©Journal of Sports Science and Medicine (2021) **20**, 448-456
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2021.448

Research article

Augmentation Index Predicts the Sweat Volume in Young Runners

Yen-Yu Liu [1,2,3], Chung-Lieh Hung [2,3,4], Fang-Ju Sun [4,5,6], Po-Han Huang [7], Yu-Fan Cheng [8] and Hung-I Yeh [2,3,4] ✉

[1] Department of Critical Care Medicine, MacKay Memorial Hospital, Taipei, Taiwan; [2] Cardiovascular Division, Department of Internal Medicine, MacKay Memorial Hospital, Taipei, Taiwan; [3] Institute of Biomedical Sciences, Mackay Medical College, New Taipei City, Taiwan; [4] Mackay Junior College of Medicine, Nursing and Management, Taipei, Taiwan; [5] Department of Medical Research, MacKay Memorial Hospital, Taipei, Taiwan; [6] Institute of Biomedical Informatics, National Yang Ming University, Taipei, Taiwan; [7] General Internal Medicine, Mackay Memorial Hospital, Taipei, Taiwan; [8] General Internal Medicine, Taipei Medical University Hospital, Taipei, Taiwan

Abstract

Sweating during exercise is regulated by objective parameters, body weight, and endothelial function, among other factors. However, the relationship between vascular arterial stiffness and sweat volume in young adults remains unclear. This study aimed to identify hemodynamic parameters before exercise that can predict sweat volume during exercise, and post-exercise parameters that can be predicted by the sweat volume. Eighty-nine young healthy subjects (aged 21.9 ± 1.7 years, 51 males) were recruited to each perform a 3-km run on a treadmill. Demographic and anthropometric data were collected and hemodynamic data were obtained, including heart rate, blood pressure and pulse wave analysis using non-invasive tonometry. Sweat volume was defined as pre-exercise body weight minus post-exercise body weight. Post-exercise hemodynamic parameters were also collected. Sweat volume was significantly associated with gender, body surface area (BSA) (b = 0.288, p = 0.010), peripheral systolic blood pressure (SBP), peripheral and central pulse pressure (PP), and was inversely associated with augmentation index at an HR of 75 beats/min (AIx@HR75) (b = -0.005, p = 0.019) and ejection duration. While BSA appeared to predict central PP (B = 19.271, p ≤ 0.001), central PP plus AIx@HR75 further predicted sweat volume (B = 0.008, p = 0.025; B = -0.009, p = 0.003 respectively). Sweat volume was associated with peripheral SBP change (B = -17.560, p = 0.031). Sweat volume during a 3-km run appears to be influenced by hemodynamic parameters, including vascular arterial stiffness and central pulse pressure. Results of the present study suggest that vascular arterial stiffness likely regulates sweat volume during exercise.

Key words: Exercise, sweat, body surface area, augmentation index, hemodynamic parameters.

Introduction

Perspiration, a physical reaction during exercise, is crucial to maintain the body's core temperature. Body heat production during exercise elevates internal temperature as well as skin temperature, and must be dissipated rapidly or damage to vital organs may occur with subsequent disability and even death may occur by heatstroke (Araki et al., 1981; Beigel et al., 2010). Thermoregulation mechanisms during exercise are complicated. Muscle contractions during exercise result in elevation of internal temperature and increases the sweat rate sequentially. However, sweat can be initiated within seconds at the start of dynamic exercise and may change rapidly before measurable alteration in the internal temperature (Shibasaki and Crandall, 2010; Van Beaumont and Bullard, 1963). The non-thermal factors including cortical irradiation and exercise pressor reflex also modulate sweating during exercise (Shibasaki and Crandall, 2010). Sweat is further influenced by other factors, including environmental temperature, relative humidity, menstrual cycle, physical fitness level, and thermoregulatory effectiveness (Araki et al., 1981; Cramer and Jay, 2015; Ichinose-Kuwahara et al., 2010).

Pulse pressure (PP) is the difference between systolic blood pressure (SBP) and diastolic blood pressure (DBP), which represents the episodic nature of cardiac contraction and the properties of arterial circulation (Dart and Kingwell, 2001). Physiologically, PP augmented with exercise is owed to increased stroke volume with increased stiffness of the large arteries and aorta. Aging, arterial compliance, vascular endothelial function, and atherosclerosis are also determinants of PP (Beigel et al., 2010). Thus, PP serves as a risk factor for cardiovascular disease. Rate pressure product (RPP) is generated from heart rate (HR) and SBP (HR x SBP/1000) and has been applied to estimate myocardial workload in cardiology and exercise physiology. Normally, values of up to 12 at rest and up to 22 in stress define the normal zone of RPP. Myocardial oxygen consumption and sufficiency of coronary perfusion can be assessed by RPP in normal young adults (Sembulingam and Ilango, 2015). However, the effects of PP and RPP on sweat volume during exercise remains unclear.

Pulse wave analysis is a non-invasive technique utilizing applanation tonometry to record the cyclic movement of radial artery wall; it is able to predict central blood pressure, systemic arterial stiffness, subclinical atherosclerosis, myocardial oxygen supply and consumption (Brazier et al., 1974; O'Rourke and Gallagher, 1996; Rosenbaum et al., 2013; Safar and London, 2000).

The augmentation pressure (AP) is an additional pressure generated from reflected wave adding on the forward wave, and the augmentation index is defined as the AP as a percentage of the PP (Stoner et al., 2014). Augmentation index standardized at a HR of 75 beats/min (AIx@HR75), an index normalized for a heart rate of 75 bpm, is equal to (-0.48*(75-HR) + Aix). Both PP and pulse wave form reflect arterial stiffness, which was reported to be affected by chemical factors, including circulating hormone and vitamin levels (Jia et al., 2018; Yeh et al., 2020).

Received: 02 April 2021 / Accepted: 13 May 2021 / Published (online): 25 May 2021

However, the influence of physical factors, such as sweat volume during exercise, on pulse pressure and pulse wave form remains unclear. In this study, we recruited young adults to each perform a 3-kilometer (km) run on a treadmill with hemodynamic monitoring before and after the exercise as well as sweat volume quantification. This study aimed to identify hemodynamic parameters before exercise that can predict sweat volume during exercise, and post-exercise parameters that can be predicted by the sweat volume.

Methods

Study design and sample

Between July 2014 and September 2016, 90 young adults were recruited to join this prospective observational study. Inclusion criteria were healthy volunteers aged 20-40 years with normal blood pressure and 12-lead surface EKG. Those who had any known cardiovascular diseases, renal diseases, significant other diseases or organ dysfunction, or who could not afford or were unable to run, or those who were not willing to provide signed informed consent or participate in the study were excluded.

Ethical considerations

This study was approved by our hospital (IRB number 14MMHIS091). All study subjects were volunteers who provided signed informed consent to participate. All procedures performed were in accordance with the ethical standards of the Helsinki Declaration and its later amendments, or comparable ethical standards.

Study procedure

The study was held in an air-conditioned gym with an average temperature of 27.0 degrees Celsius and relative humidity of 65.0%. Baseline arterial pulse wave for each participant was recorded using non-invasive tonometry technique from the radial artery utilizing the SphygmoCor device (SphygmoCor; Atcor Medical, Sydney, Australia). Operation index was > 90% for measurement of arterial waveforms. The subjects were asked to drink sufficient water. Naked body weight ($weight_{pre}$) was recorded immediately after emptying bladder and immediately before exercise in a private room. After that, the subjects put on their running clothes and each participated in a 3-km run on a treadmill (SPRINT 9875A AC Motorized treadmill, JKexer, Taipei, Taiwan). After a short period of warm-up, each subject underwent his run at a fixed speed of 10 km/hr. All volunteers tolerated the whole procedure and the total exercise time was around 18-20 minutes accordingly. Immediately after completion of the 3-km run, subjects wiped their perspiration with a dry towel, undressed in a private room, and recorded their naked body weight after the exercise ($weight_{post}$). The difference between the body weights ($weight_{pre}$ minus $weight_{post}$) was calculated as the sweat volume during the run. Fluid supplements were prohibited between the two measurements of weight. Finally, HR and blood pressure were rechecked again. The study protocol and number of participants are summarized in Figure 1.

Statistical analysis

All data are presented as mean ± standard deviation (mean ± SD). Association between sweat volume, AIx@HR75, and parameters were analyzed using Pearson correlation coefficient analysis. The parameters significantly related to sweat volume were then included in multiple linear regression analyses in 6 models. Variables in model 1 were BSA and AIx@HR75. Variables in model 2 were BSA and baseline peripheral PP. Variables in model 3 were AIx@HR75 and baseline peripheral PP. Variables in the mode 4 were BSA, AIx@HR75, and baseline peripheral PP. The enter selection method was used as the stopping rule to select clinical predictors (when variables showed statistical significance in univariate Pearson correlation coefficient analysis) in model 5. Step-wise selection method was used to choose clinical predictors as the stopping rule (when variables showed statistical significance in univariate Pearson correlation coefficient analysis) in model 6.

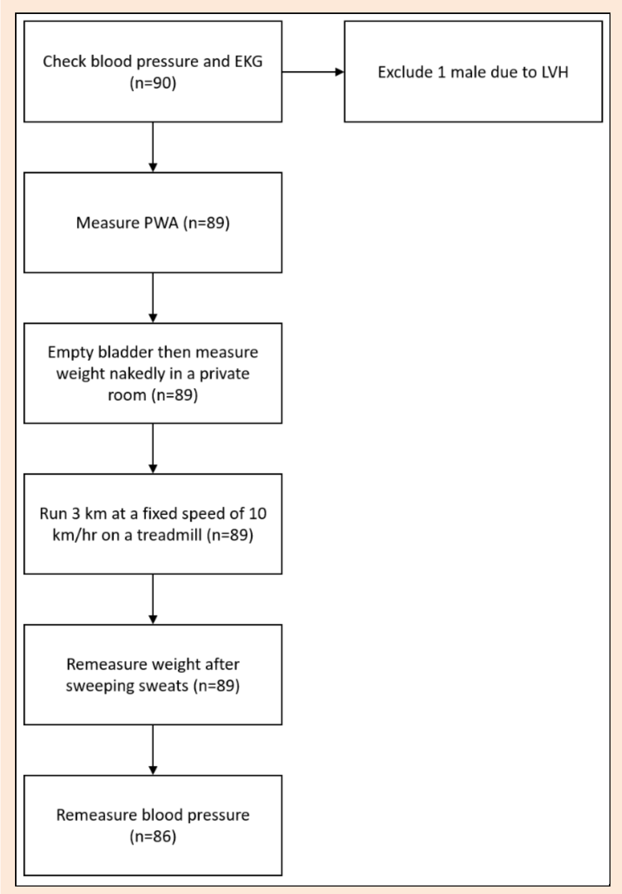

Figure 1. Flowchart of exercise and measurement of sweat volume during exercise. LVH, left ventricular hypertrophy.

For multivariate analysis of all continuous outcomes, the generalized structural equation modeling (GSEM) was performed to verify whether the relationship between BSA and all outcomes (sweat volume and change of peripheral SBP [$exercise_{post}$ minus $exercise_{pre}$]) were mediated by AIx@HR75 and peripheral PP or not in all subjects, male, and female. In the first model, the relationship between the BSA and sweat volume was examined to determine whether they were mediated by AIx@HR75 and peripheral PP or not. In the second model, the relationship between BSA and changes in peripheral SBP were examined to determine which were mediated by AIx@HR75, peripheral PP, and sweat volume or not. All reported *p* values were based on two-sided tests and those less than 0.05 were considered statistically significant. Data were analyzed using IBM SPSS release 21.0 (IBM, Armonk, New York) and the GSEM models were analyzed by Stata 15 Model Builder (Stata Corp. Houston, TX, USA).

Results

Demographics and baseline characteristics

Demographics and baseline characteristics are presented in Table 1. Among 90 subjects, one male was excluded since his EKG showed left ventricular hypertrophy, leaving 89 participants (51 males, 57%) who completed the 3-Km run. Mean age was 22.2 ± 1.9 years for mal and 21.5 ± 1.4 years for female (p = NS). Height (p < 0.001), weight (p < 0.001), BSA (p < 0.001), sweat volume (p = 0.003), peripheral SBP (p < 0.001), peripheral mean blood pressure (MBP) (p = 0.008), peripheral PP (p < 0.001), and peripheral RPP (p = 0.013) were significantly different between male and female, while mean body mass index (BMI), mean HR, and peripheral diastolic blood pressure were similar between male and female.

Pulse wave analysis

Significant differences were found in AIx@HR75 (p = 0.001), ejection duration (ED) (p = 0.001), ED percentage (p = 0.038), sub-endocardial viability ratio (SEVR) (p = 0.014), diastolic pressure-time index (p = 0.004), central SBP (p = 0.001), central PP (p = 0.001) and pulse pressure amplification (PPA)(p = 0.040) between genders, while no significant differences between genders were found in systolic pressure-time index, central DBP, and central RPP. In addition, AIx@HR75 was associated with gender (p = 0.001), height (p = 0.001), weight (p = 0.001), BSA (p < 0.001), sweat volume (p < 0.001), peripheral SBP (p = 0.003), peripheral PP (p = 0.003), ED (p < 0.001), ED percentage (p = 0.026), SEVR (p < 0.001), and PPA (p < 0.001), as shown in Table 2.

Analysis of sweat volume after 3-km run

Results of Pearson correlation analysis showed that sweat volume was significantly associated with gender (p = 0.003), height (p = 0.007), weight (p < 0.001), BMI (p = 0.011), BSA (p < 0.001), peripheral SBP (p = 0.003), peripheral PP (p = 0.001), and central PP (p = 0.004), but was negatively associated with AIx@HR75 (p = 0.001) and ED percentage (p = 0.028) in all subjects (Table 3 and Figure 2). In male, sweat volume was significantly and positively associated with peripheral SBP (p = 0.044), peripheral PP (p = 0.008), central PP (p = 0.015), but negatively associated with age (p = 0.049) and AIx@HR75 (p = 0.005) as in Table 2. Multiple linear regression models showed relationships between sweat volume and BSA (b = 0.288, p = 0.010) and AIx@HR75 (b = -0.005, p = 0.019) in model 1; BSA (b = 0.307, p = 0.010) and central PP (b = 0.005, p = 0.131) in model 2; and between AIx@HR75 (b = -0.007, p = 0.001) and central PP (b = 0.008, p = 0.006) in model 3; between BSA (b = 0.187, p = 0.126), AIx@HR75 (b = -0.006, p = 0.011) and central PP (b = 0.006, p = 0.069) in model 4; between AIx@HR75 (b = -0.007, p = 0.049) in model 5; and between BSA (b = 0.288, p = 0.010) and AIx@HR75 (b = -0.005, p = 0.019) in model 6 (Table 4).

Table 1. **Demographics and baseline characteristics.**

	Total subjects (n=89)	Male (n=51)	Female (n=38)	*p* valve
Age (years)	21.9 ± 1.7	22.2 ± 1.9	21.5 ± 1.4	0.069
Height (m)	1.70 ± 0.09	1.74 ± 0.08	1.64 ± 0.07	< 0.001
Weight (kg)	62.5 ± 10.3	66.6 ± 10.0	57.1 ± 8.1	< 0.001
BMI (kg/m^2)	21.5 ± 2.5	21.9 ± 2.5	21.1 ± 2.4	0.149
BSA (m^2)	1.72 ± 0.18	1.79 ± 0.16	1.61 ± 0.14	< 0.001
Weight loss (sweat volume; kg)	0.47 ± 0.19	0.51 ± 0.18	0.40 ± 0.17	0.003
HR (bpm)	76 ± 11	76 ± 12	76 ± 9	0.892
Peripheral SBP (mm Hg)	114.0 ± 12.7	118.6 ± 13.2	107.7 ± 8.7	< 0.001
Peripheral DBP (mm Hg)	67.1 ± 9.3	67.9 ± 10.9	66.0 ± 6.7	0.311
Peripheral MBP (mmHg)	82.7 ± 9.1	84.8 ± 10.2	79.9 ± 6.6	0.008
Peripheral PP (mm Hg)	46.9 ± 11.1	50.7 ± 12.0	41.7 ± 7.2	< 0.001
Peripheral RPP	8.68 ± 1.58	9.04 ± 1.70	8.20 ± 1.28	0.013
Pulse wave analysis				
AIx@HR75 (%)	3.4 ± 8.6	0.8 ± 7.6	7.0 ± 8.8	0.001
ED (ms)	278.8 ± 24.7	271.6 ± 22.1	288.4 ± 25.0	0.001
ED (%)	35.3 ± 4.1	34.5 ± 4.5	36.3 ± 3.2	0.038
SEVR (%)	162.7 ± 32.2	169.9 ± 36.4	153.1 ± 22.7	0.014
DPTI (mm Hg-sec/min)	3022.4 ± 411.0	3127.8 ± 443.1	2881.0 ± 317.2	0.004
SPTI (mm Hg-sec/min)	1885.0 ± 272.6	1884.1 ± 313.3	1886.1 ± 209.9	0.971
Central SBP (mm Hg)	96.4 ± 9.6	99.1 ± 10.5	92.8 ± 6.9	0.001
Central DBP (mm Hg)	68.4 ± 9.2	69.2 ± 10.8	67.2 ± 6.6	0.284
Central PP (mm Hg)	28.0 ± 6.5	29.9 ± 7.2	25.5 ± 4.3	0.001
Central RPP	7.35 ± 1.31	7.56 ± 1.45	7.06 ± 1.05	0.072
Pulse pressure amplification	1.7 ± 0.1	1.7 ± 0.1	1.6 ± 0.2	0.040

BMI, body mass index; BSA, body surface area; HR, heart rate; SBP, systolic blood pressure; DBP, diastolic blood pressure; MBP, mean blood pressure; PP, pulse pressure; RPP, rate pressure product; Aix@HR75, Augmentation Index standardized for HR at 75 bpm; ED, ejection duration; SEVR, Sub-endocardial viability ratio; DPTI, diastolic pressure-time index; SPTI, systolic pressure-time index. P value is for comparison between male and female.

Table 2. Associations between AIx@HR75 and hemodynamic parameters.

	Total		Male		Female	
	r	p	r	p	r	p
Age	-0.127	0.237	-0.096	0.501	-0.011	0.946
Gender	-0.357	0.001				
Height	-0.342	0.001	-0.211	0.137	-0.159	0.339
Weight	-0.347	0.001	-0.141	0.323	-0.346	0.033
BMI	-0.214	0.044	-0.046	0.746	-0.321	0.049
BSA	-0.371	<0.001	-0.172	0.227	-0.330	0.043
weight loss (sweat volume)	-0.353	0.001	-0.391	0.005	-0.131	0.432
Peripheral SBP	-0.310	0.003	-0.128	0.372	-0.310	0.058
Peripheral DBP	-0.054	0.614	0.058	0.684	-0.169	0.311
Peripheral MBP	-0.180	0.092	-0.014	0.923	-0.250	0.129
Peripheral PP	-0.307	0.003	-0.193	0.174	-0.218	0.188
Peripheral RPP	-0.169	0.114	0.019	0.892	-0.248	0.134
Pulse wave analysis						
ED (ms)	0.376	<0.001	0.263	0.062	0.317	0.052
ED (%)	0.236	0.026	0.177	0.215	0.178	0.284
SEVR	-0.365	<0.001	-0.346	0.013	-0.258	0.118
DPTI	0.198	0.063	0.324	0.020	0.033	0.846
SPTI	-0.159	0.137	0.056	0.697	-0.249	0.132
Central SBP	-0.089	0.407	0.053	0.712	-0.002	0.993
Central DBP	-0.038	0.723	0.076	0.596	-0.143	0.392
Central PP	-0.078	0.468	-0.036	0.800	0.220	0.185
Central RPP	-0.041	0.702	0.112	0.433	-0.101	0.548
Pulse pressure amplification	-0.674	<0.001	-0.468	0.001	-0.817	<0.001

BMI, body mass index; BSA, body surface area; HR, heart rate; SBP, systolic blood pressure; DBP, diastolic blood pressure; MBP, mean blood pressure; PP, pulse pressure; RPP, rate pressure product; Aix@HR75, Augmentation Index standardized for HR at 75 bpm; ED, ejection duration; SEVR, Sub-endocardial viability ratio; DPTI, diastolic pressure-time index; SPTI, systolic pressure-time index. P value is for comparison between male and female.

Table 3. Associations between weight loss (sweat volume) and hemodynamic parameters.

	Total		Male		Female	
	r	p	r	p	r	p
Age	-0.012	0.912	-0.277	0.049	0.326	0.046
Gender	0.311	0.003	-	-	-	-
Height	0.283	0.007	0.149	0.296	0.129	0.440
Weight	0.367	<0.001	0.257	0.069	0.286	0.081
BMI	0.269	0.011	0.232	0.101	0.240	0.147
BSA	0.368	<0.001	0.248	0.079	0.273	0.097
HR	-0.122	0.255	-0.203	0.153	-0.005	0.976
Peripheral SBP	0.311	0.003	0.283	0.044	0.055	0.742
Peripheral DBP	0.013	0.906	-0.063	0.661	0.078	0.643
Peripheral MBP	0.152	0.154	0.078	0.588	0.077	0.646
Peripheral PP	0.344	0.001	0.368	0.008	-0.005	0.974
Peripheral RPP	0.079	0.463	-0.015	0.914	0.021	0.901
Pulse wave analysis						
AIx@HR75	-0.353	0.001	-0.391	0.005	-0.131	0.432
ED (ms)	-0.114	0.288	-0.032	0.823	0.019	0.912
ED (%)	-0.233	0.028	-0.265	0.060	-0.007	0.965
SEVR	0.165	0.123	0.219	0.123	-0.192	0.249
DPTI	-0.079	0.459	-0.200	0.160	0.163	0.327
SPTI	0.137	0.202	-0.010	0.944	0.165	0.322
Central SBP	0.205	0.053	0.159	0.266	0.026	0.876
Central DBP	0.004	0.973	-0.073	0.612	0.062	0.712
Central PP	0.300	0.004	0.339	0.015	-0.054	0.749
Central RPP	0.008	0.942	-0.090	0.528	0.012	0.943
Pulse pressure amplification	0.137	0.202	0.057	0.690	0.089	0.597

BMI, body mass index; BSA, body surface area; HR, heart rate; SBP, systolic blood pressure; DBP, diastolic blood pressure; MBP, mean blood pressure; PP, pulse pressure; RPP, rate pressure product; Aix@HR75, Augmentation Index standardized for HR at 75 bpm; ED, ejection duration; SEVR, Sub-endocardial viability ratio; DPTI, diastolic pressure-time index; SPTI, systolic pressure-time index. P value is for comparison between male and female.

Table 4. Relationship between weight loss (sweat volume) and BSA, AIx@HR75 and central pulse pressure.

	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
	B	p	B	p	B	p	B	p	B	p	B	p
BSA	0.288	0.010	0.307	0.010			0.187	0.126			0.288	0.010
AIx@HR75	-0.005	0.019			-0.007	0.001	-0.006	0.011	-0.007	0.049	-0.005	0.019
Central PP			0.005	0.131	0.008	0.006	0.006	0.069				

BSA, body surface area; Aix@HR75, Augmentation Index standardized for HR at 75 bpm; PP, pulse pressure. Model 5. Adjusted for significant variables ($p < 0.05$) in table 2, using enter method in analysis. Model 6. Adjusted for significant variables ($p < 0.05$) in table 3, using step-wise method in analysis.

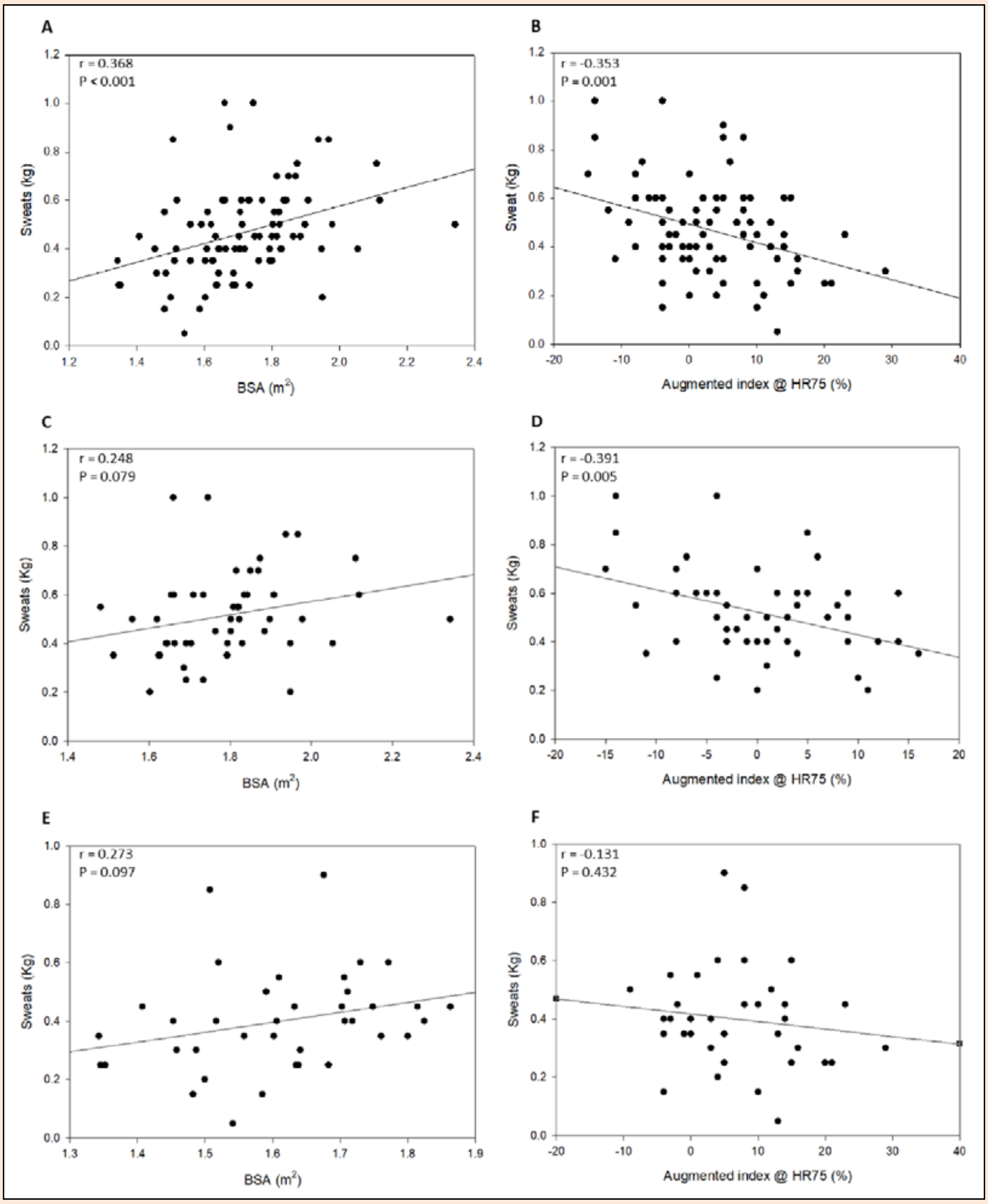

Figure 2. A, correlation between weight loss (sweat volume) and BSA. B, correlation between weight loss (sweat volume) and AIx@HR75. C, sweat volume has a trend toward BSA in male. D, correlation between sweat volume and AIx@HR75 in male. E, sweat volume has a trend toward BSA in female. F, no significant relationship is shown between sweat volume and AIx@HR75 in female. BSA, body surface area; AIx@HR75, Augmentation Index standardized for HR at 75 bpm.

Post-exercise hemodynamics

After the 3-km run, peripheral SBP ($p < 0.001$), peripheral MBP ($p = 0.036$), peripheral PP ($p < 0.001$), and peripheral RPP ($p = 0.001$) were significantly different between genders. However, mean HR, peripheral DBP after 3-km run, changes in HR, and peripheral SBP/DBP/MBP/PP/RPP ($exercise_{post}$ minus $exercise_{pre}$) were not significantly different between genders (Table 5). HR ($p = 0.005$), peripheral RPP ($p = 0.049$), and changes in exercise peripheral SBP ($p = 0.037$) were negatively associated with sweat volume in male, while only age was positively associated with sweat volume in female ($p = 0.046$, Table 6).

Table 5. Hemodynamic parameters after 3-km run.

	Total subjects (n=89)	Male (n=51)	Female (n=38)	P valve
		After 3-km run		
HR (bpm)	97 ± 11	98 ± 12	95 ± 11	0.377
Peripheral SBP (mm Hg)	112.1 ± 12.5	116.3 ± 12.4	106.3 ± 10.4	<0.001
Peripheral DBP (mm Hg)	66.5 ± 10.7	67.3 ± 12.4	65.3 ± 7.9	0.382
Peripheral MBP (mmHg)	80.7 ± 13.4	83.5 ± 11.4	78.8 ± 7.7	0.036
Peripheral PP (mm Hg)	45.1 ± 11.4	48.9 ± 10.1	41.0 ± 8.9	<0.001
Peripheral RPP	10.69 ± 2.097	11.32 ± 1.78	10.11 ± 1.48	<0.001
		Change of run (run-post minus run-pre)		
HR (bpm)	20 ± 14	21 ± 15	20 ± 14	0.695
Peripheral SBP (mm Hg)	-1.8 ± 9.7	-2.2 ± 10.8	-1.3 ± 7.9	0.699
Peripheral DBP (mm Hg)	-0.5 ± 8.9	-0.4 ± 9.4	-0.7 ± 8.3	0.892
Peripheral MBP (mmHg)	-0.9 ± 7.7	-1.0 ± 8.3	-0.9 ± 7.1	0.954
Peripheral PP (mm Hg)	-1.3 ± 10.4	-1.8 ± 11.5	-0.7 ± 8.6	0.632
Peripheral RPP	2.14 ± 1.71	2.26 ± 1.91	1.96 ± 1.40	0.417

HR, heart rate; SBP, systolic blood pressure; DBP, diastolic blood pressure; MBP, mean blood pressure; PP, pulse pressure; RPP, rate pressure product; Aix@HR75, Augmentation Index standardized for HR at 75 bpm. P value is for comparison between male and female. P value is for comparison between male and female.

Table 6. Associations between weight loss (sweat volume) and hemodynamic parameters after 3-km run.

	Total		Male		Female	
	r	p	r	p	r	p
			After 3-km run			
HR	-0.200	0.065	-0.395	0.005	0.006	0.973
Peripheral SBP	0.149	0.171	0.042	0.773	0.025	0.883
Peripheral DBP	-0.024	0.827	-0.177	0.218	0.218	0.201
Peripheral MBP	0.044	0.688	-0.113	0.435	0.160	0.352
Peripheral PP	0.206	0.058	0.269	0.059	-0.163	0.341
Peripheral RPP	-0.046	0.677	-0.280	0.049	0.036	0.836
			Change from exercise (exercise-post minus exercise-pre)			
HR	-0.079	0.467	-0.159	0.269	-0.001	0.996
Peripheral SBP	-0.204	0.059	-0.295	0.037	-0.021	0.903
Peripheral DBP	-0.035	0.746	-0.152	0.292	0.138	0.421
Peripheral MBP	-0.112	0.303	-0.244	0.087	0.100	0.562
Peripheral PP	-0.161	0.140	-0.154	0.286	-0.152	0.375
Peripheral RPP	-0.126	0.246	-0.251	0.079	0.013	0.942

HR, heart rate; SBP, systolic blood pressure; DBP, diastolic blood pressure; MBP, mean blood pressure; PP, pulse pressure; RPP, rate pressure product; Aix@HR75, Augmentation Index standardized for HR at 75 bpm. P value is for comparison between male and female. P value is for comparison between male and female.

Generalized structural equation modeling (GSEM)

A GSEM was constructed to analyze the relationship between the data obtained before exercise and sweat volume, and between sweat volume and post-exercise data (Figure 3 and Figure 4). In male, from step 1 to step 2, BSA predicted central PP (B = 19.271, $p \leq 0.001$). Central PP and AIx@HR75 predicted the sweat volume (B = 0.008, p = 0.025; B = -0.009, p = 0.003 respectively). From step 2 to step 3, sweat volume predicted changes in peripheral SBP (B = -17.560, p = 0.031). In summary, in male, BSA predicted central PP and then central PP predicted sweat volume. In addition, sweat volume predicted changes in peripheral SBP. Thus, prediction of sweat volume by BSA was mediated by central PP. Prediction of the changes in peripheral SBP by BSA were mediated by central PP and sweat volume. In parallel, in male Alx@HR75 predicted sweat volume and then sweat volume predicted the changes in peripheral SBP. Thus, prediction of the changes in peripheral SBP by Alx@HR75 were mediated by sweat volume. In contrast, in female, from step 1 to step 2, BSA only predicted AIx@HR75 (B = -21.005, p = 0.032), but not sweat volume (Table 7).

Meanwhile, in all subjects, from step 1 to step 2, BSA predicted the value of AIx@HR75 (B = -18.127, $p < 0.001$) and central PP (B = 16.387, $p < 0.001$). AIx@HR75 predicted sweat volume (B = -0.006, p = 0.008). However, from step 2 to step 3, the sweat volume associated with changes in peripheral SBP had only borderline significance (B = -10.566, p = 0.056. See Figure 4).

Discussion

The main findings of the present study were that, in all subjects, the sweat volume during a 3-km run on a treadmill was positively associated with baseline BSA and negatively associated with AIx@HR75; that is, baseline BSA and AIx@HR75 were able to predict sweat production during exercise. In addition, in male but not in female, BSA predicted sweat volume, and the prediction was mediated by central PP. Similarly, in male, BSA predicted the changes in peripheral SBP, and the prediction was mediated by central PP and sweat volume. Furthermore, Alx@HR75 predicted both sweat volume and the changes in peripheral SBP, and prediction of the latter was mediated by sweat volume.

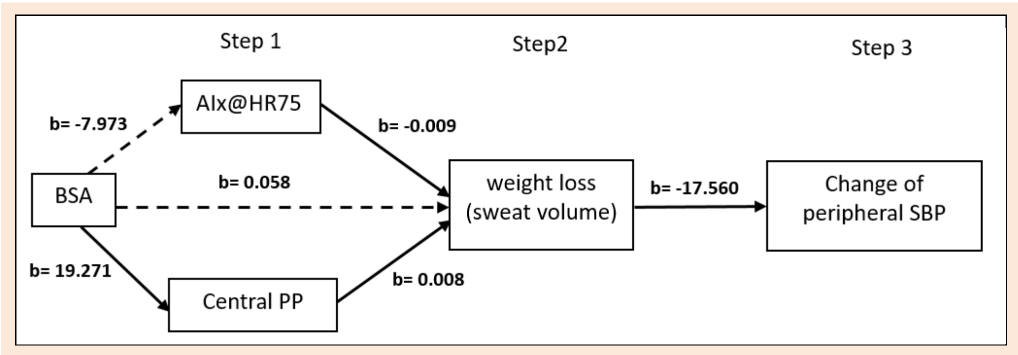

Figure 3. Generalized structural equation modeling (GSEM) in male. The solid line shows that the path was statistically significant ($p < 0.05$). Changes in peripheral SBP: $exercise_{post}$ peripheral SBP minus $exercise_{pre}$ peripheral SBP.

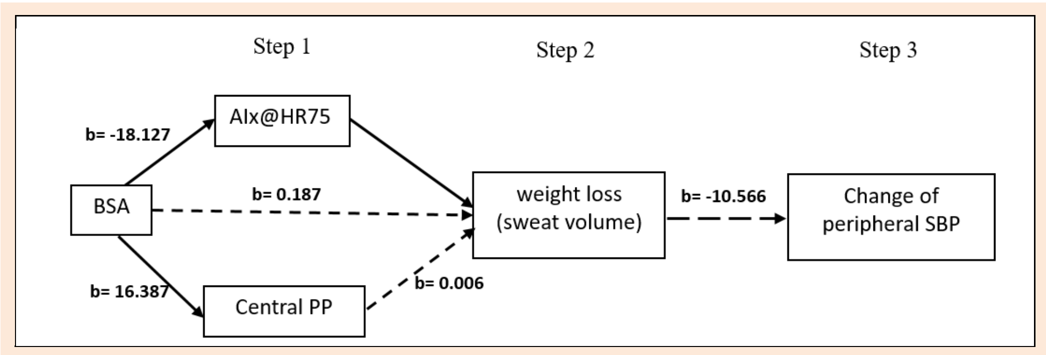

Figure 4. Generalized structural equation modeling (GSEM) in total subjects. The solid line shows that the path was statistically significant ($p < 0.05$). The long-dash line shows that the path had borderline significance ($p = 0.056$).

Table 7. Effects of Generalized structural equation modeling (GSEM) in total subjects, male and female.

	Total Subjects (n=89)			Male (n=51)			Female (n=38)		
	B	SE	p	B	SE	p	B	SE	p
				Step 1 to 2					
BSA → AIx@HR75	-18.127	4.845	<0.001	-7.973	6.447	0.216	-21.005	9.820	0.032
AIx@HR75 → sweat volume	-0.006	0.002	0.008	-0.009	0.003	0.003	0.001	0.003	0.885
BSA → central PP	16.387	3.502	<0.001	19.271	5.631	<0.001	3.222	4.995	0.519
Central PP → sweat volume	0.006	0.003	0.060	0.008	0.003	0.025	-0.003	0.006	0.625
BSA → sweat volume	0.187	0.117	0.111	0.058	0.151	0.700	0.340	0.208	0.102
				Step 2 to 3					
Sweat volume → changes in peripheral SBP	-10.566	5.539	0.056	-17.560	8.130	0.031	-0.946	7.760	0.903

BSA, body surface area; HR, heart rate; PP, pulse pressure; Aix@HR75, Augmentation Index standardized for HR at 75 bpm; P value is for comparison between male and female.

To the best of our knowledge, this is the first report describing the relationship between baseline Alx@HR75 and sweat volume during exercise. Previous studies have shown that lower baseline AIx@HR75 indicates less arterial stiffness and better endothelial function, as compared to higher baseline values.(McEniery et al., 2006; Soga et al., 2008) In addition, better endothelial function has been reported to be associated with higher sweat volume.(Takeda and Okazaki, 2018) However, AIx@HR75 was influenced by body height, HR, and gender (Fantin et al., 2007; Janner et al., 2010; Wilkinson et al., 2000). AIx@HR75 was documented as being inversely related to HR but AIx@HR75 adjusted to the HR of 75 bpm occurred independently from individuals' changes in HR (Stoner et al., 2014). The findings of the present study are consistent with previous reports that subjects with lower AIx@HR75 have more sweat volume than subjects with higher AIx@HR75 during a 3-km run.

Regarding GSEM, results of the present study show that, in male, AIx@HR75 predicts the sweat volume and then predicts the change in peripheral SBP. For BSA, it predicted central PP and then sweat volume, and then predicted the changes in peripheral SBP. These findings mean that BSA and AIx@HR75 are independent predictors of sweat volume and the changes in peripheral SBP, as are central PP and AIx@HR75. Physiologically, sweating during exercise leads to loss of body fluid, which may, by Starling law, reduce cardiac output, and then reduce blood pressure. This may explain the findings in the present study. BSA was a key factor for regulating body temperature at rest and during exercise. Besides, body fat served as an insulator, was proportional to body weight, and kept the body warm to avoid hypothermia. Subjects with heavier body weight, as well as more body fat, tended to have higher core temperatures and produced more sweat volume than thin subjects during exercise. Body weight, BMI and BSA in the present study were consistently and significantly associated with sweat volume during exercise. In addition, BSA was the most important determinant of sweat volume during exercise compared to other variables (Table

4).

Apart from AIx@HR75, endothelial function had been reported previously to be associated with central PP (McEniery et al., 2006). During exercise, elevated core temperature sequentially accompanied by increased blood flow through the conduit arteries can result in augmented central PP and increasing shear stress in order to release nitric oxide and other endothelial-derived factors (Ganio et al., 2011). Associations between cutaneous vasodilation and exocrine sweating have long been reported (Love and Shanks, 1962). Also, about 35%-45% of cutaneous active vasodilatation is attributed to the action of nitric oxide, which is central to endothelial function (Kellogg et al., 1998). Thus, results of the present study show that subjects with lower AIx@HR75, presumably to have better endothelial function, produce more sweat volume. After exercise, relative volume depletion through sweating led to different degrees of decreased peripheral SBP individually. This may explain why, in male, the BSA, as well as AIx@HR75, predict not only sweat volume, but also changes in peripheral SBP.

Temperature and relative humidity can affect the evaporation of sweat from the skin to the atmosphere, and therefore this study was conducted in an air-conditioned gym to maintain stable temperature and relative humidity. Physical fitness also plays an important role in sweat during exercise and athletes sweat more than non-athletes.(Araki et al., 1981) Furthermore, peak oxygen uptake (VO_{2peak}), the standard for evaluating cardiovascular fitness, is an indicator of endurance for exercise. Generally, athletes have a higher VO_{2peak} than non-athletes. Participants in the present study had varied exercise frequency, which was reflected by different VO_{2peak} between individuals. However, sweating during exercise was not independently altered in the groups with large differences in $V_{O2\ peak}$ in fixed heat production trial. Jay et al. (2011) established a protocol that subjects cycled for 60 minutes on a semi-recumbent cycle ergometer and pedaling cadence was fixed at 80 revolutions per minute. In the present study, the protocol was organized as a 3-km run on a treadmill at a fixed speed of 10 km/hr. Thus, we assumed that the sweat volume during exercise was not influenced by individuals' exercise habits.

Body temperature and anaerobic threshold were determinant factors of sweating, but we did not collect these data during a 3-km run. There were an important limitation in our study.

Conclusion

In conclusion, sweat volume during a 3-km run is influenced by hemodynamic parameters, including vascular arterial stiffness and central pulse pressure. Results of the present study suggest that vascular arterial stiffness likely regulates sweat volume during exercise, which is significantly related to baseline AIx@HR75 and central PP derived from PWA in an environment of controlled temperature and relative humidity. Sweat volume in such an exercise also predicts the changes in peripheral SBP. Further prospective studies are required to explore the mechanisms underlying gender differences in young adults engaging in exercise.

Acknowledgements

This work was supported by MMH-E-105-003 from the Medical Research Department of the Mackay Memorial Hospital, Taiwan. This study was approved by our hospital (IRB number 14MMHIS091). The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare. The datasets generated during and/or analyzed during the current study are not publicly available, but are available from the corresponding author who was an organizer of the study.

References

Araki, T., Matsushita, K., Umeno, K., Tsujino, A. and Toda, Y. (1981) Effect of physical training on exercise-induced sweating in women. Journal of Applied Physiology: Respiratory. *Environmental and Exercise Physiology* **51**, 1526-1532. https://doi.org/10.1152/jappl.1981.51.6.1526

Beigel, R., Dvir, D., Arbel, Y., Shechter, A., Feinberg, M.S. and Shechter, M. (2010) Pulse pressure is a predictor of vascular endothelial function in middle-aged subjects with no apparent heart disease. *Vascular Medicine* **15**, 299-305. https://doi.org/10.1177/1358863X10373300

Brazier, J., Cooper, N. and Buckberg, G. (1974) The adequacy of subendocardial oxygen delivery: the interaction of determinants of flow, arterial oxygen content and myocardial oxygen need. *Circulation* **49**, 968-977. https://doi.org/10.1161/01.CIR.49.5.968

Cramer, M.N. and Jay, O. (2015) Explained variance in the thermoregulatory responses to exercise: the independent roles of biophysical and fitness/fatness-related factors. *Journal of Applied Physiology* **119**, 982-989. https://doi.org/10.1152/japplphysiol.00281.2015

Dart, A.M. and Kingwell, B.A. (2001) Pulse pressure--a review of mechanisms and clinical relevance. *Journal of the American College of Cardiology* **37**, 975-984. https://doi.org/10.1016/S0735-1097(01)01108-1

Fantin, F., Mattocks, A., Bulpitt, C.J., Banya, W. and Rajkumar, C. (2007) Is augmentation index a good measure of vascular stiffness in the elderly? *Age Ageing* **36**, 43-48. https://doi.org/10.1093/ageing/afl115

Ganio, M.S., Brothers, R.M., Shibata, S., Hastings, J.L. and Crandall, C.G. (2011) Effect of passive heat stress on arterial stiffness. *Experimental Physiology* **96**, 919-926. https://doi.org/10.1113/expphysiol.2011.057091

Ichinose-Kuwahara, T., Inoue, Y., Iseki, Y., Hara, S., Ogura, Y. and Kondo, N. (2010) Sex differences in the effects of physical training on sweat gland responses during a graded exercise. *Experimental Physiology* **95**, 1026-1032. https://doi.org/10.1113/expphysiol.2010.053710

Janner, J.H., Godtfredsen, N.S., Ladelund, S., Vestbo, J. and Prescott, E. (2010) Aortic augmentation index: reference values in a large unselected population by means of the SphygmoCor device. *American Journal of Hypertension* **23**, 180-185. https://doi.org/10.1038/ajh.2009.234

Jay, O., Bain, A.R., Deren, T.M., Sacheli, M. and Cramer, M.N. (2011) Large differences in peak oxygen uptake do not independently alter changes in core temperature and sweating during exercise. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* **301**, 832-841. https://doi.org/10.1152/ajpregu.00257.2011

Jia, C., Yang, Y., Zhang, X., Chen, J., Chen, H., Wu, W., Cheng, H. and Xue, J. (2018) Serum 25-Hydroxyvitamin D Levels: Related to Ambulatory Arterial Stiffness Index in Hypertensive Seniors. *International Journal of Gerontology* **12**, 84-88. https://doi.org/10.1016/j.ijge.2018.02.016

Kellogg, D.L., Jr., Crandall, C.G., Liu, Y., Charkoudian, N. and Johnson, J.M. (1998) Nitric oxide and cutaneous active vasodilation during heat stress in humans. *Journal of Applied Physiology* **85**, 824-829. https://doi.org/10.1152/jappl.1998.85.3.824

Love, A. and Shanks, R. (1962) The relationship between the onset of sweating and vasodilatation in the forearm during body heating. *The Journal of physiology* **162**, 121. https://doi.org/10.1113/jphysiol.1962.sp006918

McEniery, C.M., Wallace, S., Mackenzie, I.S., McDonnell, B., Yasmin, Newby, D.E., Cockcroft, J.R. and Wilkinson, I.B. (2006) Endothelial function is associated with pulse pressure, pulse wave velocity, and augmentation index in healthy humans. *Hypertension* **48**, 602-608. https://doi.org/10.1161/01.HYP.0000239206.64270.5f

O'Rourke, M.F. and Gallagher, D.E. (1996) Pulse wave analysis. *Journal of hypertension. Supplement* **14**, 147-157.

Rosenbaum, D., Giral, P., Chapman, J., Rached, F.H., Kahn, J.F., Bruckert, E. and Girerd, X. (2013) Radial augmentation index is a surrogate marker of atherosclerotic burden in a primary prevention cohort. *Atherosclerosis* **231**, 436-441. https://doi.org/10.1016/j.atherosclerosis.2013.10.004

Safar, M.E. and London, G.M. (2000) Therapeutic studies and arterial stiffness in hypertension: recommendations of the European Society of Hypertension. The Clinical Committee of Arterial Structure and Function. Working Group on Vascular Structure and Function of the European Society of Hypertension. *Journal of Hypertension* **18**, 1527-1535. https://doi.org/10.1097/00004872-200018110-00001

Sembulingam, P. and Ilango, S. (2015) Rate Pressure Product as a Determinant of Physical Fitness in Normal Young Adults. *Journal of Dental and Medical Sciences* **14**, 8-12.

Shibasaki, M. and Crandall, C.G. (2010) Mechanisms and controllers of eccrine sweating in humans. *Frontiers in Bioscience (Scholar edition)* **2**, 685-696. https://doi.org/10.2741/s94

Soga, J., Nakamura, S., Nishioka, K., Umemura, T., Jitsuiki, D., Hidaka, T., Teragawa, H., Takemoto, H., Goto, C., Yoshizumi, M., Chayama, K. and Higashi, Y. (2008) Relationship between augmentation index and flow-mediated vasodilation in the brachial artery. *Hypertension* Research **31**, 1293-1298. https://doi.org/10.1291/hypres.31.1293

Stoner, L., Faulkner, J., Lowe, A., Lambrick, D.M., Young, J.M., Love, R. and Rowlands, D.S. (2014) Should the augmentation index be normalized to heart rate? *Journal of Atherosclerosis and Thrombosis* **21**, 11-16. https://doi.org/10.5551/jat.20008

Takeda, R. and Okazaki, K. (2018) Body Temperature Regulation During Exercise and Hyperthermia in Diabetics. *Diabetes and Its Complications* **89**. https://doi.org/10.5772/intechopen.74063

Van Beaumont, W. and Bullard, R.W. (1963) Sweating: its rapid response to muscular work. *Science 141*, 643-646. https://doi.org/10.1126/science.141.3581.643

Wilkinson, I.B., MacCallum, H., Flint, L., Cockcroft, J.R., Newby, D.E. and Webb, D.J. (2000) The influence of heart rate on augmentation index and central arterial pressure in humans. *Journal of Physiology* **525**, 263-270. https://doi.org/10.1111/j.1469-7793.2000.t01-1-00263.x

Yeh, Y.-T., Li, P.-C., Wang, J.-H., Lee, C.-J., Wang, C.-H. and Hsu, B.-G. (2020) Hyperleptinemia is an Independent Predictor for Carotid-Femoral Pulse Wave Velocity in Elderly People. *International Journal of Gerontology* **14**, 6-10.

Key points

- The body surface area and the augmentation index adjusted for heart rate (AIx@HR75) were able to predict sweat production during exercise
- Sweat volume in such an exercise also predicts the changes in peripheral systolic blood pressure (SBP).
- The vascular arterial stiffness and the central pulse pressure (PP) likely regulate sweat volume during exercise.

AUTHOR BIOGRAPHY

Yen-Yu LIU
Employment
Senior attending physician at MacKay Memorial Hospital and Part-time Clinical Lecturer at Mackay Medical College.
Degree
MD
Research interests
Exercise physiology, cardiology, and intensive care
E-mail: yenyu1012@gmail.com

Chung-Lieh HUNG
Employment
Senior Attending Physician at MacKay Memorial Hospital and Associate Professor at Mackay Medical College.
Degree
MD, Ph.D.
Research interests
Cardiology, translational medicine, and heart failure.
E-mail: jotaro3791@gmail.com

Fang-Ju SUN
Employment
Research Assistant at MacKay Memorial Hospital
Degree
M.S.
Research interests
Medical statistics and information
E-mail: fjsun.b612@mmh.org.tw

Po-Han HUANG
Employment
General internal medicine at Mackay Memorial Hospital
Degree
MD
Research interests
Endothelial function and exercise
E-mail: gklpgrpa@gmail.com

Yu-Fan CHENG
Employment
General internal medicine at Taipei Medical University Hospital
Degree
MD
Research interests
Hemodynamics, exercise and vascular adaptation
E-mail: peter03220322@gmail.com

Hung-I YEH
Employment
Associate Director at MacKay Memorial Hospital and Professor at Mackay Medical College
Degree
MD, Ph.D.
Research interests
Novel therapy in cardiovascular disease
E-mail: hiyeh@mmh.org.tw

✉ **Hung-I Yeh**
Cardiovascular Center and Division of Cardiology, Mackay Memorial Hospital, 92, Sec 2, Zhongshan North Road, Taipei 10449, Taiwan