Comparability of Spot Versus Band Electrodes for Impedance Cardiography

Jennifer J. McGrath¹, William H. O'Brien², Hilary J. Hassinger², and Purvi Shah²

¹Concordia University, Montreal, Canada

²Bowling Green State University, Ohio, USA

Abstract

Although band and spot electrodes have been compared in prior research, they have not been evaluated (a) at identical anatomical locations, (b) during a single laboratory session, (c) with measures taken in close temporal proximity, (d) using a single impedance cardiograph unit, or (e) using sufficiently powerful statistical tests. Thirty-one healthy young adults completed a psychophysiological assessment which consisted of baseline, mental arithmetic stressor, and recovery conditions. Data from spot and band electrodes were collected by alternating between electrode types every minute of the experiment. Correlations between spot and band electrodes at absolute levels of all cardiovascular measures (cardiac output, impedance derivative, basal impedance level, Heather index, heart rate, left ventricular ejection time, pre-ejection period, stroke volume) were of high magnitude ($r_{\text{avg}} = .78$), while the correlations for difference scores were lower ($r_{\text{avg}} = .50$). Analyses of mean levels indicated spot electrodes yielded significantly lower values for the impedance derivative, Heather index, and basal impedance, and higher values for cardiac output and stroke volume, than band electrodes. The advantages and disadvantages associated with spot and band electrode configurations, as well as their use in ambulatory recording, are discussed.

Keywords

impedance cardiography; cardiovascular; assessment; psychophysiology; electrode; spot; band

Impedance cardiography is a noninvasive measurement technique used to assess important parameters of cardiac functioning such as cardiac output (CO), stroke volume (SV), pre-ejection period (PEP), left ventricular rejection time (LVET), and total peripheral resistance (TPR). Several researchers have investigated the validity of impedance cardiography by correlating impedance-derived measures of cardiac functioning with direct and invasive measures of cardiac functioning (e.g., Kubicek, 1995; Sherwood et al., 1990). The validity of impedance cardiography was also evaluated by determining whether impedance-derived measures yield expected patterns of cardiovascular reactivity to laboratory stressors or pharmacological manipulations (e.g., Pranulis, 2000). Taken together, the results of these validity studies indicated that measures of cardiac function using impedance cardiography

were highly correlated with direct measures of cardiac function, and that cardiovascular reactivity patterns measured with impedance cardiography conformed to expectations.

The validity studies for impedance cardiography typically used aluminum coated Mylar band electrodes placed in a tetrapolar configuration to record variation in thoracic impedance values. The standard tetrapolar configuration involves circumferential placement of upper and lower voltage bands about the base of the neck and the chest at the level of the xiphisternal junction. Two current electrode bands are placed approximately 3 cm distal from these two voltage electrodes. The tetrapolar band electrode configuration is recommended by the methodological guidelines for impedance cardiography (Sherwood et al., 1990).

Several limitations of the tetrapolar band electrode configuration have been identified. One limitation is participant discomfort and distress. Specifically, the placement of aluminum coated Mylar bands about the neck and chest can induce choking sensations and anxiety. Additionally, participants who are allergic to metals and/or plastic tape can develop rather severe skin reactions. An additional limitation to the tetrapolar band electrode configuration is the potential for inaccurate recording. For example, Qu, Zhang, Webster, and Tompkins (1986) reported that the signal-to-noise ratio for spot electrodes was up to 45% greater than the signal-to-noise ratio for band electrodes. Qu et al. speculated that this substantial difference in the signal-to-noise ratio occurred because either spot electrodes produced a larger impedance derivative (dZ/dt) waveform or band electrodes were more susceptible to movement artifacts. Qu et al. suggested that spot electrodes provide enhanced recordings given their larger signal-to-noise ratio and lower sensitivity to movement.

Due to concerns regarding participant discomfort with band electrodes and the suggested potential for enhanced recordings using spot electrodes (e.g., Qu et al., 1986), several researchers investigated the equivalence of these two measurement methods. To date, five investigations comparing band and spot electrode configurations have been published. The key features of these investigations are summarized in Table 1.

The first investigation of spot-band comparability was conducted by Qu et al. (1986). Qu and colleagues measured signal-to-noise ratios during a standing rest period and four different levels of physical exercise. The spot electrode configuration consisted of: (a) one voltage electrode placed 4 cm above the clavicle on the anterior surface of the neck, (b) a second voltage electrode placed over the sternum at the level of the fourth rib, (c) a current electrode placed at the level of the fourth vertebrae on the posterior surface of the neck, and (d) a second current electrode placed at the level of the ninth thoracic vertebrae on the back. Band placement was not described.

Impedance measurements initially were collected using spot electrodes. After completion of the experimental protocol, spot electrodes were replaced with band electrodes and the protocol was repeated. The time interval between spot and band measurement was not provided. Results indicated the signal-to-noise ratio using spot electrodes was up to 45% greater than the signal-to-noise ratio yielded by band electrodes. Qu et al. (1986) concluded that spot electrodes yielded improved signal quality because the placement of sensors along

the midline minimized movement artifacts during exercise. Additionally, Qu and colleagues posited that the spot electrodes generated a larger dZ/dt wave which, in turn, permitted more accurate measurement of changes in thoracic impedance.

The Qu et al. (1986) study provided evidence that spot electrodes may yield more accurate impedance data. There were several problematic aspects of this study, however, that detracted from its contribution to our understanding of the comparability of spot and band electrodes. First, the authors did not evaluate the cardiac functioning parameters that are typically measured using impedance cardiography. Thus, even though the signal-to-noise ratio was greater for spot electrodes, one cannot conclude that measures of cardiac function most frequently used in cardiovascular research (e.g., CO, SV, LVET, TPR) also would be more accurate. A second limitation of the Qu et al. study is related to methodology. Because the authors ran participants through the protocol using spot electrodes first and band electrodes second, potential order effects confounded the spot-band comparisons. A final limitation of the Qu et al. study is related to small sample size ($N = 10$, 3 females, 7 males). This small sample size resulted in statistical tests with low power, and potential gender differences could not be statistically evaluated.

The second investigation of spot-band comparability was conducted by Boomsma, de Vries, and Orlebeke (1989). These investigators measured impedance conductance, basal impedance (Z_0), SV, B-wave, X-wave, dZ/dt_{peak} , PEP, LVET, and interbeat interval during a rest condition, a reaction-time task, and physical exercise. Spot electrodes were placed using the Qu et al. (1986) configuration described above. Two types of electrode bands (commercial aluminum coated Mylar or “homemade” medical tape with two 6 mm aluminum strips attached 3 cm apart) were placed using the standard tetrapolar configuration. Measurements for spot and band electrodes were taken across each task condition in a randomized order. Thus, participants underwent two resting conditions, two reaction time conditions, and two physical exercise conditions with spot and band measurements being collected across successive conditions. Results indicated the mean Z_0 of spot electrodes was lower than the mean Z_0 of band electrodes, and dZ/dt_{peak} onset was earlier for spot electrodes relative to band electrodes. Correlations for spot and band electrodes ranged from .71 to .97 ($r_{\text{avg}} = .83$). Interestingly, correlations between the two different types of band electrodes (range = .76–.90, $r_{\text{avg}} = .83$) were comparable to the spot-band correlations. Boomsma et al. concluded that spot electrodes yield more reliable data because of their lower Z_0 . Accordingly, they suggested that spot electrodes could replace band electrodes without loss of impedance signal quality.

The Boomsma et al. (1989) study supported the notion that spot electrodes could be used instead of band electrodes in impedance cardiography. These authors also used an expanded number of measures of cardiovascular functioning. Unfortunately, the use of a small sample size ($N = 12$, 6 females, 6 males) again precluded adequately powerful testing of potential spot-band differences and gender differences. A second limitation of the study was that Boomsma and colleagues used a measurement system (viz. Nihon Kohden Impedance Plethysmograph interfaced with a Beckman polygraph) that is rarely used in this area of research. Third, spot and band measurements were collected across successive experimental conditions. This temporal spacing of measurements would tend to underestimate the

magnitude of correspondence between spot and band electrodes relative to simultaneous or near-simultaneous recording. Finally, although more impedance measures were evaluated, the authors did not measure CO, which is of central interest in the cardiovascular reactivity literature.

The third investigation of spot-band comparability was conducted by Patterson, Wang, and Raza (1991). Patterson and colleagues measured Z_0 , dZ/dt_{peak} , and SV during a supine resting condition, a sitting condition, and physical exercise. The spot electrode configuration consisted of a voltage electrode placed at the suprasternal notch with a second voltage electrode placed 10 cm lower. The current for the spot electrode configuration was provided by a Mylar band electrode placed circumferentially about the waist and a spot electrode placed on the forehead. The band configuration used two voltage electrodes placed circumferentially around the lower neck and the thorax at the level of the xiphisternal joint. The current electrodes used for spot measurements were also used for the band measurements.

The voltage electrodes from the spot and band configurations were interfaced with three different impedance cardiographs and recordings were collected simultaneously throughout the experiment. Results indicated that the mean SV yielded by the spot electrodes was significantly higher than the mean SV yielded by the band electrodes. The authors also evaluated different combinations of spot-band locations and concluded that the dZ/dt waveforms significantly differed among any pairing of spot and/or band combinations. Patterson et al. (1991) concluded that placement of electrodes at varying locations resulted in substantial differences in estimates of Z_0 , dZ/dt , and SV.

The Patterson et al. (1991) study is important because it demonstrated that the *location* of the electrode as well as the *type* of electrode influenced measurement of cardiac functioning using impedance cardiography. Consequently, spot-band investigations that placed the two sets of electrodes at different levels along the thorax would be confounding electrode location with electrode type. The primary limitations of this study were related to sample size and measurement strategy. Specifically, the small sample size ($N = 10$, 10 males) precluded an adequately powerful test of potential spot-band differences, and the lack of female participants made gender comparisons impossible. Additionally, spot-band comparisons were complicated in two ways. First, the spot configuration actually used band electrodes to introduce current. Second, different cardiographs were used to record data from the spot and band electrodes. Thus, spot-band comparisons were confounded by electrode type, impedance device, and as noted above, anatomical location of electrodes.

The fourth investigation of spot-band comparability was conducted by Sherwood, Royal, Hutcheson, and Turner (1992). Sherwood and colleagues measured Z_0 , dZ/dt , CO, SV, PEP, and LVET during a resting condition and physical exercise. Recordings were taken using the Qu et al. (1986) spot electrode configuration and the standard tetrapolar band configuration. The entire protocol was run once with spot electrodes in place and once with the band electrodes in place. The order of electrode placements was counterbalanced, and an approximate 30 min period separated the two assessment sessions. Electrode data were input

to a Minnesota Impedance Cardiograph and signals were analyzed using the Cardiac Output Program (Microtronics, Inc., Chapel Hill, NC).

Like Boomsma et al. (1989) and Patterson et al. (1991), Sherwood and colleagues (1992) found the mean Z_0 for spot electrodes was significantly lower than the mean Z_0 for band electrodes. However, Sherwood and colleagues found the mean SV for spot electrodes was significantly lower than the mean SV for band electrodes. Additionally, Sherwood et al. reported that the mean CO yielded by spot electrodes was significantly lower than the mean CO produced by band electrodes. Sherwood et al. concluded that the lack of significant differences for measures of systolic time intervals (e.g., LVET, PEP) indicated that these measures were not adversely affected by variation in spot-band configurations. Alternatively, they cautioned that spot electrodes may affect measures of CO due to differences in the underlying impedance parameters such as Z_0 , dZ/dt , and/or the distance between voltage electrodes.

Sherwood et al. (1992) can be credited with using a more adequate sample size ($N = 20$, 10 females, 10 males) which permitted gender comparisons and an adequately powerful test for moderate-to-large effect sizes. They also evaluated additional impedance measures including CO. Finally, their instrumentation consisted of the Minnesota Cardiograph interfaced with the COP system. Importantly, this measurement system is commonly used in contemporary investigations using impedance cardiography.

The primary drawback of the Sherwood et al. (1992) study is related to the timing of measurement sessions. As noted above, participants were run through the rest-exercise protocol twice with a 30 min interval between assessment sessions. Even though the sessions were counterbalanced, the separation of sessions would increase error variance due to extraneous variables (e.g., habituation, changes in skin surface conductivity). For example, it might have been possible that the differences in level of CO would have been observed if the participants were run through the protocol twice using bands on both occasions. A second limitation is that the spot and band electrodes were placed at different levels on the thorax, which, as noted by Patterson et al. (1991), can lead to differences in impedance values even when similar electrodes are used.

The fifth and final investigation of spot-band comparability, conducted by Gotshall and Sexson (1994), assessed participants in both a supine and standing position. Impedance measures of Z_0 , SV, dZ/dt , and LVET were collected using two spot voltage electrodes placed on either side of the base of the neck on the midaxillary line and two spot voltage electrodes placed on either side of the thorax on the midaxillary line at the level of the xiphisternal junction. One spot current electrode was placed on the forehead and the other was placed on the anterior surface of the lower abdomen. Band electrodes were placed at the same anatomical location. Specifically, Mylar tape band electrodes were placed as a small strip on the forehead, a semicircumferential strip on the abdomen, and circumferential strips around the base of the neck and around the thorax at the level of the xiphisternal junction. Starting electrode type was randomized.

Consistent with Boomsma et al. (1989), Patterson et al. (1991), and Sherwood et al. (1992), Gotshall and Sexson (1994) observed that the mean Z_0 level for spot electrodes was significantly lower than the mean Z_0 level for band electrodes. Additionally, similar to the findings of Patterson et al., the mean SV level obtained by spot electrodes was significantly higher than the mean SV yielded by band electrodes. Gotshall and Sexson concluded that the observed spot-band differences in SV were largely attributable to the measured Z_0 differences. They suggested that direct comparisons cannot be made across studies using different electrode configurations, although comparisons of percent change may be possible.

Gotshall and Sexson (1994) demonstrated that the type and location of electrodes affected Z_0 and SV impedance values. Similar to nearly every study in this research domain, the primary limitation of this study is small sample size ($N = 14$, 6 females, 8 males), which precluded an adequately powerful test of potential spot-band differences and gender comparisons. Additionally, spot-band data were collected only during standing and sitting conditions. Thus, inferences about measurement under stressor conditions were not offered. Finally, the spot and band measurements were made during successive conditions with the experimenter interrupting the protocol to switch leads between each condition.

In summary, the combined results of the investigations reviewed above indicate that spot electrodes are apt to yield smaller Z_0 values. However, inconsistent results were reported for SV values. Potential differences on other commonly used impedance measures such as CO, LVET, and PEP have not been adequately investigated due to the use of small sample sizes, which would not be able to detect small or moderate effect sizes. Further, the use of small sample sizes has precluded the evaluation of interactions between electrode type and gender. Finally, several methodological limitations place constraints on the inferences that can be drawn from this body of studies. These limitations include: (a) placing spot and band electrodes at different anatomical locations, (b) using more than one impedance cardiograph unit, and (c) not comparing spot and band configurations in close temporal proximity.

The purpose of the present study was to compare data yielded by band electrodes and spot electrodes using a methodological approach that controlled for the limitations identified in the literature. To accomplish this, we used a larger sample that permitted adequately powerful testing of small effect sizes and exploration of potential gender differences. Second, spot electrodes and band electrodes were placed at identical levels along the thorax. Third, one impedance cardiograph unit was used to ensure that equivalent calibrations were used for both spot and band electrode configurations. Lastly, spot and band measures were made in very close temporal proximity (every other minute) within the same experimental conditions.

Method

Participants

Participants were recruited from undergraduate psychology courses. Exclusionary criteria included reported use of medications with cardiovascular effects, a history of cardiovascular complications, serious medical conditions, or serious psychopathology. Thirty-one young adults, aged 17 to 26 ($M = 20.4$, $SD = 2.4$), agreed to participate in exchange for

experimental credit. Data from three participants were omitted because they were classified as obese (Body Mass Index [BMI] greater than 30). Thus, a total of 28 participants (13 females, 15 males) were included in the analyses. Nearly all of the participants were Caucasian ($n = 26$, 92.9%). Participants were 173.2 cm tall ($SD = 10.4$), weighed 73.3 kg ($SD = 13.5$), and had an average BMI of 24.2 kg/m² ($SD = 2.9$).

Procedure

Each person participated in a single laboratory session during which cardiac impedance measurements were recorded from band and spot electrodes. Participants were to abstain from eating and vigorous exercise for 3 h prior to the experiment, and from nonprescription medicine and caffeine for 24 h prior to the experiment. Upon arrival at the psychophysiology lab, the experimenter described the procedures, demonstrated how the equipment worked, and explained the informed consent form. The participant was then seated in a comfortable chair in a temperature controlled, copper-shielded room, and asked to complete questionnaires for demographic and health history information.

Initially, participants were instructed to remain quiet and still for a 10 min baseline condition. After baseline, a mental arithmetic stressor task was presented, followed by a recovery period. The stressor and recovery conditions were each of 6 min duration. During the stressor condition, mental arithmetic problems were presented on a video monitor at a rate of two per minute. Experimenters instructed the participants to solve the problems aloud and encouraged them to continue should they cease reporting their computation; however, errors were not corrected.

Cardiovascular Measurements

Electrode Configurations—The spot electrode arrangement consisted of four 2.5 cm × 3 cm disposable ECG electrodes (Burdick CardioSens/ULTRA Disposable ECG Sensors) placed at the anatomical levels consistent with the standard tetrapolar configuration recommended by Sherwood and colleagues (1990). Specifically, spot electrodes were placed on the anterior surface of the neck and thorax, at the base and upper part of the neck, at the level of the xiphisternal junction, and the lower region of the rib cage. Next, an insulating rubber patch (4 cm × 4 cm × 1 mm) was placed over each spot electrode, to ensure there was no interference between electrode types. Then, four bands of disposable cardiograph electrode tape (Instrumentation for Medicine, Inc.) were placed directly over the spot electrodes and insulator patches, with two electrodes circumferentially placed around the base and upper part of the neck, and two electrodes placed around the thorax at the level of the xiphisternal junction and the lower region of the rib cage (i. e., standard tetrapolar configuration). Measurements were taken to ensure that the distances between electrodes were kept within the recommended specifications for the Minnesota Impedance Cardiograph ($M = 23.9$ cm, $SD = 3.3$). Finally, to record heart rate, three ECG electrodes were placed in a Lead I configuration on the thorax.

Apparatus and Recording—Separate impedance cables connected the spot and band electrodes to a junction box. A toggle switch on the junction box was used to alternate selection for the spot and band electrodes. The lead from the junction box then was

connected to a single Minnesota Model 304B Impedance Cardiograph unit, which relayed the ECG and ZCG signals to a computer software program (Cardiac Output Program, Bio-Impedance Technology, Inc.). The toggle switch was used to alternate between spot and band electrodes every minute throughout the experiment. Order of electrode sampling was randomized for each participant. Using this procedure, there were at least three spot and three band electrode samples collected per experimental condition (viz., baseline, stressor, and recovery).

ECG and ZCG signals were continuously recorded in 30 s epochs. Computer signal processing techniques scored the ensemble-averaged event waveforms and algorithmically derived the cardiovascular measures. Each epoch was manually checked to ensure accuracy of the event waveform scoring. HR, dZ/dt , PEP, LVET, and HI were derived from the event waveforms. SV was calculated using the Kubicek formula (Kubicek, Karnegis, Patterson, Witsoe, & Mattson, 1966). CO was determined using the equation $CO = HR \times SV$.

Data Reduction—For each cardiovascular measure, a mathematical average was derived for baseline, stressor, and recovery conditions for spot and band electrodes separately. Only the final 6 min of the baseline condition were included. Difference scores were determined by subtracting the baseline average from each task condition average.

Results

Data analyses were conducted using SPSS (Version 12.0). The means and standard deviations for spot and band electrodes are presented in Table 2. All electrode data were found to approximate the normal distribution, thus, no transformations were performed. Pearson product moment correlations were calculated for all cardiovascular measures across electrode type to determine the strength of the association between spot and band electrodes. For the baseline, stressor, and recovery conditions, the spot and band electrodes were significantly correlated across all cardiovascular measures (see Table 3). However, only the correlations of the difference scores for CO, HI, HR, and LVET were significant.

To evaluate mean differences across electrode type, a 2 (electrode type) $\times$ 2 (gender) repeated measures (baseline, stressor, recovery, difference score) ANOVA was conducted for each cardiovascular measure (viz., CO, dZ/dt , HI, HR, LVET, PEP, SV, Z_0). These analyses further permitted evaluation of interactions between electrode type and gender. A significant main effect was found for electrode type for CO, dZ/dt , HI, SV, and Z_0 . Specifically, spot electrodes yielded significantly lower values than band electrodes for dZ/dt ($F(3, 24) = 8.80$, $p < .001$, $\eta^2 = .52$), HI ($F(3, 24) = 18.98$, $p < .001$, $\eta^2 = .70$), and Z_0 ($F(3, 24) = 31.77$, $p < .001$, $\eta^2 = .80$); while spot electrodes yielded significantly higher values than band electrodes for CO ($F(3, 24) = 76.47$, $p < .001$, $\eta^2 = .91$) and SV ($F(3, 24) = 68.58$, $p < .001$, $\eta^2 = .90$). Follow-up analyses indicated that the mean differences between electrode types were significantly different across the baseline, stressor, and recovery conditions. Only the difference score for CO was significantly different between electrode types. Finally, there were no significant interactions between electrode type and gender.

Discussion

Previous research comparing ZCG electrodes has found that spot electrodes yield consistently smaller Z_0 than band electrodes. Some research also suggests that spot electrodes yield higher SV than band electrodes, however these findings are not uniform. Several methodological limitations, including small sample size, electrode placement at different anatomical locations, and dissimilar time intervals for collecting measurements, place constraints on the inferences that can be drawn from earlier studies. The objective of the present study was to compare data yielded by band electrodes and spot electrodes using a methodological approach that addressed these limitations. Thus, we (a) used a larger sample size, (b) placed electrodes at identical anatomical locations, (c) collected measures by alternating between spot and band electrodes in 1 min intervals, and (d) used a single ZCG measurement unit.

Results indicated that correlations of the absolute values of the impedance parameters using spot and band electrodes were highly and significantly correlated. However, there were differences in the magnitude of the correlations. Specifically, measures based exclusively on temporal events of the ECG and ZCG waveforms (e.g., HR, LVET, PEP) were correlated very highly ($r_{\text{avg}} = .93$). Measures based on basal impedance levels (e.g., Z_0 , dZ/dt , SV) also yielded highly reliable data, but the magnitude of the correlations was smaller ($r_{\text{avg}} = .69$). In contrast to the correlations of the absolute values of the impedance parameters, the correlations of the difference scores using spot and band electrodes were considerably lower. For example, the difference scores of all of the measures based on basal impedance levels yielded low and insignificant correlations ($r_{\text{avg}} = .29$). These results are not unexpected given that difference scores contain more error variance than absolute values.

An analysis of means indicated that measures based on the temporal events of the ECG and ZCG waveforms did not significantly differ as a function of electrode type. However, measures based on basal impedance levels were significantly different. Specifically, spot electrodes yielded significantly lower values for dZ/dt , HI, and Z_0 , and significantly higher values for CO and SV compared to band electrodes. Further, with the exception of CO, only the absolute values of these measures significantly differed.

The findings reported here extend and clarify the literature in several ways. First, we observed significant differences in dZ/dt . Sherwood et al. (1992) and Patterson et al. (1991) evaluated dZ/dt , but statistical comparisons were not significant. These nonsignificant findings may have been due to the use of inadequately powerful tests, methodologies that were confounded by time passage, or the placement of different electrode types at different anatomical locations.

Second, our observation of lower Z_0 levels for spot electrodes relative to band electrodes is consistent with prior reports by Boomsma et al. (1989), Patterson et al. (1991), and Sherwood et al. (1992). Given that the spot and band measures were separated by only 1 min intervals throughout the experiment, it is reasonable to argue that the increased Z_0 yielded by the band electrodes must have arisen from the electrodes themselves as opposed to changes in the conductivity of the skin, adaptation to the experimental conditions, and/or elapse of

time. The band electrodes likely introduce additional resistance to the measurement of thoracic impedance. Further, because this increased resistance is caused by the electrode rather than by thoracic impedance variation, it would function as error variance in statistical analysis. Thus, like Qu et al. (1986), it is reasonable to assert that spot electrodes have a higher signal-to-noise ratio, and in turn, better validity as a measure of thoracic impedance.

Third, we observed significantly higher SV with spot electrodes than with band electrodes. This finding is consistent with those reported by Patterson et al. (1991) and Gotshall and Sexton (1994). It is inconsistent, however, with Sherwood et al. (1992) who reported that SV was significantly lower for spot electrodes. This discrepancy in findings is difficult to reconcile. However, an analysis of the Kubicek formula suggests that our findings are internally consistent whereas those reported by Sherwood et al. (1992) are not. Specifically, the Kubicek formula states:

$$SV = \rho \times (L/Z_0)^2 \times LVET \times dZ/dt,$$

where ρ is the conductivity of the blood (a constant), L is the distance between electrodes (equivalent for spot and band electrodes in the present study because they were located at identical anatomical levels), Z_0 is the basal thoracic impedance, $LVET$ is left ventricular ejection time, and dZ/dt is the change in thoracic impedance. Given that ρ is a constant and that we observed: (a) a significantly lower Z_0 level for spot electrodes, (b) a significantly lower level of dZ/dt for spot electrodes, (c) no significant differences in $LVET$, and (d) no significant difference in L (the spot and band electrodes were at equivalent levels), it follows that SV must be higher for spot electrodes. Specifically, the L/Z_0 ratio would be substantially larger for spot electrodes because Z_0 is approximately half the magnitude of Z_0 for band electrodes. This larger ratio, multiplied by the other components of the Kubicek equation, would logically yield a larger value.

Although the present study examined the comparability between spot and band electrodes in a laboratory situation, the results also have implications for ambulatory settings. The use of band electrodes is somewhat problematic in ambulatory recording due to their obtrusiveness relative to spot electrodes. As such, researchers often use modified electrode configurations. For example, Sherwood and colleagues (1998) used a hybrid tetrapolar electrode configuration where spots were used for current electrodes, and bands were used for voltage electrodes. The results of this study, in combination with the results presented by Gotshall and Sexton (1994), suggest that the voltage electrodes are most critical for evaluating the comparability between configurations. Specifically, when the voltage electrodes are of similar type at identical locations, regardless of the current electrodes' type or location, the configurations are comparable.

The choice of spot vs. band electrode configurations has associated advantages and disadvantages. Spot electrodes are advantageous as they are more comfortable for participants and there is less resistance in the measurement of Z_0 . In contrast, band electrodes are less comfortable and have greater resistance in the measurement of Z_0 , however, they have been directly validated against direct assessment of cardiovascular

measures (i. e., thermodilution; Pickett & Buell, 1992). Future research into the validity of impedance cardiography comparing spot electrode data with “gold standard” measures of cardiovascular performance (e.g., intra-arterial measures) is needed.

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Table 1

Summary of investigations comparing spot and band electrodes for impedance cardiography.

Authors	Sample	Experimental Protocol	Measurement Device	ZCG Scoring	Spot Configuration	Band Configuration	Results
Qu et al., 1986	N=10 3 female, 7 male	Standing rest, four exercise levels. Spot electrodes run first, then band electrodes run second.	Built by authors	Ensemble averaging	Front – 4 cm above clavicle, sternum at 4 th rib Back–cervical vertebra (C4), thorax vertebra (T9)	Not described	SNR from spot up to 45% greater than band; Spot less influenced by movement
Boomsma et al., 1989	N=12 6 female, 6 male	Rest, reaction time task, physical exercise. Separate spot and band measures for each task condition using randomized order.	Nihon Kohden Impedance Plethysmograph interfaced with Beckman polygraph	Ensemble averaging; Beat-by-Beat	Qu et al., 1986	Tetrapolar	Band > Spot for Z ₀ , ZCG conductance; Spot earlier dZ/dt _{peak} detection No differences for X onset, B onset, SV, LVET, PEP
Patterson et al., 1991	N=10 0 female, 10 male	Supine, sitting, physical exercise. Simultaneous measures from different pairings of sensors using three cardiographs.	Minnesota Impedance Cardiograph	Ensemble averaging	Suprasternal notch and 10 cm lower, bands used for other two locations	Tetrapolar	Band > Spot for Z ₀ , R-Z interval, dZ/dt; Band < Spot for SV ¹
Sherwood et al., 1992	N = 20 10 female, 10 male	Rest, physical exercise. Separate assessment sessions (spot, bands counterbalanced) separated by approximately 30 minutes.	Minnesota Impedance Cardiograph	Ensemble averaging	Qu et al., 1986	Tetrapolar	Band > Spot for Z ₀ , CO, SV; Band < Spot for dZ/dt ² No differences for LVET, PEP
Goishall & Sexson, 1994	N=14 6 female, 8 male	Supine and standing positions. Electrodes changed after two measures collected for each condition.	Minnesota Impedance Cardiograph	Ensemble Averaging	1 on forehead, 2 bilateral on base of neck, xiphisternal notch, lower abdomen	Forehead strip, Base of neck (circumference), Xiphisternal notch (circumference), Abdomen (semi-circumference)	Band > Spot for Z ₀ , Band < Spot for SV No differences for HR, dZ/dt, LVET

SNR = signal-to-noise ratio; ZCG = Impedance Cardiography.

¹ Based on spot electrodes placed at upper thorax.

² Exercise condition only.

Table 2

Means and standard deviations for spot and band electrodes.

	Baseline		Stressor		Recovery		Difference Score	
	Spot	Band	Spot	Band	Spot	Band	Spot	Band
CO	6.74 (1.33)	3.48 (1.30)	7.47 (1.76)	3.77 (1.51)	6.97 (1.35)	3.56 (1.37)	0.73 (0.71)	0.29 (0.65)
dZ/dt	1.53 (0.45)	1.91 (0.59)	1.50 (0.46)	1.86 (0.64)	1.52 (0.44)	1.88 (0.59)	-0.03 (0.09)	-0.05 (0.20)
HI	9.09 (2.92)	12.25 (4.00)	9.56 (3.43)	12.86 (4.94)	9.13 (2.86)	12.26 (4.11)	0.47 (1.22)	0.61 (2.35)
HR	70.18 (8.02)	70.33 (8.28)	79.49 (11.90)	78.95 (12.35)	70.55 (7.49)	70.73 (7.62)	9.31 (7.42)	8.62 (7.42)
LVET	290.54 (17.41)	271.34 (23.83)	264.59 (21.73)	267.92 (22.86)	274.02 (18.57)	275.11 (22.57)	-5.95 (11.36)	-3.42 (10.03)
PEP	121.10 (12.75)	119.54 (14.21)	114.73 (15.04)	111.22 (19.91)	120.17 (13.77)	117.32 (15.34)	-6.37 (6.24)	-8.32 (11.51)
SV	97.94 (23.35)	50.36 (20.21)	95.42 (22.71)	48.91 (20.68)	100.37 (22.98)	51.14 (21.48)	-2.52 (6.76)	-1.45 (6.38)
Z ₀	18.96 (2.98)	30.95 (8.26)	18.77 (2.90)	30.93 (8.28)	18.73 (2.97)	30.71 (8.26)	-0.19 (0.32)	-0.03 (1.38)

Table 3

Correlations between spot and band electrodes.

	Baseline	Stressor	Recovery	Difference Score
CO	0.63	0.63	0.61	0.64
dZ/dt	0.78	0.82	0.74	0.45 ^a
HI	0.80	0.87	0.75	0.76
HR	0.99	0.98	0.99	0.90
LVET	0.91	0.92	0.94	0.51
PEP	0.91	0.82	0.88	0.29 ^a
SV	0.72	0.67	0.67	0.19 ^a
Z ₀	0.62	0.57	0.59	0.23 ^a

^a Nonsignificant finding ($p < .01$, two-tailed). All remaining correlations significant.