24-Hour Central Hemodynamic Load in Adults With and Without a History of COVID-19

Andrew R. Heckel, Danielle M. Arcidiacono, Kailee A. Coonan, Alaina C. Glasgow, Jacob P. DeBlois, Brooks B. Gump, Joon Young Kim, Kevin S. Heffernan

Syracuse University, Syracuse, NY

Disclosures: Supported by the SU Lerner Center for Public Health Promotion

Corresponding Author:

Kevin S. Heffernan, Ph.D.

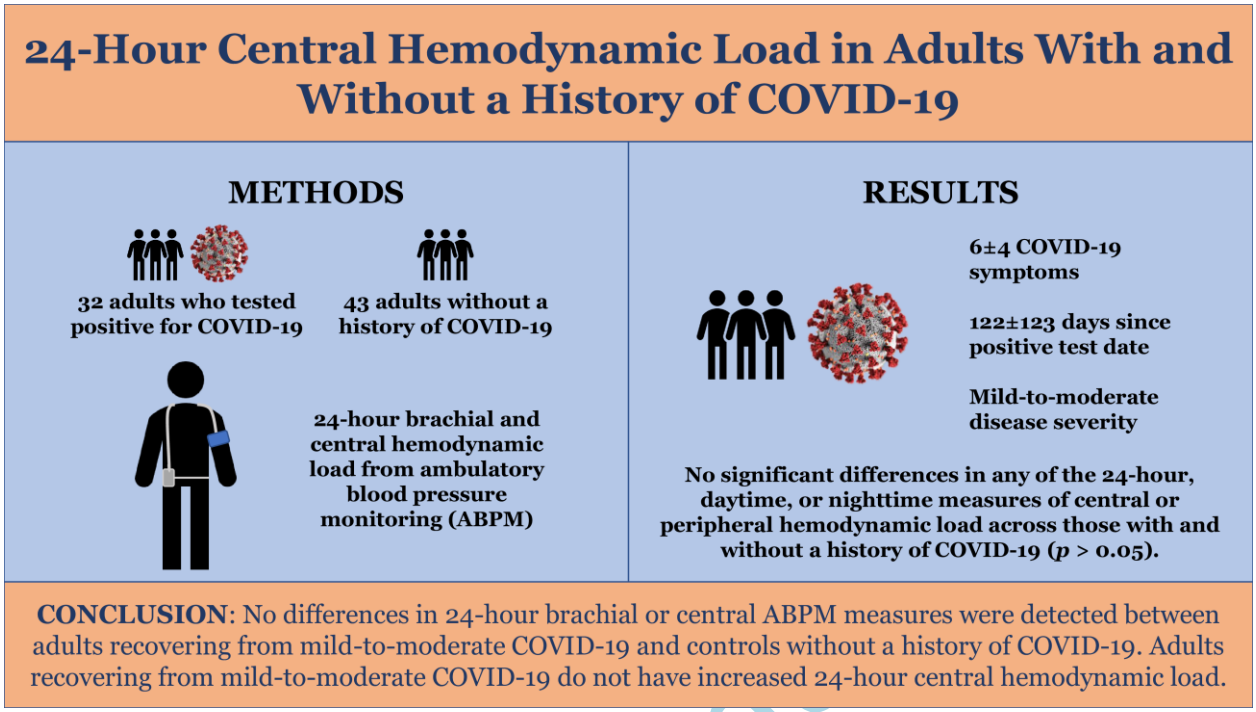
Dean's Associate Professor of Exercise Science
Director of The Human Performance Laboratory
Syracuse University
820 Comstock Ave, Syracuse NY, 13244
Phone: 315-443-9801; Fax: 315-443-9375; Email: ksheffer@syr.edu

Abstract

BACKGROUND: Although hypertension is an established risk factor for severe COVID-19 illness, little is known about the effects of COVID-19 on blood pressure (BP). Central BP measures taken over a 24-hour period using ambulatory blood pressure monitoring (ABPM) adds prognostic value in assessing cardiovascular disease (CVD) risk compared to brachial BP measures taken at a single time point. We assessed CVD risk between adults with and without a history of COVID-19 via appraisal of 24-hour brachial and central hemodynamic load from ABPM. **METHODS:** Cross-sectional analysis was performed on 32 adults who tested positive for COVID-19 (29±13 years, 22 females) and 43 adults without a history of COVID-19 (28±12 years, 26 females). Measures of 24-hour hemodynamic load included brachial and central systolic and diastolic BP, pulse pressure, augmentation index (AIx), pulse wave velocity (PWV), nocturnal BP dipping, the ambulatory arterial stiffness index (AASI), and the blood pressure variability ratio (BPVR). **RESULTS:** Participants who tested positive for COVID-19 experienced 6±4 COVID-19 symptoms, were studied 122±123 days after testing positive, and had mild-to-moderate COVID-19 illness. The results from independent samples *t*-tests showed no significant differences in any of our 24-hour, daytime, or nighttime measures of central or peripheral hemodynamic load across those with and without a history of COVID-19 ($p > 0.05$ for all). **CONCLUSIONS:** No differences in 24-hour brachial or central ABPM measures were detected between adults recovering from mild-to-moderate COVID-19 and controls without a history of COVID-19. Adults recovering from mild-to-moderate COVID-19 do not have increased 24-hour central hemodynamic load.

Keywords: COVID-19; cardiovascular; blood pressure; central blood pressure; ABPM

Graphical abstract



Introduction

Hypertension is a modifiable risk factor for cardiovascular disease (CVD) that affects more than half of the U.S. adult population [1]. Although hypertension is an established risk factor for severe COVID-19 illness [2], little is known about the effect of COVID-19 on blood pressure (BP). SARS-CoV-2, the virus responsible for COVID-19, may damage the cardiovascular system through angiotensin converting enzyme 2 (ACE2) receptor-mediated viral cell entry into vascular endothelial cells and an exacerbated hyperinflammatory immune response [3]. COVID-19 is associated with autonomic dysfunction, reductions in baroreflex sensitivity, endothelial dysfunction, and increases in arterial stiffness observed during [4-6] and following [3,7-9] active infection. Each of these cardiovascular mal-adaptations is important for BP regulation and may precede the development of hypertension [10-13]. There is emerging data to suggest that persistent elevations in BP may be part of the post-acute sequelae of COVID-19 illness [8], with the potential for increases in brachial systolic and diastolic pressures leading to new onset hypertension following COVID-19 [2]. However, these studies have focused on the recovery of hospitalized COVID-19 patients [2], and their findings stress the need for further studies exploring the BP response in those with less severe COVID-19 illness in non-clinical settings.

BP measures taken over a 24-hour period using ambulatory BP monitoring (ABPM) may add prognostic value in assessing CVD risk compared to single point BP measures [14]. 24-hour ABPM more strongly predicts CVD events and mortality compared to BP measures at a single time point [14]. Numerous measures of BP load can be obtained from ABPM, including nocturnal BP dipping, BP variability, and the ambulatory arterial stiffness index (AASI), each a significant predictor of target organ damage and future CVD events [14,15]. Moreover, BP technology has progressed such that 24-hour ambulatory *central* BP can now be assessed using a brachial

oscillometric cuff. Central pressures may have more pathophysiological relevance to CVDs than brachial pressures as the organs most susceptible to hypertension-induced target organ damage (i.e., the heart, kidneys, and brain) are exposed to central pressures [14]. Indeed, 24-hour central ABPM shows stronger associations with preclinical measures of CVD risk [14,16] and future CVD events [17] compared to 24-hour brachial ABPM. Thus, with the potential for CV mal-adaptations to persist after COVID-19 and influence BP regulation, and considering the improved utility of central BP over brachial BP in assessing CVD risk, measuring central BP over a 24-hour period may improve CVD risk assessment in individuals recovering from COVID-19.

Therefore, the aim of this study was to use 24-hour brachial and central ABPM to compare hemodynamic load between adults with and without a history of COVID-19 infection. Measures of hemodynamic load included absolute brachial and central measures of systolic BP, pulse pressure (PP), as well as the augmentation index (AIx) and pulse wave velocity (PWV). We additionally assessed brachial and central nocturnal BP dipping, the AASI and the BP variability ratio (BPVR). We hypothesized that individuals with a history of COVID-19 would exhibit higher hemodynamic load, manifesting as higher brachial and central systolic BP, PP, BPVR, AASI, AIx and PWV, as well as lesser nighttime BP dipping, compared to those without a history of COVID-19.

Methods

Participants: 75 participants, 32 adults who tested positive for COVID-19 and 43 adults without a history of COVID-19, participated in this study. Participants who tested positive for COVID-19 provided documentation of either a positive viral or antibody test to confirm previous infection. Participants without a history of COVID-19 were asked to provide documentation of a

negative antibody test to rule out previous infection. All participants provided oral informed consent over a Zoom meeting prior to study initiation and all study procedures were approved by the Syracuse University Institutional Review Board.

St*udy Design*: This study consisted of two study meetings: a Zoom consent meeting and a data collection study meeting. During the data collection study meeting, participants completed anthropometric and pulse oximetry assessments and initiated ABPM measures. Participants were asked to avoid food, sugary drinks, alcohol and caffeine for 12 hours, as well as exercise for 24 hours, prior to this meeting. This study was initially designed to be completed virtually when in-person human research was not allowed at Syracuse University. As such, 57 participants completed the data collection meeting over a Zoom video call. A box containing the study equipment and an information sheet with pictures and written explanations for how to use the equipment was dropped off at the participant's place of residence prior to the Zoom meeting. During the Zoom meeting, participants were guided through the information sheet and given verbal instructions and visual demonstrations for how to complete study procedures. Additionally, prior to ABPM initiation, participants were guided through appropriately sizing and putting on the BP cuff as well as connecting the cuff to the ABPM device. Participants then performed one manual blood pressure measurement to ensure that the blood pressure cuff was appropriately sized and connected to the ABPM device prior to initiation of the 24-hour measurements. When in-person research was allowed to return at Syracuse University, 18 participants completed the aforementioned data collection procedures during a single 15-minute visit to the Human Performance Lab on the Syracuse University campus. After completion of the data collection study meeting, all participants were sent a Research Electronic Data Capture

(REDCap) link with a series of online questionnaires to complete in the 24 hours while undergoing ABPM.

Study Measurements

Anthropometrics and Pulse Oximetry: Participants self-reported height, a method that has been validated in young and middle-aged adults [18]. In older adults (≥ 60 years), a regression equation was applied to calculate actual height from self-reported height [18]. In the subsample of participants who completed in-person data collection (n = 18), height was also measured using an automatic stadiometer for comparison of self-reported height to stadiometer measured height. Metrics for the criterion-related validity of self-reported height based on this subsample are provided in an online supplement (Figure S1). Weight and body composition were assessed using a digital scale with bioelectrical impedance analysis (Taylor Glass Body Composition Scale 5789FW, USA). Body mass index (BMI) was calculated as kg/m^2. Arterial oxygen saturation was assessed at rest using a fingertip pulse oximeter placed on the index finger.

Ambulatory Blood Pressure Monitoring: ABPM with simultaneous pulse wave analysis (PWA) was performed using the oscillometric Mobil-O-Graph device (IEM, Stolberg, Germany). This device has been validated against gold standard invasive (intra-aortic catheter) and non-invasive (applanation tonometry) methods in a variety of populations [19,20]. Participants wore an appropriately sized upper arm BP cuff and BP readings were taken every 20 minutes during the day (07:00 hr – 22:00 hr) and every 30 minutes during the night (22:00 hr – 07:00 hr). The device initially inflates and deflates to perform a brachial oscillometric BP measurement, then reinflates again for approximately 10 seconds at the level of diastole to record brachial pulse waveforms. Participants were instructed to avoid exercise and vigorous activity during ABPM

and to keep their arm still and relaxed during measurements. ≥ 70% of the expected number of measurements in the 24-hour period were required to be valid for the data to be included for analysis. These methods follow 2017 American College of Cardiology/American Heart Association guidelines for 24-hour BP monitoring in adults [21].

Mean arterial pressure (MAP) was determined as the lowest cuff pressure where the oscillations are maximal [22]. Central aortic pulse waves were derived from brachial pulse waveforms using an applied transfer function derived from the ARCSolver algorithm [23]. Central aortic waveforms were calibrated using the C2 methods (MAP/diastolic BP) [14]. The central aortic waveforms was decomposed into forward and reflected waves [23] and used to estimate PWV [24]. AIx was calculated as the ratio of the augmented pressure to pulse pressure, and was also normalized to a heart rate of 75 bpm (AIx@75). Additional ABPM calculations of hemodynamic load were performed using both peripheral and central BP measures and included:

- Pulse pressure (PP): the difference of the systolic and diastolic BPs,
- Nighttime SBP and DBP Dipping: calculated as a percentage, and defined as [(daytime BP – nighttime BP) / daytime BP] x 100 [25],
- SBP, DBP and PP Variability: standard deviation (SD) of 24-hour SBP, DBP and PP [26],
- BP Variability Ratio (BPVR): ratio of systolic to diastolic BP variability [26],
- AASI: calculated from 24-hour BP measures as 1 – regression slope of diastolic on systolic BP values [27].

Questionnaires: Participants self-reported their health history via a health questionnaire. COVID-19 disease severity was determined using the World Health Organization's guidelines for COVID-19 disease severity based on self-reported symptomology [28].

Increases in BP and new onset hypertension following COVID-19 infection mirrors trends in rising BP and increased rates of hypertension observed during the COVID-19 pandemic [29]. It is possible that COVID-19 illness may cause changes in lifestyle and mental health symptomology (i.e., reduced physical activity [30], disturbed sleep [31], and increased anxiety, depressive symptomology, and stress symptomology [32,33]) which could impact BP separate from the direct effects of COVID-19 illness on the vasculature. Thus, we included potential lifestyle and psychosocial factors that may have been affected by the COVID-19 pandemic [34-36] as potential covariates in our analytic approach (described below). Sleep quality was determined using the Pittsburgh Sleep Quality Index (PSQI). Anxiety and depressive symptomology were appraised using the Generalized Anxiety Disorder 7-item scale (GAD-7) and Center for Epidemiological Studies Depression scale (CES-D), respectively. Perception of stress was assessed using the 10-item Perceived Stress scale (PSS-10). Post-traumatic stress disorder (PTSD) symptoms since the beginning of the COVID-19 pandemic were assessed using the PTSD Checklist for the DSM-5 (PCL-5). Physical activity levels were appraised using the International Physical Activity Questionnaire (IPAQ).

Statistical Analysis: Descriptive statistics are reported as mean ± SD for continuous variables and *n* (%) for categorical variables. All data were checked for normality using box plots, histograms, Q-Q plots, and skewness and kurtosis values. An independent samples *t*-test for continuous variables and a chi square test for categorical variables were used to compare participant characteristics and potential covariates between the COVID-19 and control groups. Potential

confounders found to be significantly different between groups would be entered as covariates using Analysis of Covariance (ANCOVA) as needed. Subsequently, an independent samples *t*-test was conducted to compare our ABPM central hemodynamic measures between the COVID-19 and control groups. Statistical significance was set *a priori* at $p < 0.05$. All statistical analyses were performed using IBM SPSS Statistics version 27 (SPSS Inc., Chicago, IL).

Results

Participant Characteristics: Participant characteristics are presented in Table 1. Age, sex, race/ethnicity, BMI, body composition, and arterial oxygen saturation did not significantly differ between the COVID-19 and control groups (Table 1, $p > 0.05$ for all). Ten participants reported a history of asthma (6 COVID-19, 4 controls), one participant reported a history of pulmonary disease (1 COVID-19), and one participant reported a history of breast cancer (1 control). No participants reported a history of diabetes, renal, or hepatic disease. One participant identified as a current smoker (1 control). Six participants identified as taking blood pressure lowering medication (1 COVID-19, 5 controls). Analyses were performed excluding the six participants who reported taking blood pressure lowering medications and we found that the removal of these participants did not change our overall results. Therefore, results are presented with these individuals included. Participants in our COVID-19 group were tested 121.9 ± 122.8 days after their positive COVID-19 test date, experienced 5.9 ± 4.4 COVID-19 symptoms, and had mild-to-moderate COVID-19 disease severity. There were no significant differences between our COVID-19 and control groups in scores for the PSQI, GAD-7, CES-D, PSS-10, PCL-5 or IPAQ (all $p > 0.05$).

Ambulatory Blood Pressure Monitoring: Overall, our COVID-19 and control groups did not significantly differ in any of our central hemodynamic load measures (Table 2, $p > 0.05$ for all). 24-hour, nighttime, and daytime peripheral and central BPs did not significantly differ between the COVID-19 and control groups (all $p > 0.05$). Furthermore, peripheral and central PPs, AIx, AIx@75, and PWV did not significantly differ between the COVID-19 and control groups in 24-hour, daytime, or nighttime measures (all $p > 0.05$). Additional measures comparing BP dipping and variability between our COVID-19 and control groups are presented in Table 3. There were no significant differences in peripheral and central measures for nighttime systolic and diastolic BP dipping, systolic and diastolic BP variability, PP variability, BPVR, or AASI between our COVID-19 and control groups (Table 3, $p > 0.05$ for all).

Discussion

In order to explore CVD risk in adults following mild-to-moderate COVID-19, this study utilized 24-hour brachial and central ABPM to compare hemodynamic load between adults with and without a history of COVID-19. Contrary to our hypothesis, there were no differences in brachial or central measures of systolic and diastolic BP, PP, AIx, PWV, nocturnal BP dipping, the AASI or BPVR between adults with and without a history of COVID-19. These findings suggest that adults recovering from mild-to-moderate COVID-19 may not have augmented hemodynamic load compared to those without a history of COVID-19.

Our findings differ from previous studies observing an increased risk for new-onset hypertension and vascular dysfunction in individuals after COVID-19 illness [2-5,7]. However, there are important differences in our study design that may explain our differential findings. Most notably, previous studies finding an increased risk for new onset hypertension and ongoing

vascular dysfunction have either not included a control group [2], or used a control group on whom data collection occurred prior to the COVID-19 pandemic [3,7]. As we have mentioned, the COVID-19 pandemic itself may cause important changes to potential confounders of cardiovascular function – including sleep quality [36] and mental health symptomology [34] – that may not have been controlled for in these studies. Additionally, increases in BP and rates of new onset hypertension following COVID-19 parallels trends in rising BP and hypertension rates occurring during the COVID-19 pandemic [30]. Thus, whether the cardiovascular decrements observed in these studies are directly attributable to COVID-19 illness, or whether they are emblematic of the COVID-19 pandemic as a whole, may still need further investigation. That being said, our COVID-19 and control groups did not significantly differ in sleep quality, perceptions of stress or anxiety, depressive symptomology, PTSD symptomology, or physical activity levels, possibly contributing to our lack of group differences in our measures of hemodynamic load between our COVID-19 and control groups.

Another important distinction in our study is that our COVID-19 participants experienced predominantly mild-to-moderate COVID-19 illness, were studied, on average, four months after infection, and had no hospitalizations. Most of the previous literature on this subject has examined hospitalized COVID-19 patients in the acute phase of recovery from more severe cases of COVID-19 illness [4,5]. These patients may experience more severe cardiovascular consequences extending into recovery compared to our COVID-19 cohort. Few studies have examined outcomes from mild COVID-19 illness. Of these studies, those observing vascular dysfunction were mainly during the acute recovery period (<3 months) from COVID-19 [3,7], while an emerging literature from the post-acute recovery phase (~3 months) is showing that vascular function may return and BP may normalize four to six months into recovery [8]. Our

findings support this emerging literature and suggest that, in mild-to-moderate cases, hemodynamic load may not significantly differ between adults with and without a history of COVID-19. Thus, while it should still be noted that hypertension remains an important risk factor for an increased COVID-19 disease severity [2], our findings suggest that mild-to-moderate COVID-19 may not, in turn, increase the risk for new onset hypertension.

Limitations: Although this study provides novel insight into the effect of COVID-19 on hemodynamic load, it is not without limitations. Due to the cross-sectional study design, hemodynamic data on COVID-19 participants prior to their infection was not available for the longitudinal assessment of hemodynamic measures. COVID-19 participants were also asked to self-report their COVID-19 symptomology, on average, four months after infection; potentially subjecting this study to the limitations of recall bias. Participants were given a list of COVID-19 symptoms as prompts to help improve recall accuracy. In addition, if participants under- or over-reported COVID-19 symptomology, we do not believe this would alter interpretation of our results given our null findings. Furthermore, this study utilized an estimated measure of PWV. Although the criterion-related validity of the Mobil-O-Graph device in estimating PWV has been established against gold standard invasive and non-invasive measures [19,20], the derivation of PWV is dependent on age and SBP [37,38], limiting its ability to accurately estimate PWV. That being said, the Mobil-O-Graph device provides accurate assessments of our other measures of CVD risk, notably BP, and the conclusions of our study are not affected by the one measure of PWV. The mean age of our study population was 28 years so results may not be generalizable to middle-aged and older adults. Finally, our study population is predominantly White, limiting the external validity of our findings to other racial and ethnic groups. COVID-19 has been shown to disproportionately affect racial and ethnic minority groups in both overall case numbers and the

severity of disease outcomes [39]. Minority populations already carry an excessive cardiovascular burden compared to White populations [40]; thus, it will be important for future studies to examine the impact of COVID-19 on hemodynamic load in minority populations to better understand how COVID-19 may affect future cardiovascular risk in these groups.

Conclusion: This study found no differences in 24-hour measures of hemodynamic load, including brachial and central measures of systolic and diastolic BP, PP, AIx, PWV, nocturnal BP dipping, the AASI, and BPVR, between adults with and without a history of COVID-19. These findings of similar central hemodynamic load may be taken to suggest comparable CVD risk in adults recovering from mild-to-moderate COVID-19 compared to adults without a history of COVID-19. Given the limitations of cross-sectional study design, future studies should longitudinally examine measures of hemodynamic load in individuals recovering from COVID-19 to better determine the risk for developing future hypertension.

Acknowledgments: Supported by the SU Lerner Center for Public Health Promotion

References

1. Wu CY, Hu HY, Chou YJ, Huang N, Chou YC, Li CP. High Blood Pressure and All-Cause and Cardiovascular Disease Mortalities in Community-Dwelling Older Adults. *Medicine (Baltimore)* 2015; **94**(47)**:** e2160.

2. Akpek M. Does COVID-19 Cause Hypertension? *Angiology* 2021**:** 33197211053903.

3. Ratchford SM, Stickford JL, Province VM, Stute N, Augenreich MA, Koontz LK, Bobo LK, Stickford ASL. Vascular alterations among young adults with SARS-CoV-2. *Am J Physiol Heart Circ Physiol* 2021; **320**(1)**:** H404-H410.

4. Schnaubelt S, Oppenauer J, Tihanyi D, Mueller M, Maldonado-Gonzalez E, Zejnilovic S, Haslacher H, Perkmann T, Strassl R, Anders S, Stefenelli T, Zehetmayer S, Koppensteiner R, Domanovits H, Schlager O. Arterial stiffness in acute COVID-19 and potential associations with clinical outcome. *J Intern Med* 2021.

5. Rodilla E, Lopez-Carmona MD, Cortes X, Cobos-Palacios L, Canales S, Saez MC, Campos Escudero S, Rubio-Rivas M, Diez Manglano J, Freire Castro SJ, Vazquez Piqueras N, Mateo Sanchis E, Pesqueira Fontan PM, Magallanes Gamboa JO, Gonzalez Garcia A, Madrid Romero V, Tamargo Chamorro L, Gonzalez Moraleja J, Villanueva Martinez J, Gonzalez Noya A, Suarez-Lombrana A, Gracia Gutierrez A, Lopez Reboiro ML, Ramos Rincon JM, Gomez Huelgas R, Network S-C-. Impact of Arterial Stiffness on All-Cause Mortality in Patients Hospitalized With COVID-19 in Spain. *Hypertension* 2021; **77**(3)**:** 856-867.

6. Milovanovic B, Djajic V, Bajic D, Djokovic A, Krajnovic T, Jovanovic S, Verhaz A, Kovacevic P, Ostojic M. Assessment of Autonomic Nervous System Dysfunction in the Early Phase of Infection With SARS-CoV-2 Virus. *Front Neurosci* 2021; **15:** 640835.

7. Szeghy RE, Province VM, Stute NL, Augenreich MA, Koontz LK, Stickford JL, Stickford ASL, Ratchford SM. Carotid stiffness, intima-media thickness and aortic augmentation index among adults with SARS-CoV-2. *Exp Physiol* 2021.

8. Szeghy RE, Stute NL, Province VM, Augenreich MA, Stickford JL, Stickford ASL, Ratchford SM. Six-Month Longitudinal Tracking of Arterial Stiffness and Blood Pressure in Young Adults Following SARS-CoV-2 Infection. *J Appl Physiol (1985)* 2022.

9. Shouman K, Vanichkachorn G, Cheshire WP, Suarez MD, Shelly S, Lamotte GJ, Sandroni P, Benarroch EE, Berini SE, Cutsforth-Gregory JK, Coon EA, Mauermann ML, Low PA, Singer W. Autonomic dysfunction following COVID-19 infection: an early experience. *Clin Auton Res* 2021; **31**(3)**:** 385-394.

10. Kohara K. Central blood pressure, arterial stiffness and the heart in hypertensive patients. *Hypertension Research* 2009; **32**(12)**:** 1056-1058.

11. McEniery CM, Wallace S, Mackenzie IS, McDonnell B, Yasmin, Newby DE, Cockcroft JR, Wilkinson IB. Endothelial function is associated with pulse pressure, pulse wave velocity, and augmentation index in healthy humans. *Hypertension* 2006; **48**(4)**:** 602-608.

12. Carthy ER. Autonomic dysfunction in essential hypertension: A systematic review. *Ann Med Surg (Lond)* 2014; **3**(1)**:** 2-7.

13. Hesse C, Charkoudian N, Liu Z, Joyner MJ, Eisenach JH. Baroreflex sensitivity inversely correlates with ambulatory blood pressure in healthy normotensive humans. *Hypertension* 2007; **50**(1)**:** 41-46.

14. Weber T, Protogerou AD, Agharazii M, Argyris A, Aoun Bahous S, Banegas JR, Binder RK, Blacher J, Araujo Brandao A, Cruz JJ, Danninger K, Giannatasio C, Graciani A, Hametner B, Jankowski P, Li Y, Maloberti A, Mayer CC, McDonnell BJ, McEniery CM, Antonio Mota Gomes M, Machado Gomes A, Lorenza Muiesan M, Nemcsik J, Paini A, Rodilla E, Schutte AE, Sfikakis PP, Terentes-Printzios D, Vallee A, Vlachopoulos C, Ware L, Wilkinson I, Zweiker R, Sharman JE, Wassertheurer S, International Academic 24-Hour Ambulatory Aortic Blood Pressure C. Twenty-Four-Hour Central (Aortic) Systolic Blood Pressure: Reference Values and Dipping Patterns in Untreated Individuals. *Hypertension* 2022; **79**(1)**:** 251-260.

15. Dolan E, Thijs L, Li Y, Atkins N, McCormack P, McClory S, O'Brien E, Staessen JA, Stanton AV. Ambulatory Arterial Stiffness Index as a Predictor of Cardiovascular Mortality in the Dublin Outcome Study. *Hypertension* 2006; **47**(3)**:** 365-370.

16. Kollias A, Lagou S, Zeniodi ME, Boubouchairopoulou N, Stergiou GS. Association of Central Versus Brachial Blood Pressure With Target-Organ Damage: Systematic Review and Meta-Analysis. *Hypertension* 2016; **67**(1)**:** 183-190.

17. Roman MJ, Devereux RB, Kizer JR, Lee ET, Galloway JM, Ali T, Umans JG, Howard BV. Central pressure more strongly relates to vascular disease and outcome than does brachial pressure: the Strong Heart Study. *Hypertension* 2007; **50**(1)**:** 197-203.

18. Kuczmarski MF, Kuczmarski RJ, Najjar M. Effects of age on validity of self-reported height, weight, and body mass index: findings from the Third National Health and Nutrition Examination Survey, 1988-1994. *J Am Diet Assoc* 2001; **101**(1)**:** 28-34; quiz 35-26.

19. Hametner B, Wassertheurer S, Kropf J, Mayer C, Eber B, Weber T. Oscillometric estimation of aortic pulse wave velocity: comparison with intra-aortic catheter measurements. *Blood Press Monit* 2013; **18**(3)**:** 173-176.

20. Berukstis A, Jarasunas J, Daskeviciute A, Ryliskyte L, Baranauskas A, Steponeniene R, Laucevicius A. How to interpret 24-h arterial stiffness markers: comparison of 24-h ambulatory Mobil-O-Graph with SphygmoCor office values. *Blood Press Monit* 2019; **24**(2)**:** 93-98.

21. Whelton PK, Carey RM, Aronow WS, Casey DE, Jr., Collins KJ, Dennison Himmelfarb C, DePalma SM, Gidding S, Jamerson KA, Jones DW, MacLaughlin EJ, Muntner P, Ovbiagele B, Smith SC, Jr., Spencer CC, Stafford RS, Taler SJ, Thomas RJ, Williams KA, Sr., Williamson JD, Wright JT, Jr. 2017 ACC/AHA/AAPA/ABC/ACPM/AGS/APhA/ASH/ASPC/NMA/PCNA Guideline for the Prevention, Detection, Evaluation, and Management of High Blood Pressure in Adults: Executive Summary: A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. *Circulation* 2018; **138**(17)**:** e426-e483.

22. Smulyan H, Sheehe PR, Safar ME. A preliminary evaluation of the mean arterial pressure as measured by cuff oscillometry. *Am J Hypertens* 2008; **21**(2)**:** 166-171.

23. Weber T, Wassertheurer S, Rammer M, Maurer E, Hametner B, Mayer CC, Kropf J, Eber B. Validation of a brachial cuff-based method for estimating central systolic blood pressure. *Hypertension* 2011; **58**(5)**:** 825-832.

24. Papaioannou TG, Argyris A, Protogerou AD, Vrachatis D, Nasothimiou EG, Sfikakis PP, Stergiou GS, Stefanadis CI. Non-invasive 24 hour ambulatory monitoring of aortic wave reflection and arterial stiffness by a novel oscillometric device: the first feasibility and reproducibility study. *Int J Cardiol* 2013; **169**(1)**:** 57-61.

25. Koroboki E, Manios E, Psaltopoulou T, Vemmos K, Michas F, Alexaki E, Zakopoulos N. Circadian variation of blood pressure and heart rate in normotensives, white-coat, masked, treated and untreated hypertensives. *Hellenic J Cardiol* 2012; **53**(6)**:** 432-438.

26. Gavish B, Ben-Dov IZ, Kark JD, Mekler J, Bursztyn M. The association of a simple blood pressure-independent parameter derived from ambulatory blood pressure variability with short-term mortality. *Hypertens Res* 2009; **32**(6)**:** 488-495.

27. Li Y, Wang J-G, Dolan E, Gao P-J, Guo H-F, Nawrot T, Stanton AV, Zhu D-L, O'Brien E, Staessen JA. Ambulatory Arterial Stiffness Index Derived From 24-Hour Ambulatory Blood Pressure Monitoring. *Hypertension* 2006; **47**(3)**:** 359-364.

28. Gandhi RT, Lynch JB, Del Rio C. Mild or Moderate Covid-19. *N Engl J Med* 2020; **383**(18)**:** 1757-1766.

29. Shah NP, Clare RM, Chiswell K, Navar AM, Shah BR, Peterson ED. Trends of blood pressure control in the U.S. during the COVID-19 pandemic. *Am Heart J* 2021; **247:** 15-23.

30. Delbressine JM, Machado FVC, Goërtz YMJ, Van Herck M, Meys R, Houben-Wilke S, Burtin C, Franssen FME, Spies Y, Vijlbrief H, Van 'T Hul AJ, Janssen DJA, Spruit MA, Vaes AW. The Impact of Post-COVID-19 Syndrome on Self-Reported Physical Activity. *International Journal of Environmental Research and Public Health* 2021; **18**(11)**:** 6017.

31. El Sayed S, Gomaa S, Shokry D, Kabil A, Eissa A. Sleep in post-COVID-19 recovery period and its impact on different domains of quality of life. *The Egyptian Journal of Neurology, Psychiatry and Neurosurgery* 2021; **57**(1).

32. Klaser K, Thompson EJ, Nguyen LH, Sudre CH, Antonelli M, Murray B, Canas LS, Molteni E, Graham MS, Kerfoot E, Chen L, Deng J, May A, Hu C, Guest A, Selvachandran S, Drew DA, Modat M, Chan AT, Wolf J, Spector TD, Hammers A, Duncan EL, Ourselin S, Steves CJ. Anxiety and depression symptoms after COVID-19 infection: results from the COVID Symptom Study app. Cold Spring Harbor Laboratory, 2021.

33. Janiri D, Carfì A, Kotzalidis GD, Bernabei R, Landi F, Sani G. Posttraumatic Stress Disorder in Patients After Severe COVID-19 Infection. *JAMA Psychiatry* 2021; **78**(5)**:** 567.

34. Xiong J, Lipsitz O, Nasri F, Lui LMW, Gill H, Phan L, Chen-Li D, Iacobucci M, Ho R, Majeed A, McIntyre RS. Impact of COVID-19 pandemic on mental health in the general population: A systematic review. *J Affect Disord* 2020; **277:** 55-64.

35. Zheng C, Huang WY, Sheridan S, Sit CH, Chen XK, Wong SH. COVID-19 Pandemic Brings a Sedentary Lifestyle in Young Adults: A Cross-Sectional and Longitudinal Study. *Int J Environ Res Public Health* 2020; **17**(17).

36. Hyun S, Hahm HC, Wong GTF, Zhang E, Liu CH. Psychological correlates of poor sleep quality among U.S. young adults during the COVID-19 pandemic. *Sleep Med* 2021; **78:** 51-56.

37. Salvi P, Furlanis G, Grillo A, Pini A, Salvi L, Marelli S, Rovina M, Moretti F, Gaetano R, Pintassilgo I, Faini A, Fabris B, Carretta R, Parati G. Unreliable Estimation of Aortic Pulse Wave Velocity Provided by the Mobil-O-Graph Algorithm-Based System in Marfan Syndrome. *J Am Heart Assoc* 2019; **8**(9)**:** e04028.

38. Schwartz JE, Feig PU, Izzo JL, Jr. Pulse Wave Velocities Derived From Cuff Ambulatory Pulse Wave Analysis. *Hypertension* 2019; **74**(1)**:** 111-116.

39. Rentsch CT, Kidwai-Khan F, Tate JP, Park LS, King JT, Jr., Skanderson M, Hauser RG, Schultze A, Jarvis CI, Holodniy M, Re VL, 3rd, Akgun KM, Crothers K, Taddei TH, Freiberg MS, Justice AC. Covid-19 by Race and Ethnicity: A National Cohort Study of 6 Million United States Veterans. *medRxiv* 2020.

40. Mensah GA, Mokdad AH, Ford ES, Greenlund KJ, Croft JB. State of disparities in cardiovascular health in the United States. *Circulation* 2005; **111**(10)**:** 1233-1241.

Table 1. Descriptive characteristics

Characteristic	COVID-19 (n = 32)	Control (n = 43)	p-value
Age (years)	28.5 ± 13.0	27.6 ± 12.3	0.750
Female sex (n, %)	22, 68.8	26, 60.5	0.460
Race/Ethnicity (n, %)			0.966
NH White	26, 81.3	34, 79.1	
NH Black	1, 3.1	1, 2.3	
Hispanic/LatinX	3, 9.4	4, 9.3	
Asian/Pacific Islander	2, 6.3	4, 9.3	
BMI (kg/m^2)	24.8 ± 3.7	25.3 ± 3.8	0.549
Body Fat (%)	23.3 ± 5.0	23.8 ± 5.7	0.660
SaO_2 (%)	98.0 ± 0.8	97.9 ± 1.9	0.769
PSQI	6.7 ± 3.9	5.6 ± 3.0	0.191
GAD-7	4.9 ± 5.2	4.8 ± 4.5	0.938
CES-D	14.0 ± 11.6	10.1 ± 8.1	0.102
PSS-10	15.9 ± 7.2	15.0 ± 6.3	0.580
PCL-5	10.0 ± 11.1	10.7 ± 10.4	0.783
IPAQ (MET-min/week)	2573.6 ± 2489.6	3416.4 ± 2436.7	0.165
Days Since Positive Test Date	121.9 ± 122.8	---	---
Number of COVID-19 Symptoms	5.9 ± 4.4	---	---
COVID-19 Disease Severity (1-5)	2.29 ± 0.8	---	---

Abbreviations: NH, non-Hispanic; BMI, body mass index; SaO_2, arterial oxygen saturation; PSQI, Pittsburgh sleep quality index; GAD-7, generalized anxiety disorder-7; CES-D, center for epidemiological studies depression scale; PSS-10, 10-item perceived stress scale; PCL-5, PTSD Checklist for the DSM-5; IPAQ, international physical activity questionnaire

*$p < 0.05$

Table 2. Independent samples *t*-test results comparing 24-hour ABPM measures between the COVID-19 and control groups

Characteristic	COVID-19 (n = 32)	Control (n = 43)	p-value
24-hour measures			
Systolic BP (mmHg)	117.4 ± 10.8	118.8 ± 10.7	0.582
Diastolic BP (mmHg)	70.9 ± 8.5	71.4 ± 8.3	0.787
Heart Rate (bpm)	66.2 ± 9.2	66.3 ± 9.0	0.948
MAP (mmHg)	92.2 ± 8.9	93.1 ± 8.8	0.692
pPP (mmHg)	46.6 ± 6.5	47.3 ± 7.2	0.686
cPP (mmHg)	46.9 ± 14.0	49.5 ± 12.4	0.409
cSystolic BP (mmHg)	123.3 ± 11.8	125.8 ± 12.8	0.405
AIx (%)	22.5 ± 5.9	21.9 ± 7.5	0.709
AIx@75 (%)	17.2 ± 5.7	16.9 ± 7.0	0.862
PWV (m/s)	5.4 ± 1.1	5.5 ± 1.4	0.562
Nighttime Measures			
Systolic BP (mmHg)	109.5 ± 10.1	111.0 ± 10.6	0.546
Diastolic BP (mmHg)	63.2 ± 7.7	64.4 ± 7.9	0.540
Heart Rate (bpm)	60.0 ± 9.9	58.7 ± 9.3	0.586
MAP (mmHg)	84.5 ± 8.3	85.7 ± 8.5	0.561
pPP (mmHg)	46.2 ± 7.1	46.7 ± 7.2	0.792
cPP (mmHg)	56.4 ± 9.7	58.9 ± 14.3	0.407
cSystolic BP (mmHg)	121.6 ± 12.6	125.9 ± 14.8	0.206
AIx (%)	24.0 ± 8.6	25.4 ± 8.2	0.472
AIx@75 (%)	15.6 ± 6.5	16.0 ± 7.5	0.784
PWV (m/s)	5.0 ± 1.0	5.3 ± 1.4	0.391
Daytime Measures			
Systolic BP (mmHg)	119.1 ± 10.3	121.6 ± 11.5	0.354
Diastolic BP (mmHg)	73.2 ± 9.0	74.0 ± 8.9	0.714
Heart Rate (bpm)	68.5 ± 9.6	69.1 ± 9.2	0.775
MAP (mmHg)	94.2 ± 9.2	95.9 ± 9.3	0.457
pPP (mmHg)	45.7 ± 5.9	47.6 ± 7.7	0.266
cPP (mmHg)	43.6 ± 16.7	49.7 ± 10.9	0.082
cSystolic BP (mmHg)	123.6 ± 12.2	125.6 ± 12.9	0.518
AIx (%)	21.7 ± 5.4	20.5 ± 7.8	0.451
AIx@75 (%)	17.0 ± 6.5	17.3 ± 7.3	0.863
PWV (m/s)	5.3 ± 1.0	5.6 ± 1.5	0.363

Abbreviations: BP, blood pressure; MAP, mean arterial pressure; pPP, peripheral pulse pressure; cPP, central pulse pressure; cSystolic, central systolic; AIx, augmentation index; AIx@75, heart rate-corrected augmentation index; PWV, pulse wave velocity

*$p < 0.05$

Table 3. Independent samples *t*-test results comparing blood pressure dipping and variability between COVID-19 and control groups

Characteristic	COVID-19 (*n* = 32)	Control (*n* = 43)	*p*-value
pSBP Dipping (%)	7.99 ± 5.1	8.49 ± 6.5	0.730
pDBP Dipping (%)	13.3 ± 7.0	12.8 ± 6.7	0.727
cSBP Dipping (%)	1.40 ± 6.2	-0.40 ± 7.6	0.293
cDBP Dipping (%)	12.9 ± 7.1	11.4 ± 7.6	0.427
pSBP Variability (au)	13.3 ± 3.0	13.2 ± 2.6	0.868
pDBP Variability (au)	10.9 ± 2.2	10.3 ± 1.7	0.234
cSBP Variability (au)	13.6 ± 4.4	13.4 ± 3.4	0.846
cDBP Variability (au)	10.8 ± 2.4	10.2 ± 1.7	0.252
pPP Variability (au)	11.7 ± 4.8	10.6 ± 2.7	0.204
cPP Variability (au)	9.2 ± 2.1	9.2 ± 1.9	0.982
pBPVR (au)	1.24 ± 0.3	1.29 ± 0.2	0.400
cBPVR (au)	1.37 ± 0.8	1.37 ± 0.5	0.970
pAASI (au)	0.53 ± 0.2	0.51 ± 0.2	0.680
cAASI (au)	0.69 ± 0.2	0.76 ± 0.2	0.196

Abbreviations: p, peripheral; c, central; SBP, systolic BP; DBP, diastolic BP; PP, pulse pressure; BPVR, blood pressure variability ratio; AASI, ambulatory arterial stiffness index
*$p < 0.05$