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Temporal stability of twenty-four-hour ambulatory hemodynamic bioimpedance measures in African American adolescents

Vernon A. Barnes[a], **Maribeth H. Johnson**[b], and **Frank A Treiber**[a,c]

[a]Department of Pediatrics, Medical College of Georgia, Augusta, Georgia, USA

[b]Office of Biostatistics and Bioinformatics, Medical College of Georgia, Augusta, Georgia, USA

[c]Department of Psychiatry, Medical College of Georgia, Augusta, Georgia, USA

Abstract

Background—The reliability of ambulatory impedance cardiography has not been evaluated.

Objective—The purpose of this study was to determine the reproducibility of daytime and night-time ambulatory bioimpedance-derived measures of hemodynamic function in youth.

Methods—Thirty-five African American adolescents (ages 16.2 ± 1.4 years, 14 girls, 21 boys) with high normal systolic resting blood pressure (BP) were evaluated twice, separated by a 2-month interval. Measures were collected using the AIM-8-V3 Wearable Cardiac Performance Monitor (Bio-impedance Technology, Inc., Chapel Hill, North Carolina, USA) and the Spacelabs ambulatory BP monitor 90207 (Spacelabs Inc., Redmond, Washington, USA) from 0600 h to midnight every 20 min and from midnight to 0600 h every 30 min in the natural environment.

Results—There were no significantly different means ($P > 0.15$) between the two visits for daytime ambulatory heart rate (HR, $r = 0.81$), stroke volume (SV, $r = 0.54$), cardiac output (CO, $r = 0.56$), pre-ejection period (PEP, $r = 0.59$), left ventricular ejection time (LVET, $r = 0.74$), Heather Index (HI, $r = 0.79$), systolic BP (SBP, $r = 0.79$), diastolic BP (DBP, $r = 0.66$), mean arterial pressure (MAP, $r = 0.65$) and total peripheral resistance (TPR, $r = 0.47$). Overall means for night-time ambulatory HR ($r = 0.76$), SV ($r = 0.49$), CO ($r = 0.45$), LVET ($r = 0.43$), HI ($r = 0.82$), SBP ($r = 0.65$), DBP ($r = 0.62$), MAP ($r = 0.63$) and TPR ($r = 0.20$) were not significantly different between visits ($P > 0.06$). Mean differences ($P < 0.01$) were observed for PEP ($r = 0.57$).

Conclusions—The findings demonstrate that across 2 months in youth daytime and night-time ambulatory bioimpedance-derived measures of HR, HI, SBP, DBP and MAP are highly repeatable and SV, CO, PEP and LVET are moderately repeatable. This methodology should prove useful in cardiovascular research and clinical care.

Keywords

temporal stability; adolescent; African American; ambulatory; blood pressure; stroke volume; cardiac output; pre-ejection period; left ventricular ejection time; Heather Index; total peripheral resistance

Correspondence and requests for reprints to Vernon A. Barnes PhD, Georgia Prevention Institute, Building HS1640, Medical College of Georgia, Augusta, GA 30912, USA. Tel: + 1 706 721 2195; fax: + 1 706 721 7150; vbarnes@georgiaHealth.edu.

Conflict of interest: None

Introduction

Impedance cardiography (IC) has been widely used in the investigation of hemodynamic performance in a variety of clinical and laboratory settings [1-3]. IC-derived estimates of cardiac output (CO) have been validated via comparison with thermodilution-derived measures with participants ranging from infants to adults with cardiovascular disease (CVD) [2,4-6], with correlations ranging from 0.82 to 0.92 when IC is compared to other methods [7]. Systolic time intervals, pre-ejection period (PEP) and left ventricular ejection time (LVET) IC-derived measures, have been validated via comparisons with pulsed Doppler [8]. Several studies have shown IC to be a more reliable and effective method of monitoring systolic time intervals than arteriography [6]. Meta-analysis of published literature on the validity of IC-derived measures showed a pooled correlation coefficient of 0.84 for repeated measurement for CO for healthy people [9]. Correlations for 1-week temporal stability during subtraction, handgrip and drawing task sessions in children ranged from 0.81 to 0.86 for heart rate (HR), from 0.88 to 0.93 for PEP, from 0.77 to 0.85 for LVET, from 0.79 to 0.89 for Heather Index (HI), from 0.82 to 0.86 for stroke volume (SV), from 0.77 to 0.81 for CO, from 0.60 to 0.75 for systolic blood pressure (SBP), from 0.13 to 0.61 for diastolic blood pressure (DBP), from 0.28 to 0.67 for mean arterial pressure (MAP) and from 0.69 to 0.78 for total peripheral resistance (TPR) [3].

Limitations of clinic- and laboratory-based IC for use with only non-mobile individuals led to the development of ambulatory impedance (AI) monitoring. Early portable AI cardiographs were limited to use during dynamic exercise [4,5,10,11]. Technological advances have opened the possibility of 24-h monitoring in the natural setting outside the laboratory. AI cardiography has been used to study changes in response to naturally occurring stressors and during sleep [12-16]. Previous 24-h AI studies with one to 40 participants have presented cross-instrument reliability, feasibility and validity findings [12,14-16], but have not presented temporal stability findings from means collected in a free-living environment.

Reproducibility of non-invasive measures of cardiac performance has important implications for CVD-related research and clinical care. The link between CVD and environmental stress requires ambulatory monitoring in order to examine the impact of acute and chronic environmental stressors on hemodynamic function [15]. For example, reliable measurement of cardiac performance and hemodynamic response patterns in the natural environment is of vital importance in detecting changes that may be imposed via intervention studies. The reliability of a measurement to detect response changes over time is dependent on the reproducibility of the method [17].

This study is part of a larger study examining the impact of stress reduction on blood pressure (BP) in African American (AA) adolescents [18]. We previously reported moderate reproducibility of 24-h CO and TPR in a sample of AA adolescents [19] using the AIM-8-V3 monitoring system (Bio-impedance Technology, Inc., Chapel Hill, North Carolina, USA) [14]. Reproducibility of other daytime and night-time AI-derived measures of hemodynamic function, for example, SV, HI, PEP and LVET, have not been reported. This study expands upon that report in terms of increased sample size and additional measures of hemodynamic function (that is, HI, SV, PEP and LVET).

Methods

Participants

Permission to conduct the study was granted by the Superintendent of the Richmond County Public Schools and the Medical College of Georgia Human Assurance Committee. A BP

screening was conducted on approximately 5000 AA youth at inner-city high schools in Augusta, Georgia, USA. From this screening, 156 AA adolescents with high normal BP (that is, SBP ≥ 85th–95th percentile for sex, age and height on three occasions [20]) gave assent to participate in a study. These participants were randomly assigned to either stress reduction or health education control (CTL) groups and were evaluated on two occasions, 2 months apart [19,21]. Fifty CTL participants wore the monitors and had baseline measurements for daytime values, 42 participants had measurements at both baseline and visit 2 and 35 participants (16.2 ± 1.4 years, 14 girls) had sufficient data (≥ 50% of the measurements) to be included in the analysis. Forty-two participants had baseline measurements for night-time values, 29 participants had measurements at both baseline and visit 2 and 23 participants had sufficient data (≤ 50% of the measurements) to be included in the analysis.

Procedures

Height (via stadiometer), weight (via Detecto scale, Cardinal Scale Manufacturing Co., Webb City, MO, USA) and waist and hip circumference measurements were recorded using established protocols [22]. MAP, SBP and DBP were recorded using the Spacelabs ambulatory BP monitor (ABPM) 90207 (Spacelabs Inc., Redmond, Washington, USA) over 24-h periods in the natural environment [19]. Simultaneously, measures of hemodynamic function (that is, HR, CO, SV, PEP, LVET and HI) were obtained via the AIM-8-V3 wearable cardiac performance monitor [14]. Random recording sequences were not possible because the AIM unit was controlled manually by the ABPM via a pressure switch and the ABPM does not have a random interval recording mode. The AIM-8 is a microcomputer-based bioimpedance monitor and signal processing system, which ensemble averages, analyzes and stores the electrocardiogram, bioimpedance waveforms and cardiac function using the standard Minnesota IC (MIC; IFM Inc., Greenwich, Connecticut, USA) system [7]. The AIM system used a hybrid spot-band tetrapolar impedance electrode configuration, which has been previously described [14]. Mylar band recording electrodes were placed around the base of the neck and around the thorax over the tip of the xiphoid process. Three disposable electrocardiogram spot electrodes were used as current electrodes, with one applied behind the right ear and the other two over the right and left rib cage 6 cm below the lower band electrode. The AIM-8 has been validated against the MIC Model 304B with correlations ranging from 0.89 to 0.97 for standing and sitting for HR, SV, PEP, LVET and HI measured [14].

The AIM-8 was worn on a belt around the waist together with the Spacelabs ABPM and was programmed to initiate a 40-s ensemble-averaged data acquisition concomitant with every BP measurement. Daytime measures were recorded every 20 min from 0600 h to midnight and nighttime measures every 30 min from midnight to 0600 h.

Data editing

AIM-8 data were manually edited to remove spurious waveforms. Processing of the impedance signals was accomplished using the Cardiac Output Program (COP; Bioimpedance Technology, Inc.), which allowed for on-line ensemble averaging of impedance waveforms to filter noise and respiratory artifacts [14]. The validity of the ensemble-averaging methodology has been reported as high (intra-class correlation = 0.91) [23]. The COP system has been validated against the thermodilution technique [24]. COP calculates CO (l/min) as the product of SV (ml) and HR. TPR was calculated as (MAP/CO) • 80 (dyne-s/cm^5) [14]. Data lost due to insufficient BP measures to match CO in the calculation of TPR resulted in five fewer daytime and three fewer night-time participants in the analysis. Although the COP software automatically computes CO, SV, systolic time intervals and contractility, the system is capable of manually editing or re-analyzing

acquired impedance data. Because reliability in editing waveforms was subject to judgment differences in determining the optimal positions for the 'X', 'B' and 'Q' cursors, every waveform was examined by a trained and experienced editor of COP-derived waveforms.

Participants attended a daily health education program based in part on the National Institutes of Health guidelines on lowering BP through weight loss, diet (reducing fat and sodium intake) and increasing physical activity. This program was provided in 15-min sessions held daily at school [21]. Similar to a previous study [21], no significant changes in resting BP or other CV risk factors (for example, adiposity and weight) were observed. Participants were paid US$100 for each wearing of both the ABPM and the AI monitor.

Analyses

Paired *t*-tests were used to analyze mean differences in hemodynamic measures between the two visits. Pearson correlation coefficients (*r*-values) were calculated to examine the degree of linear relationship in hemodynamic measures across the 2-month interval.

Results

Anthropometric data were collected only at visit 1 and are shown in Table 1. Electrode distances (*L*-values) measured an average of 25.3 cm at each visit and were correlated ($r = 0.66$) with an absolute average difference of 1.66 cm.

Daytime hemodynamic measures

Overall means for HR, SV, CO, PEP, LVET, HI, SBP, DBP, MAP and TPR were not significantly different between visits (all $P > 0.14$, Table 2). Correlations for hemodynamic measures ranged from 0.47 for TPR to 0.81 for HR (Table 2).

Night-time hemodynamic measures

Overall means for HR, SV, CO, LVET, HI, SBP, DBP, MAP and TPR were not significantly different between visits ($P > 0.06$, Table 2). There was a significant mean difference across visits for PEP ($P < 0.01$). Correlations for hemodynamic values ranged from 0.20 for TPR to 0.81 for HI and are presented in Table 2.

Discussion

This is the first report of temporal stability of bioimpedance-derived measures of HR, SV, PEP HI and LVET in youth in a truly ambulatory environment. The present findings demonstrate that in a free-living environment, daytime and night-time AI-derived measures of HR, HI, SBP, DBP and MAP are highly repeatable (*r* range, 0.62–0.82), while SV, CO, PEP and LVET are moderately repeatable (*r* range, 0.43–0.57) and night-time TPR is unstable across 2 months in youth. The lack of other AI temporal stability studies prevents direct comparison of the present findings. However, our BP-related findings are comparable to those observed in ambulatory BP studies conducted in the natural setting, that is, daytime test–retest stability coefficients range from 0.72 to 0.93 for SBP and 0.53 to 0.87 for DBP across periods of 0.5–6 months [25]. The present study extends previous 24-h AI studies with one to 40 participants, reporting cross-instrument reliability, feasibility and validity findings [12,14-16] and presents temporal stability findings collected in a free-living environment in 35 participants. Similar to ambulatory BP findings [19,26], a pattern of reduced reproducibility in night-time AI-derived measures was observed in the present study. Although, in general, greater numbers of values in an aggregate measurement increases the reliability of the average, this is not the case here. MAP and its derivatives

(SBP and DBP), involving far fewer measurements than the ensemble-averaged counterparts (for example, CO), are more reliable, probably because they are more easily measured.

Sample size limitation

Although the BP results compare with those of other studies, the bioimpedance findings are subject to scrutiny in view of the limited sample size, which may have led to spurious results. Some of the non-significant results may be due primarily to the small sample size. Further study with a larger sample is recommended. Replication in future studies with a larger sample size will also make it worthwhile to analyze age, body mass index (BMI) and sex differences. A number of methodologic factors can impact reproducibility, such as consistency of electrode placement during instrumentation, minimization of electrode resistance by thorough cleansing of the placement area with alcohol and rubbing the area with an abrasive skin-prepping gel prior to electrode placement and consistency in the editing of the waveforms to exclude movement artifacts prior to data analysis [7]. Variations in the skin preparation technique and positioning of the band electrodes may impact the quality of the basal impedance (Z_o) measures, which may cause errors in measures such as SV and CO. Correlations between electrode distances (*L*-values) may be attenuated because of the narrow range of values (SD = 2.1 cm). Although efforts were made to consistently address these issues, the possibility exists that reproducibility may have been partially impacted due to slight differences in electrode installation across the two visits because more than one installer was involved. Reliability of the editing process may be impacted by the level of experience of the data editor or by differences in editing judgment decisions that would be made if more than one editor were involved.

Signal quality tends to be poor in obese individuals [27] and it should be noted that the present sample tended to be overweight (that is, BMI ≥ 30 kg/m^2). The non-random recording procedure may have biased the findings and may be improved in future studies with recordings taken randomly but averaged every 20 min.

The health education program appeared to have little effect on the variables examined in this study, as supported by previously published results [18,19]. Differences in participants' lifestyle-related activities across visits could have impacted reproducibility. That is, physical activity levels, postural position and variations in cognitive and affective states are known to account for a large percentage of variance in ambulatory BP measures [28,29]. Although the BP monitor was programmed according the participant's self-reported bedtime, future studies would benefit from measures of gross body activity as measured by a built-in actigraph in determination of actual bedtimes. Diaries were not kept in this study because it was determined that manual-based diary entry interferes with normal daily behavior and significant non-adherence has been observed in previous studies in youth [30-32]. Future studies should consider using momentary event sampling with Palm Pilot or other user-friendly personal digital assistant methodology to enable postural changes, physical activity and affective states to be controlled in the data analyses, which would help explain some of the variability in reproducibility of AI measures. Epidemiological research and intervention trials may benefit from the ability to examine a variety of indices of hemodynamic function in the natural setting in addition to BP and HR.

Conclusions

This report of moderate-to-high reproducibility of 24-h AI measures of hemodynamic function in youth has important implications in efforts to better understand the pathophysiology of CVD development. AI methodology, particularly in combination with momentary event sampling methodology, should prove useful in studies attempting to

characterize and understand factors associated with changes in hemodynamic performance in the natural environment.

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Table 1

Descriptive characteristics before testing

Age (years)	16.2 ± 1.4
Weight (kg)	86.7 ± 28.0
Height (cm)	168.5 ± 10.7
Body surface area (m^2)	1.9 ± 0.3
Body mass index (kg/m^2)	30.3 ± 9.3
Waist-to-hip ratio	0.8 ± 0.08

n = 35. Values are means ± SD.

Table 2

Comparison of means across visits

	n	Visit 1	Visit 2	Change	*P*-value	Correlation
Daytime measures						
HR (beats/min)	35	86.2 ± 9.5	86.3 ± 10.1	0.05 ± 6.0	0.95	0.81
SV (ml)	35	100.4 ± 22.3	100.8 ± 21.8	0.36 ± 21.1	0.92	0.54
CO (l/min)	35	8.6 ± 1.9	8.6 ± 1.8	0.03 ± 1.7	0.92	0.56
PEP (ms)	35	113.5 ± 11.8	115.6 ± 11.0	2.1 ± 10.4	0.25	0.59
LVET (ms)	35	253.9 ± 18.1	254.3 ± 17.5	0.40 ± 12.9	0.86	0.74
HI (ohms/s^2)	35	11.8 ± 3.6	11.2 ± 3.6	− 0.58 ± 2.3	0.15	0.79
SBP (mm Hg)	30	131.1 ± 9.4	130.6 ± 9.7	− 0.46 ± 6.3	0.69	0.79
DBP (mm Hg)	30	75.9 ± 7.4	75.5 ± 7.6	− 0.36 ± 6.1	0.75	0.66
MAP (mm Hg)	30	95.4 ± 7.7	94.9 ± 7.5	− 0.52 ± 6.4	0.66	0.65
TPR (dyne-s/cm^5)	30	1010 ± 226	1003 ± 225	− 6.2 ± 231.8	0.88	0.47
Night-time measures						
HR (beats/min)	23	73.0 ± 9.3	72.1 ± 9.9	− 0.85 ± 6.7	0.55	0.76
SV (ml)	23	97.7 ± 26.3	109.1 ± 28.5	11.4 ± 27.8	0.06	0.49
CO (l/min)	23	7.0 ± 1.9	7.8 ± 2.3	0.8 ± 2.3	0.10	0.45
PEP (ms)	23	110.5 ± 13.0	117.3 ± 10.1	6.8 ± 11.0	0.01	0.57
LVET (ms)	23	293.2 ± 25.4	298.5 ± 21.9	5.3 ± 25.3	0.33	0.43
HI (ohms/s^2)	23	8.1 ± 2.9	7.8 ± 2.1	− 0.3 ± 1.7	0.39	0.82
SBP (mm Hg)	20	120.3 ± 12.7	118.6 ± 11.3	− 1.7 ± 10.1	0.46	0.65
DBP (mm Hg)	20	63.4 ± 10.7	64.7 ± 8.8	1.3 ± 8.7	0.51	0.62
MAP (mm Hg)	20	83.5 ± 11.5	84.3 ± 8.1	0.8 ± 9.0	0.68	0.63
TPR (dyne-s/cm^5)	20	1094 ± 321	1014 ± 305	− 80.9 ± 396	0.37	0.20

Values are means ± SD. HR, heart rate; SV, stroke volume; CO, cardiac output; PEP, pre-ejection period; LVET, left ventricular ejection time; HI, Heather Index; SBP, systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure; TPR, total peripheral resistance.