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RESEARCH ARTICLE

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Reproducibility of blood pressure variability assessed by home blood pressure monitoring

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ABSTRACT

Objective: Although blood pressure (BP) variability (BPV) derived from home BP monitoring (HBPM) is a recognized cardiovascular risk marker, limited data on its reproducibility hinder its clinical application. This study aimed to address this gap.

Methods: We compared HBPM-derived BPV at two time points using three metrics [standard deviation (SDVar), coefficient of variation (CoV), and variability independent of the mean (VIM)] among 495 individuals not using antihypertensive medications (No-AH) (median time-span between HBPM exams = 392 [308–519] days) and 588 individuals using antihypertensive medications (AH) (time-span between HBPM exams = 400 [319–510] days).

Results: No significant changes were observed across the time points in systolic HBPM-derived BPV metrics: SDVar (8.55 ± 3.14 vs. 8.71 ± 3.52 in No-AH; 9.67 ± 3.62 vs. 9.50 ± 3.47 in AH), CoV (7.01 ± 2.47 vs. 7.10 ± 2.65 in No-AH; 7.65 ± 2.77 vs. 7.57 ± 2.62 in AH), and VIM (5.76 ± 2.10 vs. 5.87 ± 2.35 in No-AH; 6.29 ± 2.34 vs. 6.18 ± 2.24 in AH) (all $p > .05$). Similarly, diastolic HBPM-derived BPV metrics remained stable between the time points: SDVar-DBP (5.65 ± 2.32 vs. 5.62 ± 2.33 in No-AH; 5.99 ± 2.50 vs. 5.90 ± 2.37 in AH), CoV-DBP (7.26 ± 3.03 vs. 7.24 ± 3.13 in No-AH; 7.66 ± 3.20 vs. 7.63 ± 3.06 in AH) and VIM-DBP (4.78 ± 1.96 vs. 4.75 ± 1.97 in No-AH; 4.64 ± 1.93 vs. 4.58 ± 1.83 in AH) (all $p > .05$). However, the test–re-test correlation of all HBPM-derived BPV metrics was only modest ($r \approx .27–.45$), revealing substantial intra-individual variability. In addition, similar results were obtained in an alternative sample of 498 individuals (265 using AH and 233 not using AH) who underwent OBP and HBPM measurements at four different time points.

Conclusion: These findings demonstrate that BPV parameters derived from HBPM had high reproducibility at the population level, but limited reproducibility at the individual level.

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Reproducibility; variability; home blood pressure; blood pressure; hypertension

Introduction

Extensive evidence identifies high blood pressure (BP) as a key factor in cardiovascular disease causation[1]. However, accurately assessing BP's overall contribution to cardiovascular risk is challenging due to its natural fluctuations throughout the day[2]. Beyond the impact of average BP levels, blood pressure variability (BPV) has emerged as an equally significant contributor. Elevated BPV reflects disruptions in cardiovascular regulation, potentially amplifying its proatherogenic and target-organ damage effects independently of average BP levels[2].

Office blood pressure (OBP) and out-of-office blood pressure, measured by ambulatory blood pressure monitoring (ABPM) and home blood pressure monitoring (HBPM), are used to estimate BPV. OBP assesses long-term (visit-to-visit) BPV, while ABPM and HBPM

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capture short-term (24-hour) and medium-term (day-to-day) BPV, respectively[2]. Although short-, medium-, and long-term BPV are similarly associated with all-cause mortality[3], emerging evidence suggests that medium-term BPV is a stronger predictor of cardiovascular outcomes[4], underscoring HBPM as a valuable clinical tool for assessing BPV.

A major obstacle to the clinical use of BPV for assessing cardiovascular risk concerns its reproducibility. While long-term BPV is reported to be consistently reproducible[5], data on short-term BPV are inconsistent[6–8], and data on medium-term BPV derived from HBPM are lacking. To address this gap, this study aimed to evaluate intraindividual medium-term BPV derived from HBPM in a large multicenter sample of individuals, both with and without antihypertensive medication (AH) use.

Methods

This study retrospectively evaluated data from a convenience sample of 1,083 consecutive participants (588 using AH and 495 not using AH) aged 18 years and older who underwent OBP and HBPM measurements at two different time points between 2017 and 2021 at 139 Brazilian centers, using an online platform (telemrpa.com.br). To further evaluate the impact of a larger number of repeated HBPM measurements on the results, an alternative convenience sample of 498 consecutive participants (265 using AH and 233 not using AH) aged 18 years and older who underwent OBP and HBPM measurements at four different time points between 2017 and 2024 at 126 Brazilian centers, using the same online platform, was also retrospectively evaluated. Data on age, sex, body mass index (BMI), OBP, HBPM and AH use were gathered from all participants from both cohorts.

OBP was calculated as the average of two office readings. HBPM started the day after OBP measurements and was calculated as the average of three home BP measurements taken in the morning and in the evening, over four consecutive days, following at least three minutes of rest, before meals and prior to AH use, as previously described[9–12]. Validated devices (HEM-705CP, HEM-7113, HEM-7320 or HEM-9200T; Omron Health Care, Japan) were used for the measurements.

HBPM variability (HBPM-BPV) was defined by three metrics: the standard deviation of systolic (SDVar-SBP) and diastolic (SDVar-DBP) HBPM measurements; the coefficient of variation of systolic (CoV-SBP) and diastolic (CoV-DBP) HBPM, estimated as 100*(SDVar-SBP or SDVar-DBP)/(mean systolic or diastolic HBPM), respectively; the variability independent of the mean of systolic (VIM-SBP) and diastolic (VIM-DBP) HBPM, calculated as (SDVar-SBP or SDVar-DBP)/(mean systolic or diastolic HBPM)^{y}, respectively, where "y" is the regression coefficient derived from the association between the natural logarithm of the mean HBPM and the natural logarithm of the respective HBPM standard deviation[10]. In addition, systolic (OBPV-SBP) and diastolic (OBPV-DBP) OBP variability were calculated as the absolute difference between the two systolic or diastolic OBP measurements divided by their corresponding mean values.

Continuous variables are expressed as mean ± standard deviation, and categorical variables as proportions. Comparisons of continuous and categorical variables across time points were conducted as follows: (1) the paired *t*-test and McNemar's test were used in the cohort that only performed two HBPM sessions; and (2) one-way repeated-measures ANOVA and Cochran's Q test, both followed by Bonferroni post-hoc pairwise comparisons, were applied in participants who completed four HBPM sessions, respectively. Test–re-test reliability analyses using Pearson's correlation were conducted to assess the individual-level agreement of BPV metrics. Additionally, Pearson's correlation evaluated the relationship between OBP and HBPM variability. The study was approved by the Ethics Committee of the Oswaldo Cruz University Hospital/PROCAPE Complex Ethics Committee, which waived the requirement of informed consent. p values $<.05$ were considered significant. Statistical analysis was performed using Stata 14.1 (Stata Corp LP, College Station, TX, USA).

Results

The clinical characteristics and BP parameters of participants not using AH (42% males; 55.1 ± 13.6 years at baseline) and using AH (38% males; 61.0 ± 13.6 years at baseline) who were evaluated solely at two time points are presented in Table 1. The median [25th, 75th percentiles] time span between the two HBPM measurements was 392 [308–519] days and 400 [319–510] days among AH non-users and AH users, respectively. There were no changes in average BMI, OBP, and HBPM values between the time points in AH non-users. Conversely, systolic and diastolic HBPM values were significantly lower (127.1 ± 15.9 vs. 125.7 ± 15.8 mmHg, $p = .014$ and 78.9 ± 10.3 vs. 77.9 ± 10.1 mmHg, $p = .003$) and use of calcium-channel blockers was greater (30% vs 37%) at the second time point among AH users (Table 1).

Table 1. Comparison of the characteristics of the participants between the first and second HBPM measurements.

	Whole sample ($n = 1,083$)			AH non-users ($n = 495$)			AH users ($n = 588$)		
Variables	1st HBPM	2nd HBPM	*p* value	1st HBPM	2nd HBPM	*p* value	1st HBPM	2nd HBPM	*p* value
Male sex, %	40	40	–	42	42	–	38	38	–
Age, years	58.3 ± 13.9	59.3 ± 13.9	<.001	55.1 ± 13.6	56.0 ± 13.6	<.001	61.0 ± 13.6	62.1 ± 13.6	<.001
BMI, kg/m^2	28.8 ± 5.2	28.6 ± 5.0	.12	28.2 ± 4.8	28.2 ± 4.8	.50	29.2 ± 5.4	29.0 ± 5.2	.14
Obesity, %	35	35	.43	32	32	.68	38	37	.56
Office SBP, mmHg	131.6 ± 18.8	131.7 ± 18.7	.91	129.5 ± 17.3	130.3 ± 16.0	.27	133.4 ± 19.8	132.8 ± 20.6	.50
Office DBP, mmHg	83.4 ± 11.5	83.3 ± 11.3	.85	83.8 ± 10.9	84.2 ± 10.4	.37	83.0 ± 11.9	82.5 ± 11.9	.31
Home SBP, mmHg	124.8 ± 14.9	124.2 ± 14.6	.09	122.1 ± 13.1	122.3 ± 12.8	.56	127.1 ± 15.9	125.7 ± 15.8	.014
Home DBP, mmHg	78.7 ± 9.7	78.2 ± 9.6	.036	78.4 ± 8.9	78.5 ± 8.8	.77	78.9 ± 10.3	77.9 ± 10.1	.003
Diuretic, %	19	19	.54	–	–	–	35	34	.54
ACEI, %	8	8	1.00	–	–	–	14	14	1.00
ARB, %	40	40	1.00	–	–	–	73	73	1.00
Beta-blocker, %	15	15	.64	–	–	–	27	28	.64
CCB, %	16	20	<.001	–	–	–	30	37	<.001
Spironolactone, %	2	2	.58	–	–	–	3	4	.58
Central alpha-2 agonist, %	2	2	.55	–	–	–	3	4	.55
Direct vasodilators, %	1	1	1.00	–	–	–	1	1	1.00

Continuous and categorical variables are presented as the mean ± standard deviation and proportion. Differences in continuous and categorical variables of participants in the two distinct periods were evaluated by using the paired t-test and McNemar's test, respectively.
Abbreviations: AH, antihypertensive medications; HBPM, home blood pressure monitoring; BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; ACEI, Angiotensin-Converting Enzyme Inhibitor; ARB, Angiotensin Receptor Blocker; CCB, Calcium Channel Blocker.

The BPV parameters of participants who were evaluated solely at two time points are presented in Table 2 and Figures 1 and 2. SDVar-SBP, CoV-SBP, and VIM-SBP did not significantly change throughout the studied time points in both AH users and AH non-users. However, the test–re-test correlation of HBPM-derived systolic BPV metrics was only modest ($r \approx .40$–$.45$) (Table 2 and Figure 1). Likewise, although no changes in SDVar-DBP, CoV-DBP, and VIM-DBP were observed between the time points, the test–re-test correlation of HBPM-derived diastolic BPV metrics was very modest ($r \approx .27$–$.28$) (Table 2 and Figure 2). Similar findings were observed when stratifying the sample by sex, age ($<$ or $\geq$65 years) and the presence of obesity, and among patients using AH who had lower HBPM values at the second time point (Supplementary Tables S1–S4). In addition, significant but modest correlations ($r \approx .28$–$.48$) were observed between OBPV-SBP and the corresponding systolic HBPM-BPV parameters, as well as between OBPV-DBP and the corresponding diastolic HBPM-BPV parameters (Supplementary Table S5).

To further evaluate the impact of a larger number of repeated HBPM measurements on HBPM-BPV reproducibility, we evaluated an alternative sample of 498 individuals (265 using AH and 233 not using AH) who underwent OBP and HBPM measurements at four different time points (Supplementary Tables S6–S8). These analyses confirmed that average HBPM-BPV parameters did not significantly change across any of the studied time points in either AH users or AH non-users, but also showed that the test–re-test correlation of HBPM-BPV metrics was only modest.

Discussion

This study evaluated individuals who underwent HBPM at different time points, providing novel insights into the reproducibility of BPV assessed by HBPM. Notably, the average values of HBPM-BPV metrics did not significantly change across the evaluated time points, whereas the test–re-test correlations of all BPV metrics were only modest, indicating substantial intra-individual variability. These findings were consistent across the three distinct HBPM-BPV indices – SDVar, CoV, and VIM – and remained unchanged after stratification by sex, age, obesity, and AH use. Taken together, these results suggest that BPV parameters derived from HBPM demonstrate high reproducibility at the population level, but limited reproducibility at the individual level.

The results of our study may have relevant implications. The high reproducibility of mean SDVar, CoV, and VIM values at the population level supports the use of HBPM-BPV metrics as reliable tools for population-based research. In this regard, while ABPM remains the gold standard for diagnosing hypertension[9], studies assessing the reproducibility of ABPM-BPV have reported inconsistent results[6–8] at the population level. Additionally, recent population-based evidence suggested that HBPM-BPV might be superior in predicting cardiovascular prognosis compared to BPV derived from ABPM[4]. Therefore, the strong reproducibility of the average HBPM-BPV values shown herein, together with previous evidence of the limited prognostic ability of ABPM-BPV, suggests that HBPM may represent a more suitable approach for assessing BPV

Table 2. Comparison of blood pressure variability parameters between the first and second HBPM measurements in the whole sample and according to the use or not of antihypertensive medications.

	Whole sample ($n = 1,083$)				AH non-users ($n = 495$)				AH users ($n = 588$)			
Variables	1st HBPM	2nd HBPM	*p* value	*r*	1st HBPM	2nd HBPM	*p* value	*r*	1st HBPM	2nd HBPM	*p* value	*r*
Office BP												
OBPCoV-SBP	3.04 ± 2.47	2.98 ± 2.29	.54	.20*	2.88 ± 2.25	2.92 ± 2.23	.77	.16*	3.17 ± 2.63	3.03 ± 2.34	.29	.23*
OBPCoV-DBP	2.69 ± 2.70	2.59 ± 2.41	.34	.11*	2.53 ± 2.65	2.52 ± 2.30	.98	.01	2.83 ± 2.73	2.65 ± 2.50	.19	.18*
HBPM												
SDVar-SBP	9.16 ± 3.45	9.14 ± 3.51	.87	.44*	8.55 ± 3.14	8.71 ± 3.52	.29	.45*	9.67 ± 3.62	9.50 ± 3.47	.40	.42*
SDVar-DBP	5.83 ± 2.42	5.77 ± 2.35	.47	.27*	5.65 ± 2.32	5.62 ± 2.33	.79	.27*	5.99 ± 2.50	5.90 ± 2.37	.27	.27*
CoV-SBP	7.36 ± 2.66	7.36 ± 2.64	.99	.41*	7.01 ± 2.47	7.10 ± 2.65	.45	.41*	7.65 ± 2.77	7.57 ± 2.62	.53	.40*
CoV-DBP	7.50 ± 3.10	7.45 ± 3.10	.84	.28*	7.26 ± 3.03	7.24 ± 3.13	.90	.28*	7.66 ± 3.20	7.63 ± 3.06	.87	.28*
VIM-SBP	6.05 ± 2.25	6.04 ± 2.29	.90	.43*	5.76 ± 2.10	5.87 ± 2.35	.30	.45*	6.29 ± 2.34	6.18 ± 2.24	.28	.42*
VIM-DBP	4.71 ± 1.94	4.66 ± 1.90	.50	.27*	4.78 ± 1.96	4.75 ± 1.97	.80	.27*	4.64 ± 1.93	4.58 ± 1.83	.48	.27*

r = correlation coefficient derived from Pearson's correlation analysis, * $p < .05$.
Abbreviations: AH, antihypertensive medications; HBPM, home blood pressure monitoring; BP, blood pressure; SBP, systolic blood pressure; DBP, diastolic blood pressure; OBPCoV, coefficient of variation of office blood pressure; SDVar, standard deviation; CoV, coefficient of variation; VIM, variability independent of the mean.

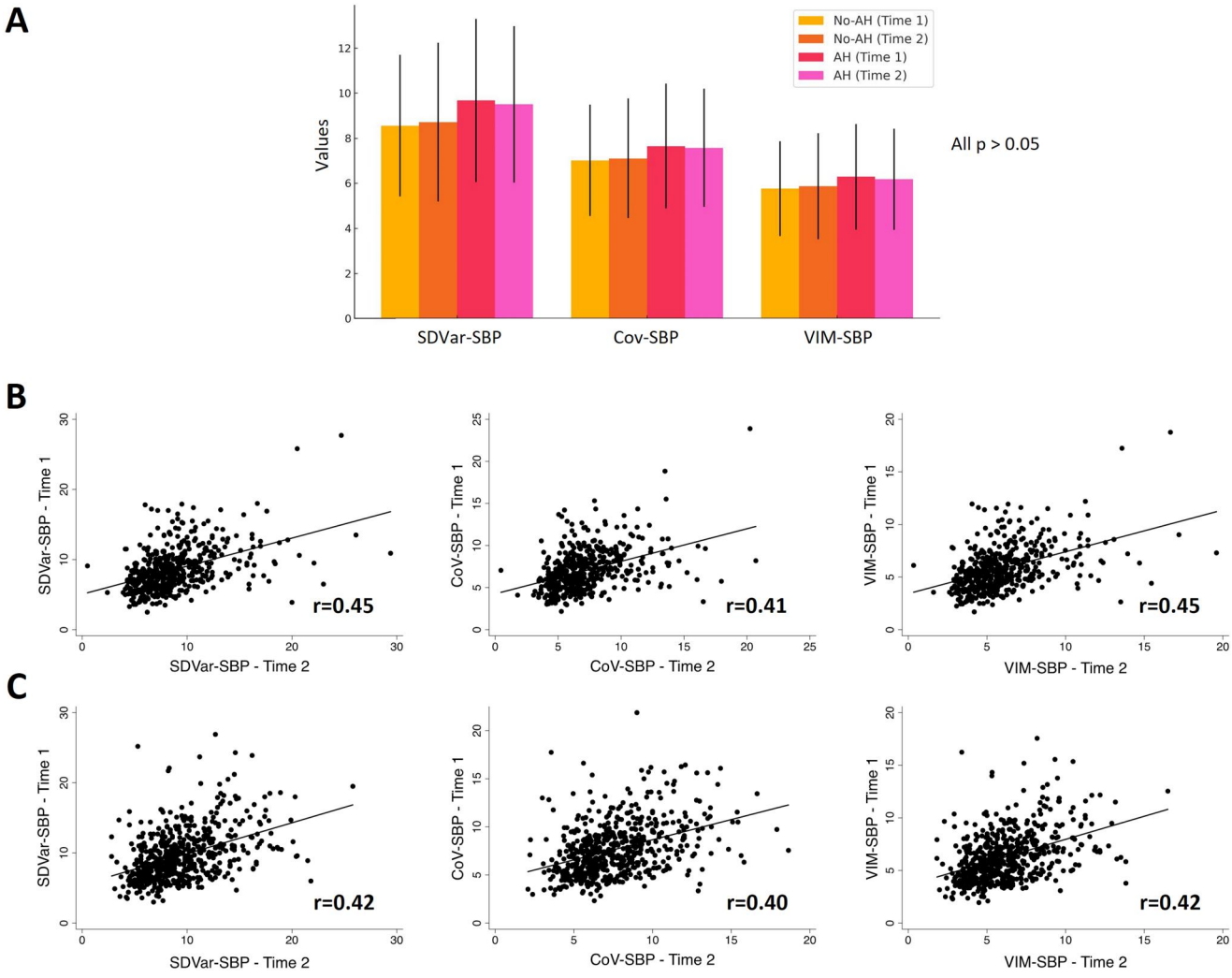

Figure 1. Reproducibility of systolic blood pressure variability derived from home blood pressure monitoring who were evaluated solely at two time points. (a) Comparison of SBP variability parameters (presented as mean ± standard deviation) between the time points assessed by paired *t*-test. (b) Test–re-test correlation of SBP variability parameters in the No-AH group. (C) Test–re-test correlation of SBP variability parameters in the AH group. *p* values for all correlation coefficients were $<.05$.
Abbreviations: No-AH, Individuals not using antihypertensive medications; AH, Individuals using antihypertensive medications; SDVar, Standard Deviation of Blood Pressure; CoV, Coefficient of Variation of Blood Pressure; VIM, Variability Independent of the Mean; SBP, Systolic Blood Pressure.

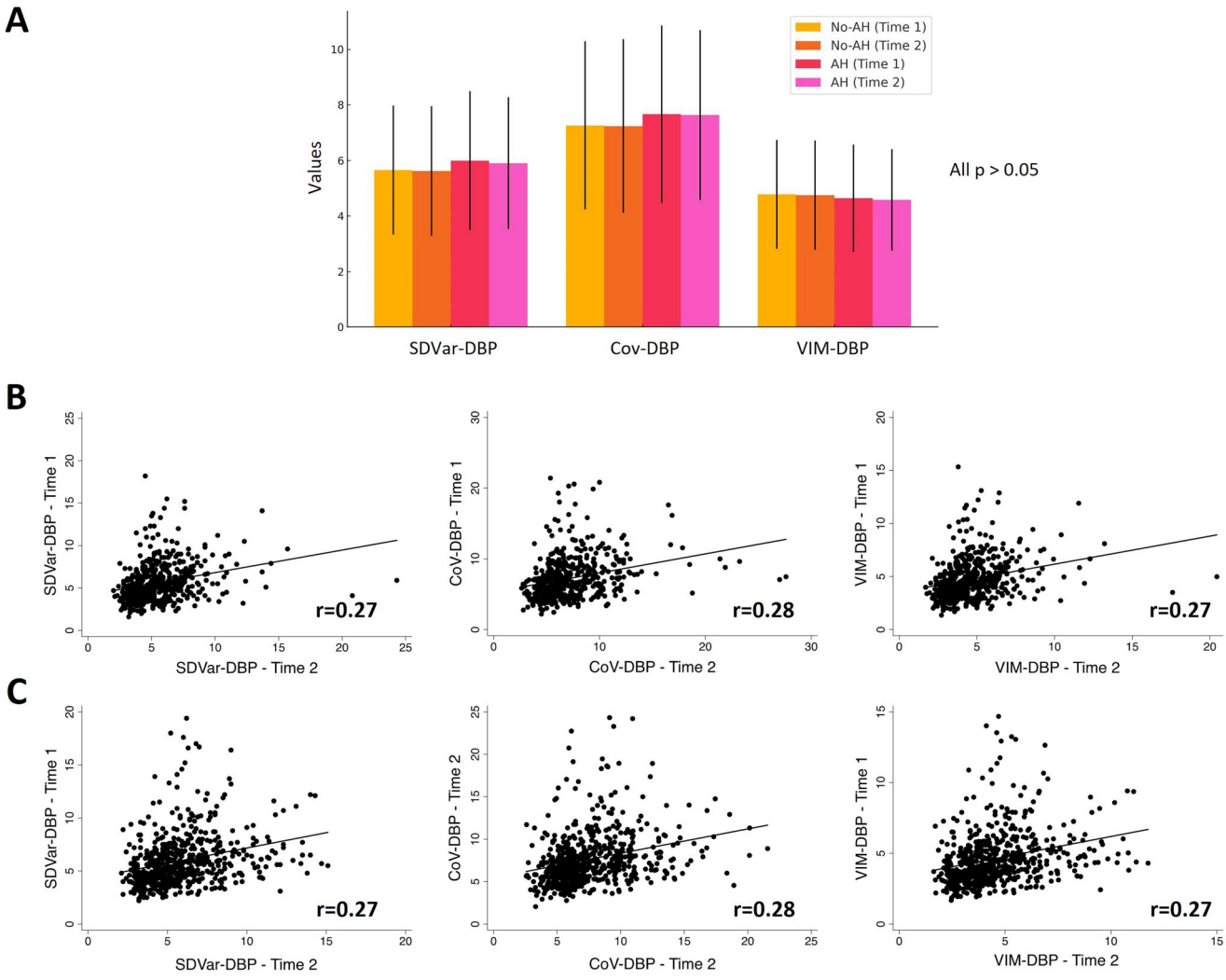

Figure 2. Reproducibility of diastolic blood pressure variability derived from home blood pressure monitoring who were evaluated solely at two time points. (a) Comparison of DBP variability parameters (presented as mean ± standard deviation) between the time points assessed by paired *t*-test. (b) Test–re-test correlation of DBP variability parameters in the No-AH group. (c) Test–re-test correlation of DBP variability parameters in the AH group. *p* values for all correlation coefficients were <.05.

Abbreviations: No-AH, Individuals not using antihypertensive medications; AH, Individuals using antihypertensive medications; SDVar, Standard Deviation of Blood Pressure; CoV, Coefficient of Variation of Blood Pressure; VIM, Variability Independent of the Mean; DBP, Diastolic Blood Pressure.

in out-of-office settings, particularly in population-based research contexts.

In contrast, the modest intra-individual reproducibility of HBPM-BPV metrics indicates that they may be less suitable for individual patient management, risk stratification, or diagnostic decision-making in real-world clinical settings. Although previous studies have demonstrated that HBPM-BPV metrics are independently associated with cardiovascular outcomes beyond mean BP levels[2], our findings raise concerns about whether a single assessment of HBPM-BPV can provide consistent prognostic value at the individual patient level. The reasons for the low reproducibility of these metrics at the individual level were not apparent in our analysis, but may be due to the influence of multiple dynamic physiological and environmental factors. These include variations in physical activity, stress, sleep, diet, autonomic tone, and baroreflex sensitivity[2]. Such fluctuations may reflect adaptive cardiovascular responses to daily life challenges rather than random measurement noise, and therefore may differ substantially between assessments[2].

Some findings warrant further consideration. A higher use of calcium channel blockers was observed at the second time point among AH users evaluated twice. Although these agents are known to reduce BP variability[13], average HBPM-BPV values remained stable over time, suggesting that such medication changes likely did not influence our results. In addition, we assessed the correlation between OBPV

and HBPM-BPV and found only a modest association between these parameters, indicating that they might not be interchangeable in clinical practice.

Some limitations of this study should be acknowledged. Its retrospective design may have introduced selection bias, potentially limiting the generalizability of the findings to broader populations. Relevant clinical information, including data on smoking, diabetes, alcohol intake and chronic kidney disease, was not available. Additionally, the absence of follow-up data and information on incident cardiovascular events limits the evaluation of BPV's prognostic significance.

Conclusions

In conclusion, this study provides novel evidence that BPV assessed by HBPM is highly reproducible at the population level, but has limited reproducibility at the individual level. These findings indicate that HBPM-BPV metrics are suitable for population-based research but may have limited applicability for individual decision-making in clinical practice.

Tranpsarency

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Declaration of financial/other relationships

The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript. This includes employment, consultancies, honoraria, stock ownership or options, expert testimony, grants or patents received or pending, or royalties. Peer reviewers on this manuscript have no relevant financial or other relationships to disclose.

Author contributions

VSGN, RB, and WN contributed to the study conception, design, and drafted the manuscript. VSGN, RB, ADMF, WN, RBa, MAMG, AMGP, WSB, RDM, ECDB, AAB, JLLF, and ACS contributed to the acquisition, analysis, or interpretation of data for the work. WN supervised the project and provided final approval of the version to be published. All authors gave final approval of the version to be published and agreed to be accountable for all aspects of the work, ensuring its integrity and accuracy.

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None.

Data availability statement

The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Ethics statement

The study received approval from the Ethics Committee of the Oswaldo Cruz University Hospital/PROCAPE Complex, with a waiver of the requirement for informed consent.

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