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Methodology

Comparison of Spot and Band Impedance Cardiogram Electrodes across Different Tasks

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ABSTRACT

Impedance cardiography has become of widespread interest as a noninvasive cardiovascular monitoring technique. This study compared the use of spot electrodes and two different types of band electrodes in the determination of systolic time intervals and stroke volume. EKG, impedance cardiogram, and phonocardiogram were recorded on 12 volunteers during rest, during a reaction time task, and after a short exercise task. Systolic time intervals (pre-ejection period and left ventricular ejection time) were computed on a beat-to-beat basis and on the ensemble-averaged signals. The only differences between spot and band electrodes were for impedance base level and electrode conductance. For stroke volume and the systolic time interval measures there were no differences between electrode arrays, nor were there any interactions with tasks. Correlations for stroke volume and systolic time interval measures as determined under different electrode conditions were around .8.

DESCRIPTORS: Impedance cardiography, Stroke volume, Systolic time intervals, Spot and band electrodes.

Measurement of changes in electrical impedance of the thorax has been used as a noninvasive technique to measure cardiac output and systolic time intervals (e.g., Lamberts, Visser, & Zijlstra, 1984). Usually conventional band electrodes are used to measure impedance. Two drawbacks to this technique are: 1) band electrodes are not always convenient to use, especially not for lengthy sessions; and 2) they are rather costly. The band electrode delivered with our apparatus (Nichiban, Nihon Kohden) costs around $8 per subject, which can be a major cost in large scale studies. By constructing our own band electrodes, we were able to reduce the cost per subject to below $1. In a comparison of home-made and Nichiban band electrodes we also included a spot electrode array as suggested by Qu, Zhang, Webster, and Tompkins (1986) because spot electrodes have the advantage of minimal inconvenience for the subject. Qu et al. (1986) compared the signal-to-noise ratio of spot and band electrodes. Both at rest and during treadmill exercise, the average signal-to-noise ratio from spot electrodes was larger than from the band electrode array. Zhang, Qu, Webster, Tompkins, Ward, and Bassett (1986) compared spot and band electrodes for the measurement of cardiac output with CO_2 rebreathing techniques. They obtained correlations between CO_2 rebreathing and cardiac output of .90 for spot electrodes and .96 for band electrodes. Penney, Patwardhan, and Wheeler (1985) used a different spot electrode array and a band electrode array simultaneously and obtained good results for both the shape and the relative height of the signal. The results for cardiac output therefore seem satisfactory. The above studies all used some form of ensemble averaging.

The objective of this study was to test and compare two different types of band electrodes and to test the effects of replacing the band electrodes with spot electrodes in the determination of stroke volume and systolic time intervals. Systolic time intervals were determined on a beat-to-beat basis and on the ensemble-averaged signal.

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Method

Subjects

Subjects were 6 female and 6 male students aged 22–32 years (mean=26.5). Subjects ranged in weight from 51 to 92 kg (mean=67.5) and in height from 1.58 to 1.89 meters (mean=174.4). All subjects were right-handed. They were paid Dfl. 25 for their participation.

Tasks and Procedure

Measurements were taken under three different conditions: during rest, during a choice reaction time task, and after physical exercise. All measurement periods lasted 4 min. Subjects performed these tasks once for each electrode array condition. Order of spot electrodes, Nichiban, and home-made electrodes was randomized; order of tasks was always rest, reaction time, exercise.

Testing took place in a sound attenuated, electrically shielded cabin, where subjects were seated in a comfortable chair. During the rest condition they were asked to relax as much as possible.

In the reaction time task each trial began with an auditory warning stimulus of 750 Hz and 60dB(A) which lasted 500 ms. After 5 s, the reaction stimulus was presented, which was a pure tone of either 500 or 1000 Hz, 60dB(A), and 500 ms duration. Auditory stimuli were presented through padded earphones. Order of high and low tones was randomized. Subjects had to respond to the high tones by pressing a key labeled "Yes" and to the low tones by pressing a key labeled "No." The next warning signal occurred 7 s after the subject's response. Before the experimental session, subjects received 18 practice trials.

Physical exercise consisted of at least 10 deep knee bends, the maximum number depending on the fitness of the subject. All measures were taken immediately after exercise.

Apparatus

EKG Ag-AgCl electrodes were placed on the sternum and the lateral margin of the chest. EKG was recorded using an amplifier with a time constant of 0.3 s and 1 MΩ impedance.

Phonocardiogram (PCG) was recorded using a Siemens-Elema AB microphone placed directly on the chest.

The impedance recording system was comprised of a Nihon Kohden Impedance Plethysmograph (AI-601G) in combination with a Differentiator (ED-601G), using either the tetrapolar aluminum band electrode system (Nichiban or home-made) or spot electrodes. Our own band electrodes consisted of medical tape (Leukopor; Beiersdorf) with two aluminium strips attached, 6 mm wide and 3 cm apart. In conditions using band electrodes the inner two measuring electrodes were placed around the base of the neck and around the thorax at the level of the xyphisternal joint (Kubicek, Patterson, & Witsoe, 1970). The current electrodes were placed 3 cm above and 3 cm below the measuring electrodes (imposing a current of 350 μA, with a frequency of 50 KHz and an output impedance >40 KΩ). The spot electrodes were disposable pregelled Ag-AgCl electrodes (AMI type 1650-005, Medtronic). Current electrodes were placed behind the cervical vertebra C_4 and behind thorax vertebra T_9. The measuring electrodes were placed 4 cm above the clavicle on the front of the neck and over the sternum at the fourth rib (Qu et al., 1986; Zhang et al., 1986). The electrode placement is illustrated in Figure 1. Conductance (1/R) of the ICG electrode arrays was measured after the rest condition by attaching the electrodes to a Conductron 330 (Enting Com.) and applying a sine wave voltage of 0.775 V, 5 Hz.

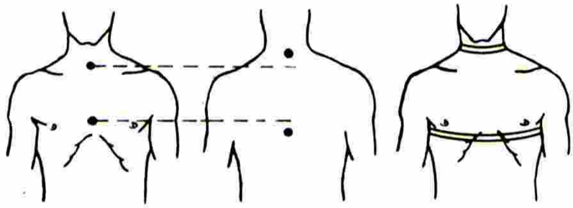

Figure 1. Placement of the spot and band electrodes. The inner electrodes are voltage electrodes, the outer ones are current electrodes.

The base thorax impedance Z_0 was continuously displayed and recorded by the experimenter every minute. Thorax impedance change, ΔZ, was measured with a time constant of 5 ms and a high-frequency cutoff of 75 Hz. To obtain the first derivative of the thorax impedance change, dZ/dt, ΔZ was passed through the differentiator. EKG, PCG, and dZ/dt were measured continuously during all task and resting conditions and were simultaneously recorded on a Beckman polygraph. All signals were digitized at 250 samples/second via a 12-bit A-D converter and stored on disk as binary data files. Data files were then sent from a PDP11/23 to a DEC PDP11/44 computer where data quantification took place.

Data Quantification

EKG data were used to determine the time between successive R-waves and the onset of the Q-wave relative to the next R-wave. In the dZ/dt signal the times of three waveform components relative to the preceding R-wave were identified (in ms): 1) the dZ/dt B-wave, which corresponds to the onset of left ventricular ejection; 2) the dZ/dt X-wave, which corresponds to the completion of left ventricular ejection; and 3) the time of peak height of dZ/dt ($(-dZ/dt)_{max}$). The value of $(-dZ/dt)_{max}$ (in Ω/s) was recorded to be used in the computation of stroke volume. PCG was used to localize the onset of the second heart sound, which is coincident with the completion of left ventricular ejection. When no single X-point was apparent in the dZ/dt tracings, the aortic component of the second heart sound was used instead.

Waveform analysis was fully automated: First the original series were passed through software filters (13 Hz low-pass filters for EKG and ICG and 3 Hz low-pass for PCG) to eliminate high frequency components introduced by muscle tension. Peaks, troughs, and bending points in the filtered signals were defined as the zero crossings of first, second, and third derivatives. Depending on filter and signal characteristics, the filtered signal could be displaced with regard to the original signal. It was therefore still necessary to look for the correct points in the unfiltered signal. This was done by using the points in the filtered signal as a starting point. All signals could be displayed and the markers indicating the points detected by the program could be replaced interactively. Correct automatic detection turned out to be independent of the electrode array used, but was subject dependent. For 3 out of the 12 subjects participating in the study, automatic detection of the dZ/dt X-wave was unreliable.

The detection of the above events allows computation of pre-ejection period (PEP) and left ventricular ejection time (LVET) on a beat-to-beat basis. A comparison is made between averaged beat-by-beat PEP and LVET and the PEP and LVET derived from ensemble-averaged signals for all task and resting conditions. Ensemble-averaging was performed by summing all waveforms time-synchronized to the EKG R-wave. Both for the beat-to-beat and the ensemble-averaged analyses, all data from the 4-min measurement periods were used.

Stroke volume (SV) was computed according to the formula developed by Kubicek, Patterson, and Witsoe (1970):

$$SV = \rho \, (L/Z_0)^2 \, (-dZ/dt)_{max} \, LVET,$$

where ρ is the resistivity of the blood (135 Ω/cm), L is the distance between voltage electrodes in cm (L was assessed separately for each electrode array; for the band electrodes average distance between measuring electrodes was used), and LVET is in seconds. Because Z_0 was not recorded on a beat-to-beat basis, only ensemble-averaged stroke volume was computed.

Analysis

For all variables (1/R, Z_0, SV, B-wave, X-wave, Peak, PEP, and LVET) ANOVAs for repeated measures were carried out with Sex (2) as a between subjects variable and Electrodes (3) and Tasks (3) as within subjects variables. If necessary, degrees of freedom for these last variables were adjusted using the BMDP2V (Dixon, 1985) Greenhouse-Geisser correction. For electrode conductance, ANOVA with Sex and Electrodes as variables was performed. To determine whether individual differences are stable under different electrode conditions, correlations were computed between the dependent variables measured with the different electrodes for all task conditions.

Results

Table 1 gives the *F*-ratios for all main effects and Table 2 gives the means for the different electrode × task conditions, for both the beat-by-beat (BB) averages and the ensemble-averaged (EA) signals. Conductance and Z_0 show a significant effect of electrodes, both being lower for the spot electrodes. The time of the dZ/dt peak also shows an electrode effect. As can be seen from Table 2, peak detection was about 5 ms earlier for the spot electrode conditions. Z_0, dZ/dt X-wave, and LVET showed a significant effect of sex (mean Z_0 was 27.0 for females and 20.0 for males; average ensemble-averaged dZ/dt X-wave and LVET were 380.5 and 305.8 ms for females and 349.8 and 277.7 ms for males). Task effects were absent for conductance and Z_0 and were significant for all other variables. There were no significant interactions for any of the dependent variables.

Table 3 shows the correlations between the dependent variables measured with the different electrodes. There were no differences between tasks for the pattern of correlations, so Table 3 shows the median correlations of the three tasks. Correlations between average beat-to-beat and ensemble-averaged measures were above .95 in all electrode × task conditions.

Discussion

Differences in conductance between spot and band electrodes are to be expected. Spot electrodes have a contact area of just 2 cm^2 per electrode. The contact area of the band electrodes is roughly 20 times larger and a 20 times higher conductance is found.

Table 1

F-ratios for ANOVA of average beat-to-beat (BB) and ensemble-averaged (EA) signals

	F-ratios[a]													
					B		X		Peak		PEP		LVET	
Main Effects	1/R	Z_0	IBI	SV	BB	EA	BB	EA	BB	EA	BB	EA	BB	EA
Sex	—	47.3	—	[4.7]	—	—	5.1	6.4	—	—	—	—	7.7	9.5
Electrodes	52.7	137.2	—	—	—	—	—	—	4.7	4.6	—	—	—	—
Task	—	—	[2.9]	19.8	51.0	47.5	8.6	4.4	41.6	32.4	53.5	56.8	15.6	52.5

Note. 1/R = conductance of the ICG electrode array, Z_0 = base thorax impedance, IBI = interbeat interval, SV = stroke volume, B and X = time of onset and completion of left ventricular ejection (relative to EKG R-top), Peak = time of peak height of dZ/dt (relative to EKG R-top), PEP and LVET = pre-ejection period and left ventricular ejection time.

[a]All $p<.05$, except the values in brackets, which are $p<.10$.

Table 2

Means of average beat-to-beat (BB) and ensemble-averaged (EA) signals

	Mean Values													
					B (ms)		X (ms)		Peak (ms)		PEP (ms)		LVET (ms)	
Tasks	1/R (1/Ω)	Z_0 (Ω)	IBI (ms)	SV (ml)	BB	EA	BB	EA	BB	EA	BB	EA	BB	EA
Spot Electrodes														
Rest	16.6	13.7	953	79.6	82.4	80.3	372.5	371.3	133.4	133.6	125.7	124.0	290.2	291.0
Reaction Time		13.5	915	76.3	79.8	78.0	367.6	367.7	129.8	130.0	123.0	121.7	288.1	289.7
Exercise		13.4	956	98.3	57.6	55.6	360.1	361.7	111.3	112.0	101.7	99.0	302.3	306.0
Home-Made Tape														
Rest	290.6	28.6	950	81.9	82.0	81.0	369.9	370.3	137.4	137.7	125.7	125.0	287.9	289.3
Reaction Time		28.5	910	76.5	80.3	80.0	368.6	365.7	134.4	134.3	124.0	123.3	288.0	285.7
Exercise		28.8	935	100.8	62.0	60.6	357.3	360.0	117.5	119.3	106.0	104.7	295.2	299.3
Nichiban Tape														
Rest	268.2	28.8	915	78.7	84.2	83.0	366.5	366.0	138.7	139.0	127.6	126.3	282.3	283.7
Reaction Time		28.8	901	74.6	82.3	81.3	365.4	363.7	136.1	136.3	125.6	124.3	283.2	281.7
Exercise		28.9	937	97.4	62.7	60.7	356.8	360.0	118.4	121.0	106.5	104.0	294.2	299.7

Note. 1/R = conductance of the ICG electrode array, Z_0 = base thorax impedance, IBI = interbeat interval, SV = stroke volume, B and X = time of onset and completion of left ventricular ejection (relative to EKG R-top), Peak = time of peak height of dZ/dt (relative to EKG R-top), PEP and LVET = pre-ejection period and left ventricular ejection time.

Table 3

Median correlations beween the dependent measures under different electrode arrays for average beat-to-beat (BB) and ensemble-averaged (EA) signals

	Correlations[a]											
			B		X		Peak		PEP		LVET	
Electrode Arrays	Z_0	SV	BB	EA	BB	EA	BB	EA	BB	EA	BB	EA
Spot Electrode vs. Band Electrode with Home-made Tape	.78	.74	.81	.80	.94	.94	.78	.71	.76	.83	.95	.97
Spot Electrode vs. Band Electrode with Nichiban Tape	.71	.77	.81	.82	.86	.85	.84	.84	.81	.81	.87	.89
Band Electrode, Home-made Tape vs. Nichiban Tape	.89	.89	.81	.77	.84	.86	.78	.76	.77	.81	.90	.88

[a]All significant at $p<.01$, N=12.

The typical base impedance of about 14 Ω for the spot electrode array and about 29 Ω for the band electrodes was also found by Qu et al. (1986). One explanation for this finding is that a certain proportion of Z_0 is contributed by the band electrode itself. This favors the spot electrode array over the band electrodes, because a lower impedance contribution of the measuring system itself makes the derived signal more reliable. The distance between measuring electrodes may also influence Z_0. Lamberts et al. (1984) found that Z_0 increases as the distance between voltage electrodes increases. Although the distance between spot electrodes was smaller than the distance between band electrodes, the average difference was only 6 cm, which can explain only a small part of the 15Ω difference in base impedance, so the contribution of the electrodes themselves remains the most important explanation. The distance between measuring electrodes may also influence the computation of stroke volume, because $(-dZ/dt)_{max}$ decreases with increasing voltage electrode distance, though not in a linear fashion (Lamberts et al., 1984). Results for stroke volume do not indicate, however, that this influenced the results obtained in this study. Again, this may be because of the relatively small difference between spot and band measuring electrode distances.

No differences were found for systolic time interval measures using the different electrode arrays. Moreover, correlations between these measures under different task conditions were also reasonable.

Of course, these correlations depend not only on the similarity of the signals under different electrode conditions, but also on the short term stability of these measures.

These results indicate that band electrodes can be replaced by spot electrodes without causing major changes in the impedance signal. Spot electrodes are more comfortable for the subjects and thus may permit longer measurement periods. In addition, this study also shows that commercial and home-made band electrodes can yield similar results.

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Announcements

Thirtieth Annual Meeting
Society for Psychophysiological Research

From October 17th through 21st, 1990, the Thirtieth Annual Meeting of the Society for Psychophysiological Research will be held at the Boston Park Plaza Hotel and Towers in Boston, Massachusetts, USA. Information regarding submission of papers may be obtained from the 1990 program chairman: Gregory A. Miller, Department of Psychology, University of Illinois, 603 East Daniel Street, Champaign, IL 61820, USA (217/333-4507). Registration information may be obtained from the Society's convention manager: Joanne Fetzner, Society for Psychophysiological Research, 2101 Winchester Drive, Champaign, IL 61821, USA (217/398-6969).

Nominations for the
Early Career Contribution Award, 1990

Members of the Society for Psychophysiological Research are invited to make nominations for the 1990 Distinguished Scientific Award for an Early Career Contribution to Psychophysiology. The ground rules are as follows:

(1) Any member of the Society is eligible to be nominated who has been engaged in active research or other related activities for no more than five years since receiving the doctorate or finishing research training. The five-year time limitation in the case of those holding a medical degree would incorporate the period commencing with the completion of the residency if the individual has not been previously engaged in research. Whereas the award can be made on the basis of a single project, the committee will be looking more for the presence of a program of outstanding research. Thus, candidates who have had several years of productive post-doctoral research are more likely to become award recipients.

(2) Anyone wishing to nominate a person for this award should submit that person's name, along with a brief statement as to why the nomination is being made, to: Ray Johnson, Jr., Ph.D., The National Institutes of Health, Building 10, Room 5C422, 9000 Rockville Pike, Bethesda, Maryland 20892. The deadline for receipt of nominations is March 1, 1990.

(3) Individuals previously nominated and not receiving the award may be nominated again provided they still meet the longevity guidelines. The five-year time limitation may be extended with permission of the Selection committee for outstanding candidates who were previously nominated their last year of eligibility or where special extenuating circumstances apply.

(4) Nominees will be contacted and requested to furnish a curriculum vitae, reprints, and other documentation that testify to their contribution to psychophysiology.

(5) As in the past, the awardee(s) will be given the opportunity to address the annual meeting of the Society and to publish their talk in *Psychophysiology* following editorial consultation.