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Original research

Finger blood flow (FBF) measurement among vibration-exposed groundskeepers: a pilot study in the southeastern USA

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► Additional supplemental material is published online only. To view, please visit the journal online (https://doi.org/10.1136/oemed-2024-109979).

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Received 15 November 2024
Accepted 21 March 2025

ABSTRACT

Objectives This study assessed finger blood flow (FBF) among groundskeepers using laser Doppler flowmetry (LDF) and evaluated the association of the FBF with hand-arm vibration (HAV) exposure dose.

Methods Baseline FBF measured before a work shift ($FBF_{baseline}$) and daily changes in FBF before and after a work shift (ΔFBF_{daily}) were measured among 17 groundskeepers and 10 office workers using LDF (PeriFlux 6000, Perimed, Järfälla, Sweden) for 3 days. Study participants' health-related information was obtained through questionnaires, while HAV exposure and demographic information were pulled from our previous study conducted in parallel with the present study. Linear mixed models were employed to estimate the association between HAV exposure dose and FBF.

Results The average $FBF_{baseline}$ for right and left hands was 241.5 and 239.9 perfusion units (PUs), respectively, among the exposure group and 305.6 and 307.3 PU, respectively, among the reference group. The average ΔFBF_{daily} for right and left hands was 44.2 and 25.4 PU, respectively, among the exposure group and −35.2 and −33.2 PU, respectively, among the reference group. A significant negative association between lifetime HAV exposure and $FBF_{baseline}$ was observed in the linear mixed model after adjusting for age, body mass index, race/ethnicity and hypertension (right hand: β=−0.0006 and p=0.0055; left hand: β=−0.0009 and p=0.0068). Inconsistent significances were observed between lifetime HAV exposure and ΔFBF_{daily} and between daily HAV exposure and ΔFBF_{daily}.

Conclusions A significant negative association between lifetime HAV exposure and baseline FBF among groundskeepers was observed, supporting FBF measurement using LDF as a promising health indicator for vascular disorders induced by HAV.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Vascular disorders are the best-known component of hand-arm vibration syndrome (HAVS). Various methods have been used to examine the vascular health of HAVS in HAV-exposed workers predominantly in temperate zones, and changes in blood flow in the fingers have been reported. However, no robust vascular health indicator for HAV exposure exists, which can include those workers in warm environments where clinical features of HAV disorders are less known.

WHAT THIS STUDY ADDS

⇒ This study measured finger blood flow (FBF) using laser Doppler flowmetry (LDF) among groundskeepers in the Southeastern region of the USA, and a significant relationship between lifetime HAV exposure dose and baseline FBF was found. The study findings support the current knowledge on the pathophysiological mechanisms of the vascular effects of HAV, which have not been completely understood. FBF measurement using LDF appears to be a promising health indicator for the vascular disorders induced by HAV exposure for the groundskeepers in subtropical climate.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ The study results can be used as baseline data for the establishment of a threshold value of a non-invasive vascular health indicator or biomarker. The present study, along with future long-term panel studies, will allow us to establish a reliable cause-and-effect relationship and, in turn, reliable standards for occupational exposure to HAV in the USA.

INTRODUCTION

Long-term, excessive exposure to hand-arm vibration (HAV) is associated with HAV syndrome (HAVS), which is a complex of vascular, neurological and musculoskeletal disorders.[1] It is estimated that over 2 000 000 workers in the USA are exposed to HAV through power tool use, with a 20%–50% prevalence of HAVS.[2] HAVS may become irreversible and lead to disability of upper extremities if allowed to progress.[3 4] Therefore, establishment of a dose–response relationship between HAV exposure and HAVS with power tool operators such as groundskeepers is essential to initiate early interventions. Results of such studies will benefit power tool operators' health and safety in general.

Studies have examined vascular and neurological health effects of HAVS to establish the dose–response relationship with HAV exposure, including vibration-induced white finger (VWF), vibrotactile thresholds, tingling and numbness.[5–8]

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To cite: Chen N, Yang S, Leach JM, *et al*. *Occup Environ Med* Epub ahead of print: [please include Day Month Year]. doi:10.1136/oemed-2024-109979

VWF is a finger blanching triggered by cold due to vasospasms, the best-known vascular disorder of HAVS. The International Organization for Standardization (ISO) 5349-1: Mechanical vibration-Measurement and evaluation of human exposure to hand-transmitted vibration proposed the relationship between daily vibration exposure, A(8), and the years of vibration exposure before VWF onset.[9] For example, 10% prevalence of VWF is expected to occur in 5.8 years in persons who have been continuously exposed to an A(8) of 5 m/s^2. The prevalence of VWF among power tool operators along with vibration exposure magnitude, was the major factor for the evaluation of the suitability of exposure limits set by the guidelines and standards, including American Conference of Governmental Industrial Hygienists Threshold Limit Values and EU directive 2002/44/EC.[10–13] However, a poor agreement of the ISO 5349 exposure–response relationship has been reported.[13] Moreover, the finger blanching is less common among the workers in warm environments (ie, subtropical/tropical regions) and thus coldness in the fingers is often considered as a surrogate clinical feature for vascular disorders.[14 15] The standardised peripheral vascular function tests to help diagnose VWF are the measurement of finger skin temperature (ISO 14835-1) and finger systolic blood pressure (ISO 14835-2) through cold provocation.[16 17] The tests may cause pain and discomfort to VWF patients, and a low sensitivity of the test has been reported in mild VWF.[15] There is the inevitable need for an alternative vascular health indicator of HAVS which is more objective, non-invasive and sensitive to biological changes in both cold and warm environments.

Animal experiments and human biopsy studies suggested that the smooth muscle layer of the vibration-exposed vessels may experience proliferation in reaction to micro-injuries induced by vibration.[18–20] The thickening of the arterial smooth muscle layer results in maintained vasoconstriction and decreases in the internal diameter of arteries, leading to a reduction in blood flow.[19 21] It was also suggested that the vessels may experience abnormal vasoconstriction or dilation due to damage to neuroreceptors in the fingertips and disruptions of the nervous system after long-term exposure to vibration.[18 22] In Stoyneva *et al*'s study, a significantly lower baseline finger blood flow (FBF) was observed among HAV patients compared to healthy subjects, while sympathetic stimulation resulted in an increase in FBF among the patients due to reduced self-regulatory responses.[23] The current literature strongly supports the measurement of changes in FBF as a promising vascular health indicator for HAV exposure. For the validation of FBF as a reliable health indicator which is sensitive to the early biological changes, information about the association between HAV exposure and FBF in HAV-exposed and non-exposed individuals is essential. However, there is limited research on the relationship between HAV exposure dose and FBF among HAV-exposed workers, especially in warm climates where the vascular symptoms of HAV have been less reported.[14]

Several techniques such as laser Doppler flowmetry (LDF), nailfold videocapillaroscopy (NVC) and strain gauge venous occlusion plethysmography have been used to measure the FBF among both HAVS patients and healthy controls.[23–25] High-magnification NVC estimates the velocity of individual red blood cells (RBCs).[25 26] The nailfold capillary RBC velocity is likely to be a good indicator of acute exposure; however, determining RBC velocity is complex and not routinely performed.[25–27] The strain gauge venous occlusion plethysmography measures the FBF under a pressure given on the upstream of the vessels using an inflated cuff.[28] However, the diagnostic power of plethysmography is less known.[25] LDF is a non-invasive quantification method of microcirculation determined by the Doppler shift of the laser light which is reflected back by the moving RBCs.[29 30] LDF is considered to be the gold standard to evaluate skin microcirculation and has been widely used in numerous HAV studies.[23 31 32]

According to the US Bureau of Labor Statistics, there are more than 60 000 groundskeepers in the southeastern USA (ie, Alabama, Georgia, South Carolina, Mississippi and Louisiana), with an expected growth rate of 9.7% from 2022 to 2032.[33 34] In the present study, groundskeepers in the southeastern US region were chosen as the study population as groundskeepers are at risk of developing HAVS.[35] Also, the tropical/subtropical weather may increase the risk of HAVS because of the difficulties in self-awareness due to the lower prevalence of finger blanching,[14] in addition to the lack of robust diagnostic tests for the vascular health of HAVS.[15] The purposes of this study were to assess FBF among groundskeepers using LDF and to evaluate the association of the FBF with HAV exposure dose which was reported in our previous study.[36] The assessment of FBF was twofold: baseline FBF measurement which is more likely to reflect the vascular effects of lifetime HAV exposure and changes in FBF measurement before and after a work shift which may be considered sympathetic stimulation.

METHODS

Study population and monitoring plan

Groundskeepers and office workers whose age was over 18 years from two universities in Alabama were recruited as an exposure group and a reference group, respectively. This study was conducted in parallel with our HAV exposure assessment study (ie, the same study participants), as shown in online supplemental figure 1 with details on HAV exposure assessment and recruitment process. 6 days of FBF measurement were scheduled on the same vibration monitoring days for each participant: the first 3 days were scheduled within a week, and approximately a month later, another 3 days were scheduled within a week to take monthly variations into account. On each day of FBF measurement, FBF both before and after a work shift was measured for each participant.

Questionnaire

A questionnaire adapted from the EU Risks of Occupational Vibration Exposures (VIBRISK) project was used to obtain the study participants' social history and health-related information; details can be found in online supplemental figure 1.[37]

Measurement of FBF

LDF (PeriFlux 6000, Perimed, Järfälla, Sweden) with small angled thermostatic probes was used to measure FBF in arbitrary perfusion units (PUs). Calibration was conducted by suspending the probes in the colloidal latex particles (PF 100 Motility Standard, Perimed, Järfälla, Sweden) in every 45 days as recommended by the manufacturer. The probe was attached to the middle finger of both hands using double-sided tape strip and was placed at the most distal point of the smallest whorl on the finger to ensure a consistent measurement location (figure 1). The room temperature was controlled at 21°C±3°C to minimise the temperature influence on the blood flow measurement.

The entire duration for FBF measurement was 12 min in a seated position. The first 6 min was measured without heating the probe to allow the study participant's FBF to stabilise. Then, the probe was heated up to 43°C±1°C for the next 6 min to measure the FBF under the controlled skin temperature to be

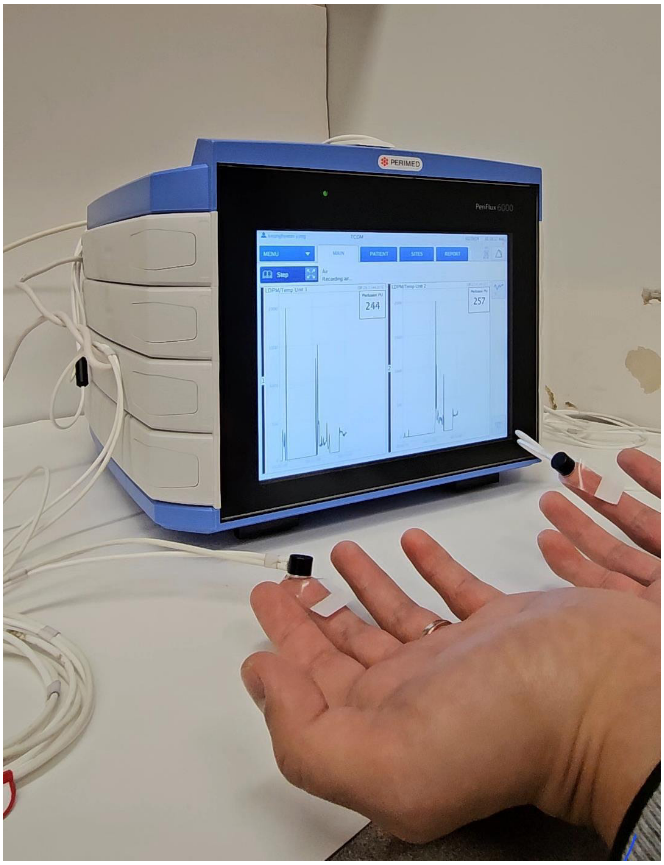

Figure 1 Laser Doppler flowmeter with thermostatic probes attached to the middle fingers for finger blood flow measurement.

comparable among study participants. The baseline FBF ($FBF_{baseline}$) was defined as the FBF measured before the start of work. The daily changes in FBF (ΔFBF_{daily}) were defined as the difference between the FBF measured before a work shift and the FBF measured after a work shift ($FBF_{after} - FBF_{before}$).

Statistical analysis

All FBF data were downloaded using PSW ExM V.5.3.6 (Perimed, Järfälla, Sweden). The descriptive statistics of participants' social history, health-related information and FBF measurements ($FBF_{baseline}$ and ΔFBF_{daily}) were analysed in R V.4.3.0. The data on demographic characteristics, lifetime cumulative HAV exposure dose ($a_{hv\text{-}lifetime}$) and daily HAV exposure dose ($a_{hv\text{-}daily}$) were obtained from our previous study for statistical analyses.[36]

No obvious direction of skewness for both $FBF_{baseline}$ and ΔFBF_{daily} data was observed. The FBF measurements showed more symmetric and closer to normal distribution while log-transformed FBF measurements skewed left. Thus, the FBF measurement data were used in the following analysis without log transformation.

The first 3-day average $FBF_{baseline}$, ΔFBF_{daily}, and $a_{hv\text{-}daily}$ by each study participant, as well as individual $a_{hv\text{-}lifetime}$ between exposure and reference groups were compared for both hands using a two-sample t-test with unequal variance. The association between $FBF_{baseline}$ and $a_{hv\text{-}lifetime}$ was investigated for both hands using a linear mixed model with study participants as a random effect and first 3-day $FBF_{baseline}$ as three repeated measures (nlme version 3.1-162, R V.4.3.0), and the significance level was set at $p<0.05$. Analysis was conducted for potential confounding variables, including body mass index (BMI), hand surgery, alcohol, smoking, diabetes and hypertension, through fitting the model while adjusting for demographic characteristics and each of the social history and health-related variables. Only the significant variable(s) were considered in fitting the models to avoid overfitting. Three models, one without adjusting for potential confounders, another with adjusting for demographic characteristics (ie, race/ethnicity and age) and the other with adjusting for both demographic characteristics and social/health-related history, were tested. The association between ΔFBF_{daily} (ie, $FBF_{after} - FBF_{before}$) and $a_{hv\text{-}lifetime}$ was also investigated using a linear mixed model as that of $FBF_{baseline}$ while adjusting for one more covariate, $a_{hv\text{-}daily}$, in consideration of the potential association between daily FBF changes and daily HAV exposure level.[24] In this linear mixed model, the first 3-day ΔFBF_{daily} and $a_{hv\text{-}daily}$ were used as repeated measures. The mean $a_{hv\text{-}daily}$ of all participants was substituted for individual $a_{hv\text{-}daily}$ if no individual data was available. The association between ΔFBF_{daily} and $a_{hv\text{-}lifetime}$ was additionally investigated through fitting the above three models without adjusting for $a_{hv\text{-}daily}$ in consideration of potential collinearity between ΔFBF_{daily} and $a_{hv\text{-}daily}$. Q-Q plots and the Shapiro-Wilk normality test were also conducted for each model to examine the fitness of the data to the models.

RESULTS

17 groundskeepers and 10 office workers were recruited in the study. All participants completed 6 days of FBF measurement. Vibration exposure data for 3–6 days were obtained from the participants, except for two participants: one participant for 2 days and the other participant for 1 day, as reported in our previous study.[36]

Study participants' characteristics and FBF measurements

Table 1 shows the descriptive statistics for participants' social history, health-related information and FBF measurements ($FBF_{baseline}$ and ΔFBF_{daily}) in the exposure and reference groups, along with HAV exposure doses ($a_{hv\text{-}daily}$ and $a_{hv\text{-}lifetime}$) previously reported.

The first 3-day average $FBF_{baseline}$ was 241.5 PU (range 191.9–351.8 PU) for the right hand and 239.9 PU (range 137.8–350.6) for the left hand among the exposure group. For the reference group, the 3-day average $FBF_{baseline}$ was 305.6 PU (range 226.2–365.7 PU) for the right hand and 307.3 PU (range 208.9–389.2 PU) for the left hand. Comparing the 3-day average $FBF_{baseline}$ between groups, significant differences of 64.1 PU ($p=0.004$) for the right hand and 67.4 PU ($p=0.012$) for the left hand were observed. The first 3-day average ΔFBF_{daily} was 44.2 PU (range −49.9 to 156.5 PU) and 25.4 PU (range −45.8 to 137.4 PU) for the right and left hands, respectively, among exposure group while it was −35.2 PU (range −141.9 to 19.8 PU) and −33.2 PU (range −80.6 to 22.2 PU) for the right and left hands, respectively, among reference group. Comparing between groups, there were significant differences of 79.4 PU ($p=0.002$) for the right hand and 58.6 PU ($p=0.003$) for the left hand in the 3-day average ΔFBF_{daily}. The individual FBF data for all 27 study participants for the entire measurement period are available in online supplemental table 1.

The average $a_{hv\text{-}lifetime}$ was 76 520.6 and 61 955.5 hours·m/s^2 among the exposure group with an average of 13 years work experience in the grounds maintenance industry and 2306.2 and 2205.8 hours·m/s^2 among the reference group with an average of 0 year work experience in the grounds maintenance industry for the right and left hands, respectively.[36] Significant differences in average $a_{hv\text{-}lifetime}$ between groups were found for the right

Table 1 Social history, health-related information, baseline finger blood flow ($FBF_{baseline}$), daily changes in FBF (ΔFBF_{daily}), daily HAV exposure dose ($a_{hv\text{-}daily}$) and lifetime cumulative HAV exposure dose ($a_{hv\text{-}lifetime}$) in the exposure group

	Exposure group N=17 (63.0%)	Reference group N=10 (37.0%)	
Number of participants (African American/Caucasian/Hispanic)*	17 (4/7/6)	10 (2/5/3)	
Years of working in industries where involved the regular use of vibrating equipment (range)*	13 (1–27)	0 (0–0)	
Age in years (range)*	44 (23–67)	43 (22–73)	
Biological sex (male/female)*	17/0	10/0	
Dominant hand (right/left)*	15/2	10/0	
Long-term medication or hand surgery (hypertension/diabetes/hand surgery)	5 (3/1/2)	2 (1/0/1)	
Smoke/alcohol use (smoke/alcohol)	12 (3/12)	8 (6/7)	
Body mass index, (range)	30 (22–42)	29 (21–36)	
	Mean±SD (range)		**P value**
Right hand			
$a_{hv-lifetime}$ in hours·m/s^2*†	76520.6±53 224.5 (1459.5–154234.9)	2306.2±4889.3 (0–15 408.9)	<0.001
$a_{hv-daily}$ in hours·m/s^2*‡†	10.5±3.8 (4.8–17.5)	4.0±1.6 (2.3–7.6)	<0.001
$FBF_{baseline}$ in perfusion units (PU)‡†	241.5±47.3 (191.9–351.8)	305.6±50.8 (226.2–365.7)	0.004
ΔFBF_{daily} in PU‡†	44.2±67.3 (–49.9–156.5)	–35.2±50.8 (–141.9–19.8)	0.002
Left hand			
$a_{hv-lifetime}$ in hours·m/s^2*†	61955.5±43406.6 (1253.1–140702.6)	2205.8±4847.1 (0–15 217.2)	<0.001
$a_{hv-daily}$ in hours·m/s^2*‡†	9.3±2.9 (4.8–14.8)	3.4±1.5 (2.0–6.8)	<0.001
$FBF_{baseline}$ in PU‡†	239.9±60.1 (137.8–350.6)	307.3±61.5 (208.9–389.2)	0.012
ΔFBF_{daily} in PU‡†	25.4±53.6 (–45.8–137.4)	–33.2±38.0 (–80.6–22.2)	0.003

*Data are reported in our previous study.[36]
†p<0.05 under the two-tail t-test with unequal variance.
‡Showing the mean of the first 3 day sampling by each participant.
HAV, hand-arm vibration.

hand (74 214.4 hours·m/s^2) and the left hand (59 749.7 hours·m/s^2), p<0.001 for both hands. The average $a_{hv\text{-}daily}$ was 10.5 and 9.3 hours·m/s^2 for the right and left hands, respectively, among the exposure group and 4.0 and 3.4 hours·m/s^2 for the right and left hands, respectively, among the reference group. There were significant differences in $a_{hv\text{-}daily}$ between groups for the right hand (6.5 hours·m/s^2) and the left hand (5.9 hours·m/s^2), p<0.001 for both hands.

The survey results on the neurovascular health symptoms among the groundskeepers, including colour changes and numbness or tingling in the fingers, are reported in online supplemental table 2.

Association between HAV exposure dose and FBF measurements

There was a significant association between $a_{hv\text{-}lifetime}$ and $FBF_{baseline}$ (table 2A, online supplemental figure S2). For every 10 000 hours·m/s^2 increase in $a_{hv\text{-}lifetime}$, a significant reduction in $FBF_{baseline}$ by 5–6 PU for the right hand and 6–9 PU for the left hand was estimated in the three models (ie, without adjusting, with adjusting for demographic characteristics, and with adjusting for both demographic characteristics and social/health-related history). No obvious deviation from the diagonal line in the Q-Q plots was observed, and the Shapiro-Wilk normality test was not significant throughout the models.

The association between $a_{hv\text{-}lifetime}$ and ΔFBF_{daily} was significant only for the left hand in the three models (table 2B, online supplemental figure S3). For every 10 000 hours·m/s^2 increase in $a_{hv\text{-}lifetime}$, a significant increase in ΔFBF_{daily} by 5–6 PU for the left hand was estimated in the three models, while there was an increase in ΔFBF_{daily} by 2–5 PU for the right hand but with no significance observed. No change was observed in the direction of the ΔFBF_{daily} estimates as well as statistical significance for the left hand with or without $a_{hv\text{-}daily}$ in all three models. No obvious deviations from the diagonal line in the Q-Q plots were observed, and the Shapiro-Wilk normality test was not significant except for one of the right-hand simple models.

DISCUSSION

In our previous study, we reported that all of the study participants' biological sex was male, and the age distribution was comparable between the groups.[36] The proportions of study participants who had long-term medication for hypertension or diabetes were higher in the exposure group (24%) than in the reference group (10%). Long-term use of hypertension medication or some diabetic drugs such as calcium antagonists, ACE-inhibitors, and selective beta-blockers may increase blood flow,[38–43] while people who need the medication for hypertension or diabetes may have lower extremity blood flow. Thus, the effects of the long-term medication for hypertension on the FBF were considered as a potential confounder to control in fitting the linear mixed model in this study. Also, the use of other medications such as attention-deficit/hyperactivity disorder (ADHD) drugs and calcitonin gene-related peptide-antagonists may increase the risk of hypertension. High blood pressure can lead to decreased blood flow. The information on the use of such medications, however, was not collected in this study. The proportion of participants who reported hand surgery (10%–12%) and alcohol usage (70%–71%) was similar between the groups. A higher proportion of smoking history (60%) in the reference group was observed. Smoking is a major risk factor for arteriosclerosis and endothelial dysfunction.[44] The lower percentage of smoking (18%) in the exposure group than in the reference group (60%) may be associated with less dysfunction

Table 2 Association between (a) lifetime cumulative HAV exposure dose ($a_{hv\text{-}lifetime}$) and baseline finger blood flow ($FBF_{baseline}$) and (b) lifetime cumulative HAV exposure dose ($a_{hv\text{-}lifetime}$) and daily changes in FBF (ΔFBF_{daily}) after adjusting for none (simple), demographic characteristics, or demographic, and social/health-related history in linear mixed model

	Simple*	Demographic*†‡	Demographic + social/health history*‡§
(A)	β, p value (95% CI)		
Right hand			
$a_{hv-lifetime}$	−0.0005, 0.0047** (−0.0009 to −0.0002)	−0.0005, 0.0053** (−0.0009 to −0.0002)	−0.0006, 0.0055** (−0.0010 to 0.0002)
Age		−0.6817, 0.3686 (−2.222 to 0.8586)	−0.4550, 0.5938 (−2.202 to 1.292)
Race/ethnicity-Afr		−26.20, 0.2917 (−76.51 to 24.10)	−16.12, 0.5921 (−77.75 to 45.51)
Race/ethnicity-His		16.52, 0.4790 (−31.05 to 64.09)	17.63, 0.4584 (−30.91 to 66.18)
Hypertension			−21.82, 0.5481(−96.13 to 52.50)
AICc, BIC	939.6, 948.5	924.9, 939.7	918.0, 934.5
Left hand			
$a_{hv-lifetime}$	−0.0006, 0.0343¶ (−0.0012 to <−0.0001)	−0.0007, 0.0346 (−0.0013 to −0.0001)	−0.0009, 0.0068 (−0.0015 to 0.0003)
Age		−0.1329, 0.8955 (−2.207 to 1.942)	0.8976, 0.4023 (−1.286 to 3.081)
Race/ethnicity-Afr		−28.65, 0.3843 (−95.59 to 38.28)	14.75, 0.6891 (−60.86 to 90.36)
Race/ethnicity-His		23.06, 0.4634 (−41.03 to 87.16)	29.57, 0.3177 (−30.51 to 89.66)
Hypertension			−93.66, 0.0468¶ (−185.8, to 1.476)
AICc, BIC	954.7, 963.6	940.2, 955.0	929.0, 945.6
(B)	β, p value (95% CI)		
Right hand			
$a_{hv-lifetime}$	0.0002, 0.4160 (−0.0003 to 0.0008)	0.0003, 0.3543 (−0.0003 to 0.0008)	0.0005, 0.0779 (−0.0001 to 0.0011)
$a_{hv-daily}$	2.551, 0.3362 (−2.721 to 7.823)	4.102, 0.1412 (−1.406 to 9.610)	4.771, 0.0727 (−0.4552 to 9.997)
Age		−0.0470, 0.9662 (−2.322 to 2.228)	−0.8090, 0.4565 (−3.027 to 1.409)
Race/ethnicity-Afr		−18.27, 0.6140 (−92.32 to 55.78)	−6.024, 0.8582 (−75.29 to 63.24)
Race/ethnicity-His		−64.09, 0.0829 (−137.3 to 9.068)	−73.89, 0.0352¶ (-142.1 to 5.649)
Smoking			69.62, 0.0385¶ (4.041 to 135.2)
AICc, BIC	989.9, 1001	973.7, 990.2	962.9, 981.1
Left hand			
$a_{hv-lifetime}$	0.0005, 0.0478¶ (<0.0001 to 0.0010)	0.0006, 0.0173¶ (0.0001 to 0.0011)	0.0006, 0.0330¶ (0.0001 to 0.0012)
$a_{hv-daily}$	1.393, 0.5582 (−3.348 to 6.135)	2.368, 0.3179 (−2.343 to 4.079)	2.359, 0.3247 (−2.401 to 7.120)
Age		−0.5776, 0.4812 (−2.250 to 1.094)	−0.5653, 0.5196 (−2.360 to 1.230)
Race/ethnicity-Afr		−32.82, 0.2204 (−86.78 to 21.14)	−33.01, 0.2280 (−88.29 to 22.27)
Race/ethnicity-His		−67.34, 0.0140¶ (−119.6 to 15.03)	−67.18, 0.0161¶ (−120.5 to 13.82)
Smoking			−1.059, 0.9669 (−53.54 to 51.42)
AICc, BIC	974.8, 985.8	957.1, 973.6	951.3, 969.5

*First 3-day sampling results used for the linear mixed model as repeated-measures data.
†Adjusting for age and race/ethnicity.
‡Information of age and race/ethnicity were obtained from our previous study.[36]
§Adjusting for age, race/ethnicity, and hypertension.
¶p<0.05.
**p<0.01.
AIC, Akaike information criterion; BIC, Bayesian information criterion; HAV, hand-arm vibration.

in hand veins and arteriosclerosis, which effects may move to the opposite direction of the vascular effects of HAV. Average BMI was greater (1 kg/m^2) in the exposure group. Higher BMI may be linked to overweight or obesity and thus associated with cardiovascular diseases,[45] which may affect the blood flow in the same direction as the effects of HAV. Thus, smoking and BMI were also considered as potential confounders to control in fitting the linear mixed model. Three groundskeepers reported colour changes while 7–8 groundskeepers reported numbness or tingling (online supplemental table 2). The results were consistent with the studies conducted in warm environments where finger blanching is less reported. In relation to the FBF results, the groundskeepers, whether they had the vascular symptom or not, showed a lower 3-day average $FBF_{baseline}$, indicating that $FBF_{baseline}$ may be an early, objective indicator of the vascular health of HAVS.

In the present study, a significantly lower $FBF_{baseline}$ was observed in the exposure group compared with the reference group (table 1). In the Stonyneva *et al*'s study, lower baseline FBF values (62 PU) in VWF patients compared with healthy controls (178 PU) were reported.[23] The average $FBF_{baseline}$ of the present study was higher than the Stonyneva *et al* study, mainly for two reasons. First, their probe temperature adjusted at 32°C was lower than our probe temperature, 43°C. The higher probe temperature is more likely to increase the FBF, increasing the average $FBF_{baseline}$. Second, most of our study participants in the exposure group did not report finger blanching, implying they are either without vascular disorders or at preclinical stages, while the participants in Stonyneva *et al*'s study were already diagnosed as having secondary Raynaud's phenomenon (ie, VWF).

The positive value of the first 3-day daily average change in FBF (ΔFBF_{daily}) observed in the exposure group means that FBF measured after a work shift was higher than the FBF measured before a work shift. On the other hand, the negative value of ΔFBF_{daily} from the reference group indicates that FBF was decreased after their regular work shift. Although we found significant differences in ΔFBF_{daily} between groups, considering the fact that the range of ΔFBF_{daily} (exposure group: −45.8 to 156.5 PU; reference group: −141.9 to 22.2 PU) was in both directions with relatively high SDs, more investigations are needed.

Regarding the association between $a_{hv\text{-}lifetime}$ and the 3-day average $FBF_{baseline}$, the yearly average HAV dose of the groundskeepers can be calculated to be 5886.2 hours·m/s^2 for the right hand and 4765.8 hours·m/s^2 for the left hand by dividing the lifetime HAV dose by 13 years. With the coefficients of $a_{hv\text{-}lifetime}$, −0.0005 to −0.0006 for the right hand and −0.0006 to −0.0009 for the left hand, it means that the $FBF_{baseline}$ decreases 2.9–3.5 PU every year on the right hand and 2.9–3.7 PU on the left hand of the groundskeepers. The results are aligned with the hypothesis that the thickening and fibrosis of the smooth muscle layer narrow down the internal diameter of the vessels, thus decreasing the blood flow through the vessels.[18 19 21] Furthermore, the results indicate that the baseline FBF measurement using LDF can be a promising non-invasive health indicator for preventing HAVS among the power tool operators. A significantly lower 3-day average $FBF_{baseline}$ on the left hand was observed among the participants who had long-term medication for hypertension, implying that the injuries on the vessels induced from other sources than vibration may have contributed to the decrease in $FBF_{baseline}$. However, careful interpretation is required due to the limited number of participants who reported long-term medication for hypertension.

Studies reported decreased responses of FBF to sympathetic stimulations through standing up and deep breathing in VWF patients compared with healthy participants, implying the dysregulation of vessels.[18 23] If we assume that the job activities for both groundskeepers and office workers were sympathetic stimulations, ΔFBF_{daily} may be the response of finger vessels to sympathetic stimulations. Negative ΔFBF_{daily} can be interpreted as vasoconstriction, whereas positive ΔFBF_{daily} as vasodilation. In the present study, the increase in ΔFBF_{daily} in response to the increase in $a_{hv\text{-}lifetime}$ may indicate a reduction in vasoconstrictions among the individuals with higher lifetime HAV exposure. The inconsistent statistical significance between $a_{hv\text{-}lifetime}$ and ΔFBF_{daily} may have been contributed by the limited sample size and other uncontrollable factors. For example, groundskeepers had higher physical activity which may belong to sympathetic stimulations. The higher sympathetic stimulation is known to induce more vasoconstriction at the peripheral microvessels. The higher sympathetic stimulation among groundskeepers may have induced more reduction in the FBF_{after}, leading to smaller ΔFBF_{daily} in groundskeepers, underestimating the effect size of ΔFBF_{daily}. Also, a study observed vasoconstrictions in healthy subjects during and after acute HAV exposure.[24] The negative association between ΔFBF_{daily} and $a_{hv\text{-}daily}$ was anticipated to reflect vasoconstrictions. However, the direction of the association was positive, with no statistical significance found. One of the reasons would be that a $shift_{hv\text{-}daily}$ may induce both immediate effects and cumulative effects because of a full 8-hour work shift.

There were limitations in the study. First, although the FBF was measured under the controlled room and skin temperature and habituation time was given before FBF measurement for the body to adjust to the room temperature, the random error from the measurement of the FBF may still exist. It is possible that the FBF may have been affected by body temperature if the subject did not habituate to the room temperature. However, the entire study period included from spring to early winter, containing both warmer and colder outdoor ambient temperatures, which is more likely to cause the variations in both directions. Second, the frequency weighting system in ISO 5349-1 was employed in the present study. It is suggested that the vascular system on the fingers is more sensitive to vibration with higher frequency,[46 47] implying the use of the ISO 5349-1 frequency weighting system which weighs heavily on the lower frequency range (≥25 Hz) may underestimate the association between the FBF and HAV exposure. In fact, ISO published a new frequency-weighting system, ISO/TR 18570, but its adoption by the current manufacturers of HAV measuring devices as well as researchers is limited. Third, LDF is primarily used to measure skin microcirculation because of the limited penetration of the laser light.[30] The surface blood flow measured at the middle finger in the present study provides a portion of the entire circulation within the digit.[48] Lastly, although there were no exclusion criteria related to race/ethnicity and sex among groundskeepers, selection bias may still exist because of the recruitment method. The study participants' biological sex reflected well the current demographic characteristic of this occupation, considering the fact that the majority of the groundskeepers, 95%, are male in the USA.[49] Nonetheless, it limits the generalisation of the results to all groundskeepers including female workers. Although the significant coefficient of $a_{hv\text{-}lifetime}$ was observed consistently throughout the $FBF_{baseline}$ models under the small size and limited observation periods, providing more confidence to the results, more studies with larger sample sizes and longer observation periods are needed to confirm the results from the present study.

CONCLUSIONS

A significant association between lifetime HAV exposure and baseline FBF was found among groundskeepers. The present study demonstrated the FBF measurement using LDF as a promising health indicator for the vascular disorders of HAVS among power tool operators, supporting the current knowledge on the pathophysiological mechanisms of HAVS. Long-term follow-up studies with larger sample sizes are needed to establish the dose–response relationship between HAV exposure and vascular disorder as FBF.

Contributors Writing—original draft: NC and JO; writing—reviewing and editing: all authors (NC, SY, JML and JO); data collection: NC and SY; data curation: NC, SY and JO; methodology: NC, JML and JO; funding acquisition: NC and JO; conceptualisation: NC and JO; formal analysis: NC; guarantor: JO.

Funding This study was supported in part by the National Institute of Occupational Safety and Health (NIOSH) Pilot/Small Project Research Training (PPRT) Grant through the Deep South Center for Occupational Health and Safety (Grant #T42OH008436).

Disclaimer Its contents are the sole responsibility of the author and do not represent the official views of NIOSH.

Competing interests None declared.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and UAB Office of Institutional Review Board approval was obtained for this study (UAB IRB #300008388). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on reasonable request. The data underlying this article cannot be shared publicly due to the privacy of individuals that participated in the study. Deidentified data can be shared on reasonable request to the corresponding author.

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