Ambulatory impedance cardiography: a feasibility study

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Sherwood, Andrew, Judy McFetridge, and J. Stanford Hutcherson. Ambulatory impedance cardiography: a feasibility study. J. Appl. Physiol. 85(6): 2365–2369, 1998.—A wearable, ambulatory impedance monitor (AIM) has been developed to permit impedance cardiographic measurements while patients and volunteers engage in normal daily activities. The AIM system was developed for use with a new hybrid tetrapolar spot-band electrode configuration and was designed to be comfortable and inconspicuous. The objective of the present study was to provide a preliminary evaluation of AIM comparability with the widely validated Minnesota model 304B impedance cardiograph with standard tetrapolar band electrodes. Orthostatic challenge was used to systematically alter cardiac function in a laboratory setting in 11 healthy men and women. Both while the subjects were sitting and while they were standing, the AIM yielded measures of cardiac function, including heart rate, preejection period, left ventricular ejection time, and stroke volume, that were similar to those acquired by using the reference Minnesota model 304B system (all Pearson R correlations > +0.87, all P < 0.001). Cardiac responses to postural shift, expressed as change measures from sitting to standing, were also comparable for the AIM and Minnesota reference monitoring systems. Potential applications, including the assessment of 24-h hemodynamic profiles, are illustrated and discussed.

ambulatory monitoring; cardiac function; preejection period; stroke volume; hemodynamics

Impedance cardiography has been used to examine cardiovascular responses to a wide range of stimuli. These include responses to exercise (3), mental stress (15), sleep (1), orthostatic challenge (2), and a variety of pharmacological challenges (5). Studies reported to date have been conducted almost exclusively in the laboratory or clinical environment, because the typical measurement equipment is of limited portability. Measurement of blood pressure (BP) and the electrocardiogram (ECG) was once also restricted to laboratory and clinical settings, but technological advances have led to the availability of ambulatory BP (ABP) and Holter monitors that record physiological data during the patient's and volunteer's normal daily activities. Over the past 10 years, ambulatory studies have yielded new insights into both normal physiological processes and pathophysiological mechanisms. Examples from Holter monitoring include spectral analysis of heart rate (HR) variability to index autonomic control (11) and ECG analysis of myocardial ischemia in coronary heart disease (12). ABP monitoring has led to the identification of “white coat hypertension” (4), and ABP has been shown to correspond more closely with end-organ damage than does clinic BP (8).

Impedance cardiography provides assessments of a number of indexes of cardiac function, including HR, preejection period (PEP; an inversely related index of myocardial contractility), left ventricular ejection time (LVET), the Heather index (HI; an index of myocardial contractility), and stroke volume (SV). Cardiac output (CO) may also be derived from the HR and SV measurements, and simultaneous BP measurement permits the derivation of systemic vascular resistance (SVR). Indeed, a growing body of literature of laboratory and clinic studies has united impedance cardiography with BP measurement to document hemodynamic responses in terms of BP, CO, and SVR patterning (15).

The primary objective of the present study was to assess how a newly developed ambulatory impedance monitor (AIM) would compare with established impedance cardiographic instrumentation. The AIM was developed to be used with a recording electrode configuration designed to maximize signal fidelity while simultaneously considering patient comfort. The Minnesota model 304B with a standard tetrapolar band electrode configuration was used as a reference impedance cardiographic system, because it remains the most widely validated standard (13). Moreover, the study's objective was not to revisit the validation of impedance cardiography as a technique per se but rather to evaluate whether the AIM system, with its unique hardware and electrode configuration, would yield cardiovascular function indexes similar to those that are obtained with standardized impedance cardiographic methodology. Orthostatic responses associated with volitional relaxed sitting and standing postures were used to systematically alter cardiac function, providing an ecologically relevant manipulation suitable for the laboratory assessment of a monitor designed for ambulatory recording. In addition, one individual volunteered to wear the instrument for 24 h on a typical workday, and his data

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are presented to illustrate the potential value of ambulatory impedance cardiography.

METHODS

Subjects

The study sample consisted of 11 healthy volunteers and comprised five men and six women: six Caucasians, four African-Americans, and one Asian. Subjects ranged in age from 20 to 41 yr (mean 25 yr). The mean height of subjects was 68 in. (range 58.5–77 in.), and the mean weight was 177.9 lbs. (range 122.5–266.5 lbs.). All subjects read and signed a written consent form approved by the Institutional Review Board before their participation.

Measurements

Minnesota 304B. The Minnesota model 304B (IFM, Greenwich, CT) is a commercially available impedance cardiograph that has been the most widely used in research studies (13). This instrument utilizes a 4-mA constant-current source with 100-kHz oscillator frequency. The Minnesota 304B also includes ECG signal input and amplification. The tetrapolar band electrode configuration, first described by Kubicek and colleagues (6), was employed for impedance signal (thoracic impedance \(Z_0\)) and first derivative of pulsatile impedance \(dZ/dt\) acquisition, as it represents the reference standard that has been most extensively validated (13). The inner two recording electrode bands were positioned around the base of the neck and around the thorax over the tip of the xiphoid process. The outer two current electrode bands were positioned to encompass the neck and thorax, at least 3 cm away from each of the recording electrodes. The ECG was recorded independently by using disposable ECG electrodes (Cleartrace, Conmed, Utica, NY) placed on the chest in a lead II configuration.

AIM. The AIM is a microcomputer-based wearable bioelectric impedance monitor and signal processing system designed for 24-h ambulatory measurement. It consists of a small \(3 \times 4 \times 1.5\)-in. plastic enclosure that contains a credit-card-sized bioelectric impedance cardiograph, a credit-card-sized microcomputer and data logger, and a 9-V battery. The AIM generates an 80-kHz, 2-mA constant sine wave alternating current. The AIM computer section ensemble averages, analyzes, and stores the ECG, \(dZ/dt\), and \(Z_0\) waveforms and the computed cardiac function indexes during each measurement sequence.

A tetrapolar combination of spot and band electrodes was specifically developed for use with the AIM system. The recording electrodes were Mylar band electrodes placed around the base of the neck and around the thorax over the tip of the xiphoid process, identical to that for the Minnesota reference configuration (in this validation study, it was, therefore, necessary to apply the inner two recording band electrodes only once, for use with both instruments). Disposable ECG spot electrodes (Cleartrace) were used as current electrodes, with one applied behind the right ear (over the base of the mastoid process) and the other over the lower right rib cage, 6 cm below the lower recording band electrode. ECG recording with the AIM system utilized only one additional disposable spot electrode, placed on the lower left rib cage; the two impedance current spot electrodes served simultaneously as sources for the ECG signal, approximating a lead II configuration. The AIM spot-band impedance electrode configuration and ECG electrode placement are illustrated in Fig. 1. The AIM was worn on a belt around the waist during the entire test protocol.

Procedure

The study was designed to assess the effects of posture on impedance-derived indexes of cardiovascular function, measured by the two impedance cardiographic systems. Measurements from the two systems could not be recorded concurrently because of electrical interactions between them. Therefore, sitting and standing measurements were recorded with one system and then repeated with the other, with order counterbalanced across subjects.

The test procedure began by instrumentation of subjects with ECG and impedance electrodes. Next, subjects were randomized to one of two possible test orders, and either the AIM with two-band and two-spot electrode configuration or the Minnesota with four-band electrodes was set up for signal acquisition. Subjects were seated and asked to relax quietly for 5 min. In each of the last 2 min, a 30-s sequence of ECG and impedance signals was recorded and processed to derive HR, SV, PEP, LVET, and HI, which were representative of relaxed sitting values. Next, subjects were asked to stand and adopt a comfortable posture for 5 min. Again, in each of the last 2 min, ECG and impedance signals were recorded for 30 s and processed to derive HR, SV, PEP, LVET, and HI, which, this time, were representative of relaxed standing values. This procedure was then replicated exactly but using the impedance system (AIM or Minnesota) designated for testing in second order by the counterbalancing randomization.

Derivation of Cardiac Function Measures

The basal \(Z_0\), the \(dZ/dt\), and the ECG waveforms from both the AIM and Minnesota impedance cardiographs were acquired, each at a 500-Hz sample rate, and were processed by using specialized ensemble-averaging software (COP, Bioimpedance Technology, Chapel Hill, NC). This system utilizes ensemble averaging to filter noise and respiratory artifact from the impedance cardiographic waveforms and has been validated against the invasive thermodilution technique (14). In accordance with recommended standards (13), PEP was computed as the time interval (ms) between the ECG Q wave and the \(dZ/dt\) B point, LVET was computed as the time interval (ms) between the \(dZ/dt\) B point and X point, SV was derived by using the Kubicek equation (6), and HI was
computed as maximum dZ/dt (dZ/dt\text{max}) divided by the Q-wave
to-dZ/dt\text{max} time interval.

Data Analysis

The effects of the impedance monitoring system (AIM and Minnesota) and posture (sitting and standing) were evaluated by using repeated-measures analysis of covariance (ANCOVA) tests for each cardiovascular measure. The order
of testing (AIM and Minnesota) was entered as a covariate. Correlation analyses (Pearson's R) were employed to evaluate the correspondence between the two measurement systems across individuals. The effects of posture were also defined as percent change for each cardiovascular measure from sitting to standing posture and were analyzed by repeated-measures (AIM and Minnesota) ANCOVA. An \( \alpha \) level of 0.05 was adopted.

RESULTS

Posture and Monitor Effects

Mean values for the five indexes of cardiac function measured while the subjects were sitting and standing with the AIM and Minnesota monitoring systems are shown in Table 1. Standing, compared with sitting, was associated with significantly higher HR (\( P < 0.05 \)), longer PEP (\( P < 0.05 \)), and shorter LVET (\( P < 0.01 \)). There were also nonsignificant trends toward lower SV (\( P < 0.1 \)) and smaller HI (\( P < 0.1 \)) associated with standing compared with sitting. There were no significant differences for any of the measures associated with the impedance monitoring system used, nor was there any monitor by posture interactions.

Correlation Analyses

Pearson R values for the correlations between the AIM and Minnesota cardiac function indexes measured while the subjects were sitting and standing are shown in Table 2. As may be seen, all correlations are positive and statistically reliable, indicating good correspondence between the two measurement systems.

Postural Responses to Standing

For each index of cardiac function, the response to standing was computed as the difference between stand-

Example 24-h Hemodynamic Study

One subject, a 41-yr-old healthy man, volunteered to undergo 24-h testing on a typical workday. In addition to the AIM system, the subject was instrumented with the Suntech (Raleigh, NC) Accutracker ABP monitor, programmed to take a BP measurement every 15-min during waking hours and every 30-min during sleep. The ABP monitor activated the AIM device to initiate a 30-s ensemble average impedance data acquisition concurrent with every ABP measurement. The 24-h recording period tracked the course of a normal work-
day, evening relaxation at home, and overnight sleep. SVR was derived from each of the 84 simultaneously

Table 1. Cardiovascular variables in subjects during sitting and standing postures measured by using the AIM monitor and the Minnesota 304B

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sitting</th>
<th>Standing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate, beats/min</td>
<td>63.8 ± 8.4</td>
<td>65.3 ± 9.3</td>
</tr>
<tr>
<td>Stroke volume, ml</td>
<td>106.2 ± 31.7</td>
<td>111.2 ± 31.5</td>
</tr>
<tr>
<td>Preejection period, ms</td>
<td>126.9 ± 9.2</td>
<td>125.7 ± 13.8</td>
</tr>
<tr>
<td>LV ejection time, ms</td>
<td>284.2 ± 17.2</td>
<td>283.0 ± 22.0</td>
</tr>
<tr>
<td>Heather index</td>
<td>8.4 ± 3.0</td>
<td>9.5 ± 3.5</td>
</tr>
</tbody>
</table>

Values are means ± SD for 11 subjects. AIM, ambulatory impedance monitor; LV, left ventricular.

Fig. 2. Responses to standing, expressed as % change from sitting value (means ± SE) for heart rate (HR), stroke volume (SV), preejection period (PEP), left ventricular ejection time (LVET), and Heather index (HI) recorded by using AIM and Minnesota model 304B systems.
recorded BP and CO values, i.e., SVR (dyn·s·cm⁻²) = (mean BP/CO) * 80, where mean BP = [(systolic BP – diastolic BP)/3] + diastolic BP. As may be seen from the 24-h hemodynamic profile obtained, illustrated in Fig. 3, systolic and diastolic BP showed a circadian variation, with the lowest pressures occurring during overnight sleep and the highest during the workday. Interestingly, SVR was the more significant determinant of BP variations across the 24-h period (systolic BP/SVR correlation = +0.35, P < 0.01; diastolic BP/SVR correlation = +0.50, P < 0.001), with CO showing a nonsignificant positive correlation. However, posture was associated with substantial alterations in SVR. Controlling for posture, over the course of the daytime waking hours (6 AM to 11 PM), CO was revealed to be strongly related to systolic BP variations (R = +0.61, P < 0.01), whereas SVR maintained its association with diastolic BP (R = +0.32, P < 0.05). It is of note that, in considering these associations, it should be remembered that the SVR and BP measures are computationally dependent.

DISCUSSION

The AIM yielded measures of cardiac function that were comparable with those acquired by using the impedance cardiographic standard: the Minnesota 304B with a tetrapolar band electrode system. The AIM system incorporated a new hybrid spot-band electrode configuration, designed to be less conspicuous and more comfortable for 24-h monitoring. Nonetheless, the AIM generated SV, PEP, LVET, and HI values that were comparable with those measured by using the impedance standard. These findings were evident when individuals were tested both while sitting and while standing. Moreover, the cardiac responses to postural shift, expressed as change measures from sitting to standing, were also comparable for the AIM and Minnesota reference monitoring systems. These observations suggest that the AIM system is capable of measuring cardiac function with the same strengths and limitations that have been established for the impedance cardiographic technique, based on >100 previous validation studies employing the standard Minnesota system and a variety of invasive and noninvasive reference techniques (13). In other words, the AIM system should yield valid measures of systolic time intervals (PEP and LVET) in absolute terms and valid relative change measures for SV and CO (13).

The ensemble-averaging approach to signal acquisition and processing was a common aspect of both the AIM and Minnesota systems. This approach has been shown to effectively filter movement and respiratory artifact from the impedance cardiogram, making it especially well suited to monitoring during physical activity (10). These strengths of ensemble averaging are, therefore, likely to excel at optimizing impedance signal fidelity for the recording of individuals performing their normal daily activities in the ambulatory environment.

The observations over 24 h of hemodynamic monitoring made in one of the study subjects provide an illustration of how ambulatory impedance cardiography may present the opportunity for hemodynamic studies in the natural environment. One limitation of the 24-h hemodynamic data illustrated in the present report is that they are not validated. Nonetheless, it is of note that the impedance waveforms recorded were of surprisingly high fidelity, presenting no ambiguity in their interpretation and the computation of the various indexes of cardiac function. Therefore, there was no indication that the 24-h hemodynamic data lacked the validity generally attributed to impedance cardio-
graphic data. Because there is, presently, no other technology available to make possible 24-h ambulatory CO measurements, it is likely to be difficult to establish the validity of the AIM system in the ambulatory environment.

Naturalistic studies of the hemodynamic mechanisms of BP regulation may help further our understanding of the etiology of cardiovascular disease. Laboratory studies have indicated that elevated SVR is a feature of vascular hypertrophy and hypertension (7), whereas recurrent surges in CO may promote vascular endothelial damage and atherosclerosis (9). The AIM system, by permitting the assessment of hemodynamic phenomena in the natural environment, may help further our understanding of the pathophysiology of cardiovascular disease.

In summary, the AIM holds the potential for providing insights into previously unexplored aspects of cardiovascular control during the activities of daily living. Its comparability to the Minnesota standard suggests that the data generated by the AIM should share the same strengths and limitations offered by impedance cardiography in general (13). Strengths include the noninvasive, unobtrusive, and risk-free nature of the impedance technique. Limitations include the prerequisite of a structurally normal heart and volumetric measures (i.e., SV and CO) that are generally considered to be limited in validity to relative change indexes. Just as ambulatory ECG and ABP assessment has led to the recognition of previously unappreciated cardiovascular disease, the AIM may help identify previously unexplored aspects of cardiovascular control during the activities of daily living.

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