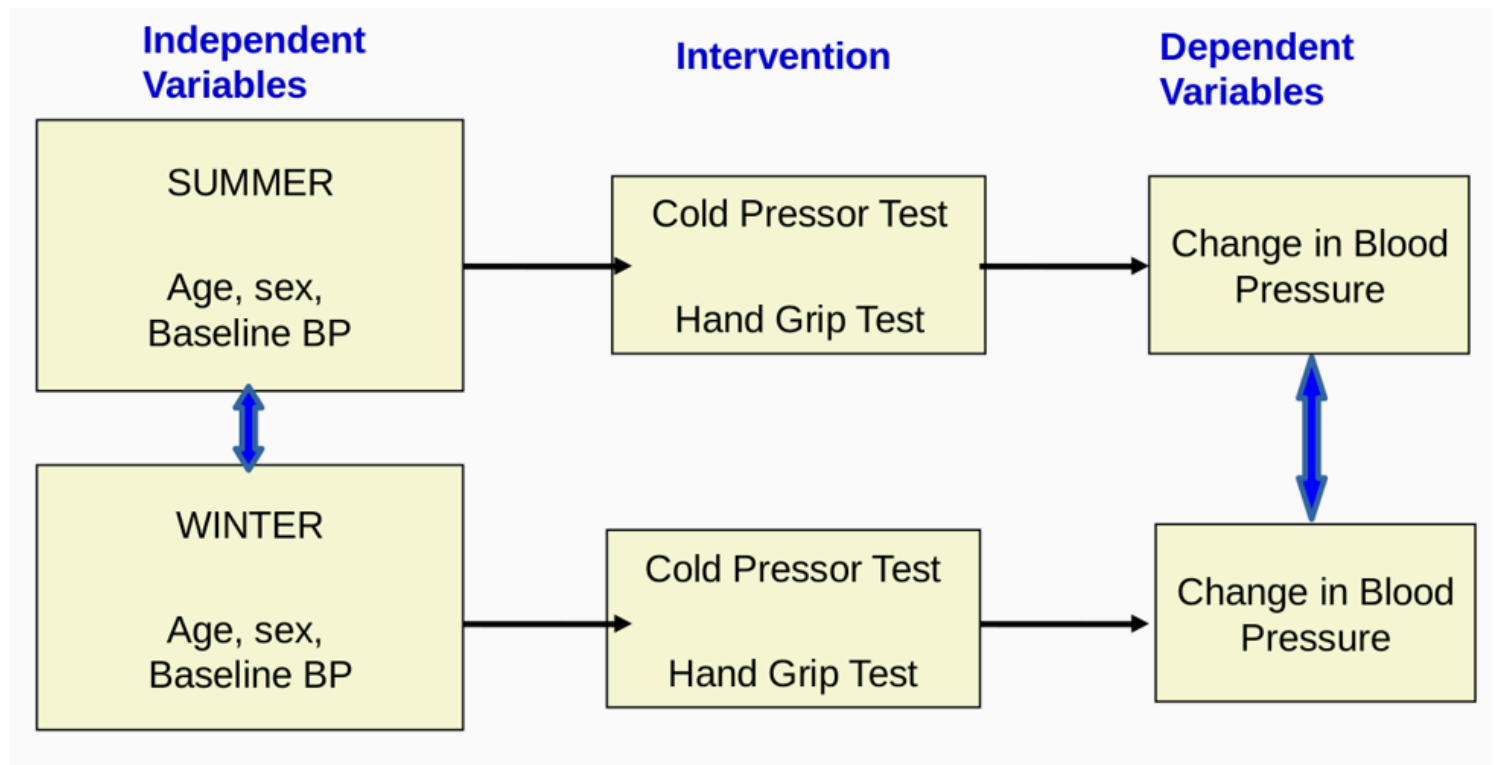


Figure 1

Flow chart for the procedures of this study

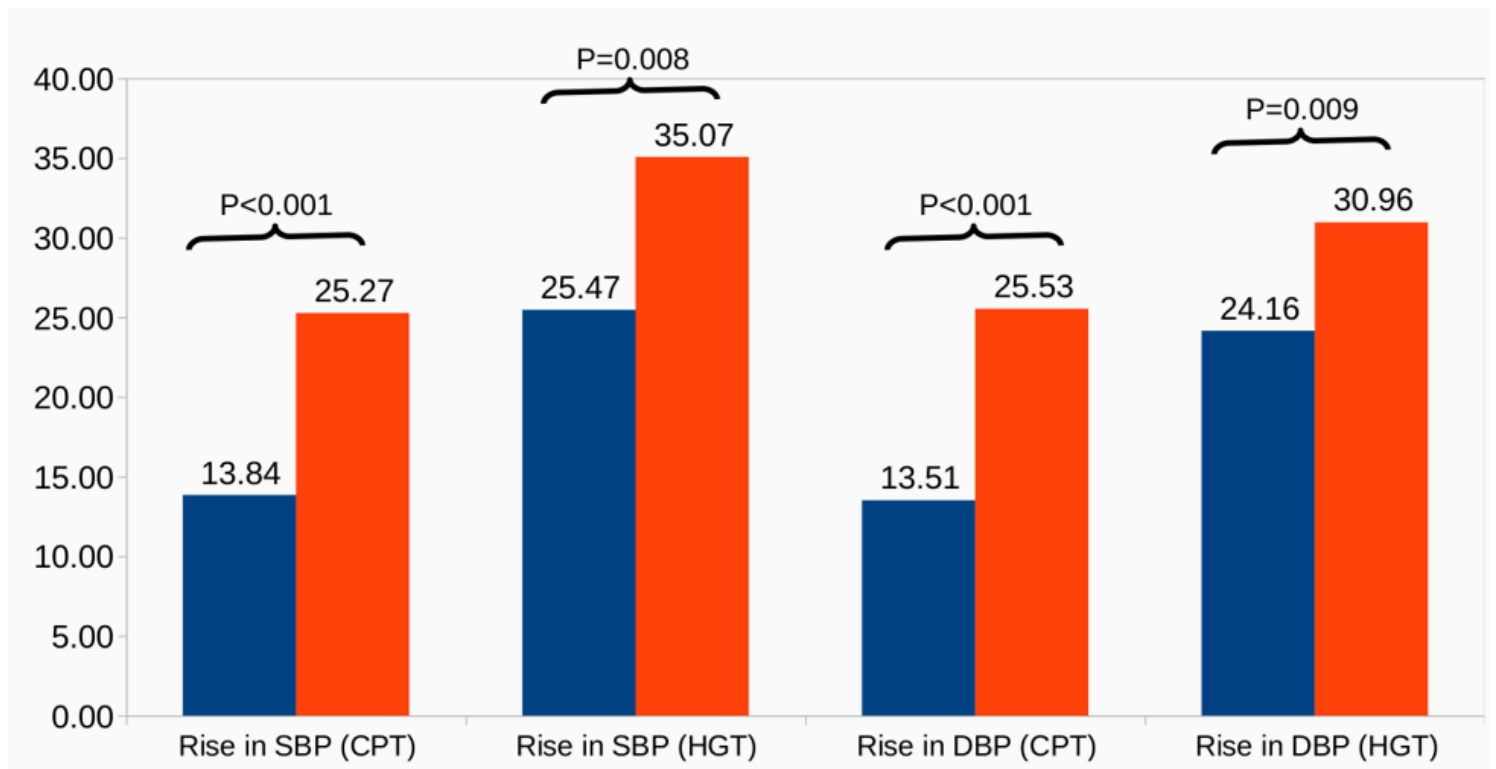


Figure 2

Mean rise in SBP and DBP during CPT and HGT in summer (red bar) and winter (blue bar)