

Detection of Characteristic Points of Impedance Cardiogram and Validation Using Doppler Echocardiography

S. M. M. Naidu^{1,2}, Uttam R. Bagal^{1,3}, Prem C. Pandey¹,
Suhas Hardas⁴, Niranjan D. Khambete⁵

¹Dept. of Electrical Engineering, Indian Institute of Technology Bombay, Mumbai, India

²DIST, International Institute of Information Technology, Pune, India

³Dept. of Biomedical Engineering, MGM College of Engineering & Technology, Navi-Mumbai, India

⁴Hardas Heart Care, Shivajinagar, Pune, India

⁵Dept. of Clinical Engineering, Deenanath Mangeshkar Hospital and Research Centre, Pune, India

<mohans@isquareit.ac.in>, <uttambagal@gmail.com>, <pcpandey@ee.iitb.ac.in>,
<suhas_h@hotmail.com>, <niranjan.d.khambete@gmail.com>

Abstract—Impedance cardiography is a noninvasive technique for monitoring the variation in thoracic impedance during cardiac cycle. Estimation of the stroke volume and other cardiovascular indices using impedance cardiography requires error-free detection of characteristic points in the impedance cardiogram (ICG). A technique for automatic detection of ICG characteristic points using R peaks in ECG as reference is presented. It does not require pre-processing of the ICG signal for baseline correction and adjustment of detection parameters. The technique is validated using Doppler echocardiography as a reference technique, by recording ICG and ECG signals simultaneously along with velocity profile of blood flow at the level of left ventricular outflow tract. Application of the technique on the recordings from healthy subjects in pre-exercise and post-exercise conditions and from cardiac patients under rest condition showed a very low detection error.

Keywords—Impedance cardiography; ICG characteristic points; Doppler echocardiography

I. INTRODUCTION

Impedance cardiography is a noninvasive technique for sensing of variation in the impedance of the thorax due to changes in blood volume during the cardiac cycle and relating this variation to stroke volume (SV), cardiac output (CO), and other cardiovascular indices [1]–[6]. A low-amplitude current (< 5 mA) of 20 – 100 kHz, not causing nerve stimulation and muscle contraction, is passed through the thorax via a pair of band or spot electrodes. The resulting voltage is sensed by the same or another pair of electrodes placed within the current injecting electrodes [7], [8]. The negative derivative of impedance change is known as the impedance cardiogram (ICG). It may be used for beat-to-beat monitoring of SV, CO, systolic time intervals, and some other cardiovascular indices which may provide valuable information about cardiovascular functioning [9]–[12].

Several researchers, as cited in [13], have reported that ICG can be used for measurement of systolic time intervals. Kim [14] reported that the monitoring of SV during exercise

may be useful in the diagnosis of cardiovascular diseases related to pulmonary artery, dilated cardiomyopathy, aortic stenosis and other valvular diseases. A study by Zang *et al.* [15], involving ECG and ICG recordings from healthy volunteers in supine, upright, and sitting positions, reported that ICG can be used to monitor cardiovascular function under transient conditions. From a study of recordings from 20 healthy subjects and 18 patients with Fallot Syndrome, Nowakowski *et al.* [16] found ICG to be a sensitive and fairly accurate technique to observe SV changes. Wong *et al.* [17], on the basis of a study involving 22 normotensive subjects, reported that ECG and ICG together can be used for getting information on systolic blood pressure.

Most of the impedance cardiography applications require determination of some of the characteristic points of the ICG waveform. A technique for automatic detection of the B, C, and X points in the ICG waveform is presented. It works in the presence of baseline drift and does not require selection or adjustment of processing parameters. It is evaluated on recordings from healthy subjects and cardiac patients, using Doppler echocardiography as the reference technique.

II. ICG CHARACTERISTIC POINTS

Impedance cardiogram is characterized by the characteristic points labeled as the A, B, C, X, and O points, which correlate with various cardiac events. Lababidi *et al.* [18] carried out a simultaneous recording of ECG, ICG, and phonocardiogram (PCG) from 27 subjects and observed that the A, B, C, and X points were associated with the atrial and ventricular systole while the O point was associated with the early diastole. An example of the simultaneously recorded ICG, impedance change, ECG, and PCG are shown in Fig. 1. The small negative deflection from baseline in ICG lying between the beginning of the P wave and the QRS complex in ECG is the A point [19]–[21]. It is associated to atrial systole [14]. The deflection in ICG preceding the large change in the impedance is the B point [5], [7], [14], [18], [22]–[24]. It is associated with the opening of the aortic valve and coincides

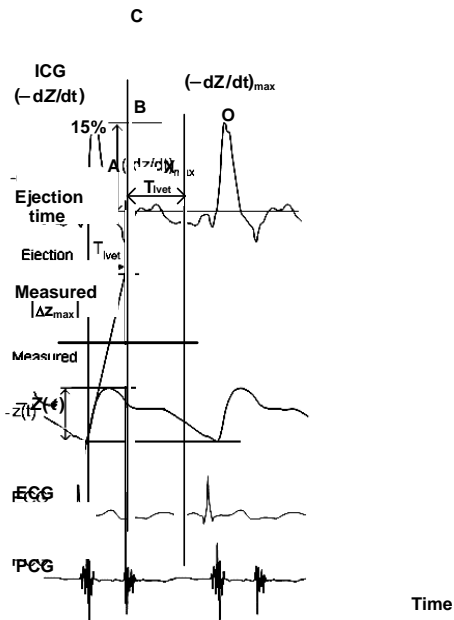


Fig. 1. ICG and other related signals and ICG characteristic points, adapted from [8].

with the main part of the first heart sound. The C point is the peak in ICG and is associated with the maximum acceleration of the blood ejected from the ventricles [14]. The X point corresponds to minimum negative deflection after the C point and coincides with the second heart sound [14]. It is associated with the intra-cardiac fluid inversion [8], [23], [24]. The O point corresponds to the peak positive deflection in ICG after the X point [8] and it is associated with rapid filling of the ventricles during wider opening of the mitral valve [14], [23].

III. SIGNAL PROCESSING

The artifacts in ICG due to respiration, body movements, and other sources lead to errors in detecting its characteristic points, particularly the B and X points [19]. A denoising technique is generally employed to suppress the artifacts. As the spectra of the artifacts related to respiration (0.4 – 2 Hz) and body movements (0.1 – 10 Hz) overlap with that of ICG (0.8 – 20 Hz) [2], it is difficult to suppress the artifacts by filtering. Ensemble averaging, coherent ensemble averaging, filtering, adaptive filtering, and wavelet-based methods have been reported for suppressing the artifacts [2], [3], [9]. Wang *et al.* [25] and Zhang *et al.* [4], as cited in [25], used an ensemble average technique to reduce the disturbances in the ICG. Kim *et al.* [26] and Woltjer *et al.* [24], as cited in [25], reported that an averaging method can effectively suppress the respiratory artifacts in recorded impedance cardiogram. It is to be noted that the disturbing components with zero mean get effectively suppressed by averaging carried out over long time duration. However, ensemble averaging suppresses the beat-to-beat information in the cardiogenic activity due to event latencies and variable shape of ICG signal during respiration [27]. In order to retain the beat-to-beat information, we use a wavelet-based denoising technique with scale dependent thresholding [28] for pre-processing of the ICG signals. It has

been reported to provide SNR improvement of approximately 23 dB for ICG signals contaminated with respiratory artifact. Detection of ICG points is carried out on both the unprocessed and denoised ICG in order to assess the sensitivity of the proposed technique for characteristic point detection to the presence of artifacts.

Several techniques for detection of the ICG characteristic points have been reported without using reference waveforms from other sensors. Threshold-dependent multi-scale wavelet-based techniques [29], [30] were tested on simulated ICG signal with added Gaussian noise. The sensitivity and positive predictivity of the variable threshold dependent multi-scale wavelet-based technique [30] was reported as 99.8%. However, results with their application on clinical recordings are not available. For beat-to-beat changes in cardiac events, Naidu *et al.* [31] reported an automatic technique for beat-to-beat detection of the characteristic points from ICG, using ECG R-peaks as a reference for cycle identification. The R-peaks were detected using Pan-Tompkin algorithm [32] and the characteristic points were detected based on empirically defined time-domain features in ICG during the cardiac cycle. For the detection of C points, the technique showed sensitivity of 99.4% and detection error of 1.8%. The detection errors reported were 11.7% and 6.5% in the detection of the less prominent B and X points respectively. To further improve the performance of the technique as reported in [31], a detailed empirical examination of the ICG signal has been carried out for selecting the time-domain features in the waveform for detecting the characteristic points without a need for adjusting the processing parameters. These features of the clinically important B, C, and X points are used in detecting them.

C point detection: The ICG segment equal to one-third of the R-R interval and starting from the point corresponding to the R peak in ECG is scanned for the point with the highest value. This point is taken as the C point. In case of the condition of double peaking within the selected segment, as occurring in some cardiac patients, the higher peak gets selected as the C point.

B point detection: The ICG segment equal to one-fifth of the C-C interval preceding the C point is scanned for the point with the lowest value and is marked as the valley point. The difference between the values at the C point and the valley point is calculated as the peak-to-peak height H_{pp} . The B point is the deflection or notch preceding the C point and is located by scanning the first difference of the ICG waveform for a change of sign in the interval starting backwards from the point corresponding to $0.32H_{pp}$ below the C point and up to the valley point. In the absence of this change of sign, the B point is located as the point at $0.72H_{pp}$ below the C point.

X point detection: The ICG segment equal to one-third of the C-C interval and starting from the T peak in ECG is scanned for the lowest value and the point is marked as the X point. The peak of the T wave itself is located by scanning the ECG cycle for its peak lying within one-third of the R-R interval starting from the R peak.

The A and O points are not considered as significant for obtaining clinical information on beat-to-beat basis and our method does not detect them.

IV. METHOD OF EVALUATION

Several researchers [33], [34], have reported the use of Doppler echocardiography for beat-to-beat estimation of SV and some other cardiac indices. It can be used as a reference for validation of some of the indices calculated using impedance cardiography. With this objective, recording of ICG and ECG was carried out simultaneously along with Doppler echocardiography.

The recordings were carried out in the clinical setup of a hospital (Hardas Heart Care, Pune), after approval from its Ethics Committee. The informed consent form was read and signed by all the subjects participating in the investigation. The continuous wave Doppler echocardiography recordings were carried out using iE33 Ultrasound System (Philips Ultrasound, Bothell, WA) with ultrasound gel applied for a good contact of the transducer with the chest skin. The left ventricular outflow velocity profile was recorded for further analysis. The ICG, ECG, basal impedance, variation in thoracic impedance, and continuous wave Doppler echocardiogram were simultaneously recorded. The ICG and other related signals were recorded using HIC-2000 Bio-electric Impedance Cardiograph (Bio-Impedance Technology, Chapel Hill, NC) with an excitation current of 1 mA and 100 kHz, impedance waveform calibration of 40 mV/ Ω , and four-electrode configuration with Ag-AgCl disposable ECG electrodes as spot electrodes for current injection as well as voltage sensing. The distance between voltage sensing electrodes was measured. The signals were acquired using the 8-channel 16-bit data acquisition card KUSB-3100 (Keithley, Cleveland, Ohio) at a sampling frequency of 500 Hz.

Detection of the ICG characteristic points has been reported to be difficult during heart rate variability. In order to test the proposed technique under such conditions, an exercise protocol was used to introduce significant beat-to-beat variations. The blood pressure, pulse rate, height, and weight of the subjects were recorded. Doppler gain, wall filter (the cutoff frequency of the high-pass filter used for removing the low frequency components related to heart movements), and the scale factor (the range for the display) were adjusted to optimize the quality of the Doppler recordings. Recordings with poor quality Doppler images were discarded.

Two sets of recordings were made. The first set was from healthy subjects with no past history of cardiovascular diseases and as examined and confirmed by a cardiologist. For these subjects, heart rate variability was introduced by exercise. After recording, the subject was asked to exercise for 10 minutes and the recordings were repeated. Both recordings were made with the subject lying in the left-lateral supine position to facilitate Doppler echocardiography. Further, use of supine position avoided motion artifacts. The second set of recordings was from cardiac patients. These were taken under the resting condition, without any exercise by the subject. The first set of recordings was from six healthy subjects. The second set was from four patients: two having undergone angioplasty, one diagnosed for moderate-to-severe aortic stenosis, and one with suspected mild mitral stenosis.

ICG signals were pre-processed using wavelet-based denoising technique with scale dependent thresholding [28].

Detection of the ICG characteristic points was carried out on both the unprocessed and the denoised ICG. A program was developed for detecting the characteristic points of the input ICG and marking them on waveform, for later visual examination. An example of the simultaneously recorded ICG and ECG with synchronized Doppler echocardiogram frame is shown in Fig. 2.

An evaluation of the automated detection technique was carried out by comparing the detected points with the points marked by visual examination of the waveforms. Detection by the technique of a visually located point was counted as true point (TP). When the technique failed to detect a point as located by visual examination, it was counted as failed detection (FD). When a point detected by the technique did not correspond to a visually detected point, it was counted as misdetection (MD). The following performance indices, similar to those used in [30], were calculated.

$$\text{Sensitivity} = TP / (TP+FD) \quad (1)$$

$$\text{Positive predictivity} = TP / (TP+MD) \quad (2)$$

$$\text{Detection error} = (FD+MD) / (TP+FD) \quad (3)$$

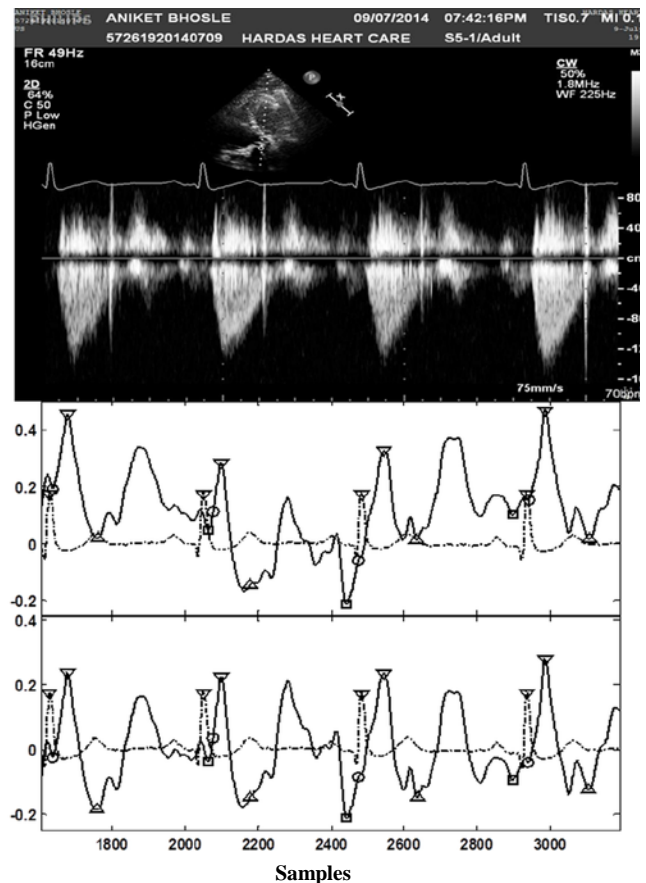


Fig. 2. Simultaneously recorded ICG and ECG (arbitrary vertical scale) with synchronized Doppler echocardiogram frame. Upper trace is the blood velocity profile at LVOT with ECG recorded by the Doppler echocardiograph. The middle trace shows the unprocessed ICG and simultaneously acquired ECG by the impedance cardiograph. The lower trace shows the denoised ICG along with ECG. ICG: solid trace marked with the detected B, C, and X points. ECG: dotted trace marked with R-peaks.

The above performance indices were calculated separately for each of the characteristic points.

As there are no correlates of the B and X points which can be consistently detected in ECG or Doppler echocardiogram, their detection was validated only with reference to visually located points. The C-C interval defines a cardiac cycle and as such it can be compared with peak-to-peak interval of the aortic flow velocity profile. The correspondence is approximate because of variability in the delay between the C point and the peak of aortic velocity profile. A statistical analysis of the closeness of the values of the C-C interval from ICG and the peak-to-peak interval of velocity profile from Doppler echocardiography was carried out by calculating the mean error, RMS error, and correlation coefficient.

V. RESULTS

The technique was evaluated by applying it on a total of 447 cardiac cycles in the recordings from six healthy subjects and four cardiac patients. Example of the detection of ICG points is shown in Fig. 3. The results show excellent match with visually marked points in the unprocessed and in the denoised signals. A qualitative visual examination of the automatically detected points across the recordings showed a very small number of errors. A quantitative evaluation was carried out by calculating the performance indices as given in (1) – (3). The values of the indices for the detection of the B, C, and X points, in the unprocessed as well as the denoised waveforms, are given in Table I. For detection of the C point, the technique showed excellent sensitivity (99.5%) and very low detection error (1.0%) in the unprocessed as well as the denoised signals. Detection errors of relatively less distinct B and X points, significantly reduced in this modified automated detection technique compared to the earlier reported in [31].

TABLE I. EVALUATION INDICES (%) FOR DETECTION OF CHARACTERISTIC POINTS. SENS.: SENSITIVITY, POS. PRED.: POSITIVE PREDICTIVITY, DET. ERROR: DETECTION ERROR

ICG Point	Unprocessed ICG			Denoised ICG		
	Sens.	Pos. pred.	Det. error	Sens.	Pos. pred.	Det. error
B	98.5	98.5	2.9	99.0	99.0	1.9
C	99.5	99.5	1.0	99.5	99.5	1.0
X	98.5	98.5	2.9	99.0	99.0	1.9

The results for the unprocessed ICG and the denoised ICG were almost similar.

Agreement of the cardiac cycles as detected from ICG with those detected from Doppler echocardiography was examined by a statistical analysis. The values of mean error, RMS error, and correlation coefficient are given in Table II for the healthy subjects and in Table III for the cardiac patients. It is seen that the mean errors (indicating the estimation bias) are very small as compared to the mean values of the intervals and the standard deviation of the errors are smaller than or comparable to the standard deviations of the intervals for all subjects. The correlation coefficients between the C-C intervals from ICG and the peak-to-peak intervals of the aortic flow velocity profile from Doppler echocardiography are high and statistically significant ($p < 0.0001$) for all the healthy subjects in both pre-exercise and post-exercise conditions and also for the cardiac patients. For the cycles from all the subjects concatenated together, the correlation coefficients are 0.98 and 0.98 for healthy subjects and cardiac patients, respectively. These results show that the C-point detection technique works satisfactorily for beat-to-beat estimation under conditions of significant heart rate variability.

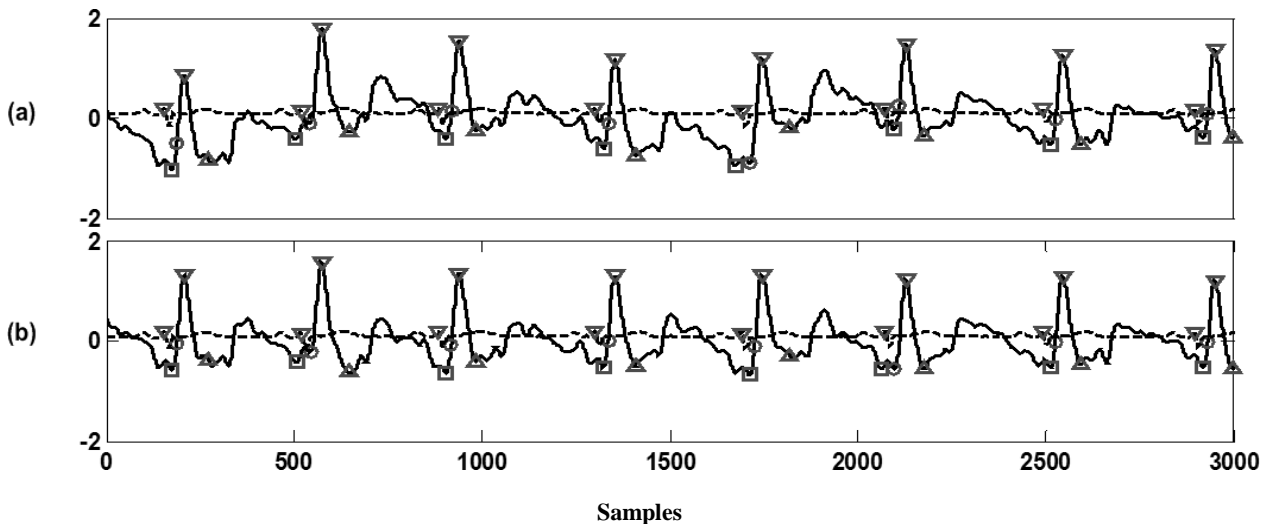


Fig. 3. Detection of the B, C, and X points in ICG recorded from a patient under resting condition: (a) unprocessed ICG and (b) denoised ICG.

TABLE II. COMPARISON OF ICG AND DOPPLER ECHOCARDIOGRAPHY (DE) RESULTS FOR HEALTHY SUBJECTS: MEANS AND STANDARD DEVIATIONS (SD) OF DE VELOCITY PROFILE PEAK-TO-PEAK INTERVALS, ECG R-R INTERVALS, ICG C-C INTERVALS. STATISTICAL MEASURES COMPARING C-C INTERVALS WITH DE PEAK-TO-PEAK INTERVALS: MEAN ERROR ($\bar{\epsilon}$), RMS ERROR (σ_{ϵ}), CORRELATION COEFFICIENT (r).

Subject (age)	Condition, No. of cycles	Mean(ms)			SD (ms)			DE-CC Comparison		
		DE	RR	CC	DE	RR	CC	$\bar{\epsilon}$ (ms)	σ_{ϵ} (ms)	r
AK (18)	Pre.-ex., 19	865	877	877	49	49	48	-12.0	25.2	0.87
	Post-ex., 24	712	715	715	22	17	16	-3.2	19.6	0.91
GS (23)	Pre.-ex., 19	706	708	707	36	31	31	4.1	16.6	0.79
	Post-ex., 26	570	572	570	11	9	14	-2.7	7.7	0.78
JR (24)	Pre.-ex., 57	843	846	848	45	44	41	-4.2	18.9	0.92
	Post-ex., 89	602	590	588	16	29	31	2.3	22.5	0.82
KP (24)	Pre.-ex., 79	869	873	873	17	17	17	-0.5	20.2	0.88
	Post-ex., 93	756	758	759	16	14	13	-2.2	9.7	0.81
MD (26)	Pre.-ex., 20	867	869	869	31	28	30	-1.3	17.3	0.84
	Post-ex., 16	708	704	703	26	38	37	5.3	23.0	0.84
SA (26)	Pre.-ex., 68	763	770	770	53	56	57	7.2	25.5	0.90
	Post-ex., 74	663	663	663	18	11	11	-0.3	18.7	0.86
All	Pre.-ex., 262	807	814	814	66	62	62	-6.5	2.6	0.98
	Post.-ex., 322	677	676	676	73	76	77	1.7	1.3	0.97

TABLE III. COMPARISON OF ICG AND DOPPLER ECHOCARDIOGRAPHY (DE) RESULTS FOR CARDIAC PATIENTS: MEANS AND STANDARD DEVIATIONS (SD) OF DE VELOCITY PROFILE PEAK-TO-PEAK INTERVALS, ECG R-R INTERVALS, ICG C-C INTERVALS. STATISTICAL MEASURES COMPARING C-C INTERVALS WITH DE PEAK-TO-PEAK INTERVALS: MEAN ERROR ($\bar{\epsilon}$), RMS ERROR (σ_{ϵ}), CORRELATION COEFFICIENT (r).

Subject (age)	Condition, No. of cycles	Mean (ms)			SD (ms)			DE-CC Comparison		
		DE	RR	CC	DE	RR	CC	$\bar{\epsilon}$ (ms)	σ_{ϵ} (ms)	r
AB (30)	Rest, 41	867	865	865	34	35	36	2.0	15.7	0.84
DS (54)	Rest, 64	704	703	703	9	6	8	1.6	7.1	0.77
GK (48)	Rest, 40	893	891	891	21	24	22	2.2	28.2	0.87
SD (53)	Rest, 56	811	808	810	47	47	45	3.0	7.7	0.99
All	Rest, 201	805	803	803	81	81	81	2.3	15.3	0.98

VI. CONCLUSION

A modified, time-domain technique for automatic detection of B, C, and X points in the ICG waveform has been presented. It works well in the presence of baseline drift and does not require selection of the processing parameters. Use of the technique on pre-exercise and post-exercise recordings from healthy subjects and cardiac patients showed that the points were detected with a high sensitivity, with a low detection error, with very similar results for the unprocessed and the denoised ICG waveforms. Statistical analysis of the measurements made from the detected C points by using the automatic detection technique showed good agreement with those obtained from the Doppler echocardiography. It needs to be further evaluated on recordings from a larger number of healthy subjects and patients. Further evaluation by using the detected points in estimation of SV and other cardiac indices also needs to be carried out.

REFERENCES

- [1] W. G. Kubicek, J. N. Karnegis, R. P. Patterson, D. A. Witsoe, and R. H. Mattson, "Development and evaluation of an impedance cardiac output system," *Aerosp. Med.*, vol. 37(12), pp. 1208–1212, 1966.
- [2] V. K. Pandey and P. C. Pandey, "Cancellation of respiratory artifact in impedance cardiography," in *Proc. 27th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Shanghai, China, 2005, pp. 5503–5506.
- [3] V. K. Pandey, "Suppression of artifacts in impedance cardiography," Ph.D. Thesis, Biomedical Engineering, Indian Institute of Technology Bombay, Mumbai, India, 2009.
- [4] Y. J. Zhang, M. H. Qu, J. G. Webster, W. J. Tompkins, B. A. Ward, and D. R. Jr. Bassett, "Cardiac output monitoring by impedance cardiography during treadmill exercise," *IEEE Trans. Biomed. Eng.*, vol. 33(11), pp. 1037–1042, 1986.
- [5] M. H. Qu, Y. J. Zhang, J. G. Webster, and W. J. Tompkins, "Motion artifacts from spot and band electrodes during impedance cardiography," *IEEE Trans. Biomed. Eng.*, vol. 33, pp. 1029–1036, 1986.
- [6] W. G. Kubicek, "On the source of peak first derivative (dz/dt) during impedance cardiography," *Ann. Biomed. Eng.*, vol. 17(5), pp. 459–462, 1989.
- [7] B. E. Hurwitz, L. Y. Shyu, S. P. Reddy, N. Schneiderman, and J. H. Nagel, "Coherent ensemble averaging technique for impedance cardiography," in *Proc. 3rd Annu. IEEE Symp. Comput. Based Med. Syst.*, Chapel Hill, NC, 1990, pp. 228–235.
- [8] R. P. Patterson, "Fundamentals of impedance cardiography," *IEEE Eng. Med. Biol. Mag.*, vol. 8(1), pp. 35–38, 1989.
- [9] L. Y. Shyu, S. P. Reddy, J. H. Nagel, and N. Schneiderman, "New signal processing techniques for improved reliability of impedance cardiography," in *Proc. 10th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, New Orleans, LA, 1989, vol. 1, pp. 41–42.
- [10] P. B. Barde, G. D. Gindal, R. Singh, and K. K. Deepak, "New method of electrode placement for determination of cardiac output using impedance cardiography," *Indian J. Physiol. Pharmacol.*, vol. 50(3), pp. 234–240, 2006.
- [11] X. Wang, H. H. Sun, M. Joseph, V. D. Water, and D. Adamson, "Impedance cardiography in critical-care monitoring," in *Proc. 11th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Seattle, WA, 1989, pp. 1549–1550.
- [12] J. A. McFetridge-Durdle, F. S. Routledge, M. J. Parry, C. R. Dean, and B. Tucker, "Ambulatory impedance cardiography in hypertension: a validation study," *Eur. J. Cardiovasc. Nurs.*, vol. 7(3), pp. 204–213, 2008.
- [13] H. H. Woltjer, B. W. G. J. Arntzen, H. J. Bogaard, and P. M. de Vries, "Optimalisation of the spot electrode array in impedance cardiography," *Med. Biol. Eng. Comput.*, vol. 34(1), pp. 84–87, 1996.
- [14] D. W. Kim, "Detection of physiological events by impedance," *Yonsei Med. J.*, vol. 30(1), pp. 1–11, 1989.
- [15] H. Zang and J. K. Li, "Noninvasive monitoring of transient cardiac changes with impedance cardiography," *Cardiovasc. Eng.*, vol. 8, pp. 225–231, 2008.
- [16] A. Nowakowski, T. Palko, and J. Wtorek, "Advances in electrocardiographic methods in medical diagnostics," *Bull. Polish Acad. Sci., Tech. Sc.*, vol. 53(3), pp. 231–243, 2005.
- [17] M. Y. M. Wong, E. Pickwell-Macpherson, and Y. T. Zhang, "Impedance cardiography for cuffless and non-invasive measurement of systolic blood pressure," in *Proc. 31st Annu. Int. Conf. Eng. Med. Biol. Soc.*, Minneapolis, MN, 2009, pp. 800–802.
- [18] Z. Lababidi, D. A. Ehmke, R. E. Durnin, P. E. Leaverton, and R. M. Lauer, "The first derivative thoracic impedance cardiogram," *Circulation*, vol. 41(4), pp. 651–658, 1970.
- [19] T. Ono, M. Miyamura, Y. Tasuda, T. Ito, T. Saito, T. Ishiguro, M. Yoshizawa, and T. Yambe, "Beat-to-beat evaluation of systolic time intervals during bicycle exercise using impedance cardiography," *Tohoku J. Exp. Med.*, vol. 203(1), pp. 17–29, 2004.
- [20] K. Takada, T. Fujinami, K. Senda, K. Nakayama, and S. Nakano, "Clinical study of A-waves (atrial wave) in impedance cardiograms," *Am. Heart J.*, vol. 94(6), pp. 710–717, 1977.
- [21] R. L. Summers, W. C. Shoemaker, W. F. Peacock, D. S. Ander, and T. G. Coleman, "Bench to bedside: electrophysiologic and clinical principles of noninvasive hemodynamic monitoring using impedance cardiography," *Acad. Emerg. Med.*, vol. 10(6), pp. 669–680, 2003.
- [22] T. Sodolski and A. Kutarski, "Impedance cardiography: a valuable method of evaluation of hemodynamic parameters," *Cardiol. J.*, vol. 14(2), pp. 115–126, 2007.
- [23] H. J. Keim, J. M. Wallace, H. Thurston, D. B. Case, J. I. Drayer, and J. H. Laragh, "Impedance cardiography for determination of stroke index," *J. Appl. Physiol.* vol. 47(5.1), pp. 797–809, 1976.
- [24] J. Bour and J. Kellett, "Impedance cardiography: a rapid and cost effective screening tool for cardiac diseases," *Eur. J. Intern. Med.*, vol. 19(6), pp. 399–405, 2008.
- [25] A. Krivoshei, "Bio-impedance signal decomposer: enhanced accuracy and reduced latency solution," *Estonian J. Eng.*, vol. 17(3), pp. 201–219, 2011.
- [26] D. W. Kim, C. G. Song, and M. H. Lee, "A new ensemble averaging technique in impedance cardiography for estimation of stroke volume during treadmill exercise," *Front. Med. Biol. Eng.*, vol. 4(3), pp. 179–188, 1992.
- [27] S. B. Raza, R. P. Patterson, and L. Wang, "Filtering respiration and low-frequency movement artefacts from the cardiogenic electrical impedance signal," *Med. Biol. Eng. Comput.* vol. 30(5), pp. 556–561, 1992.
- [28] V. K. Pandey and P. C. Pandey, "Wavelet based cancellation of respiratory artifacts in impedance cardiography," in *Proc. 15th Int. Conf. Digital Signal Processing*, Cardiff, Wales, UK, 2007, pp. 191–194.
- [29] Y. Shyu, Y. S. Lin, C. P. Liu, and W. C. Hu, "The detection of impedance cardiogram characteristic points using wavelet transform," *Comput. Biol. Med.*, vol. 34(2), pp. 165–175, 2004.
- [30] M. Rizzi, M. D' Aloia, B. Castagnolo, "High sensitivity and noise immune method to detect impedance cardiography characteristic points using wavelet transform," *J. Applied Science*, vol. 9(8), pp. 1412–1421, 2009.
- [31] S. M. M. Naidu, P. C. Pandey, and V. K. Pandey, "Automatic detection of characteristic points in impedance cardiogram," in *Proc. Comput. Cardiol.*, Hangzhou, China, 2011, pp. 497–500.
- [32] J. Pan, W. J. Tompkins, "A real-time QRS detection algorithm," *IEEE Trans. Biomed. Eng.*, vol. 32(3), pp. 230–236, 1985.
- [33] D. B. Northridge, I. N. Findlay, J. Wilson, E. Henderson, and H. J. Dargie, "Noninvasive determination of cardiac output by Doppler echocardiography and electrical bioimpedance," *Br. Heart J.*, vol. 63(2), pp. 93–97, 1990.
- [34] D. Arora, R. Chand, Y. Mehta, and N. Trehan, "Cardiac output estimation after off-pump coronary artery bypass: a comparison of two different techniques," *Ann. Card. Anaesth.*, vol. 10(2), pp. 132–136, 2007.