ROBUST CHARACTERISTIC POINTS FOR ICG
Definition and Comparative Analysis

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Abstract: The impedance cardiogram (ICG) is a promising tool for non-invasive and cost effective assessment of the hemodynamic state, especially in low acuity and home settings. Important diagnostic parameters are related to characteristic points within the ICG, i.e. the B and the X points that are assumed to mark the opening and closure of the aortic valve., respectively. Based on synchronized echocardiography-ICG data obtained from healthy subjects at rest, we compare 4 existing alternatives for the ICG's characteristic point definitions associated detection algorithms. We show that those points exhibit considerable biases with respect to the intended onsets of the systole and diastole compared to the Echocardiography Goldstandard. We introduce a new approach to determine these characteristic points based on the analysis of the ICG morphology. For its implementation a computationally simple algorithm, based on high order derivatives, is proposed. This algorithm is evaluated using simultaneously recorded echocardiographies and ICG signals. The achieved results show that the proposed method enables the identification of the main characteristic points, B and X, with significantly smaller errors and much higher correlations compared to current state of the art methods and existing alternative characteristic point definitions.

1 INTRODUCTION

The impedance cardiogram (ICG) is one of the reference methods for portable devices in assessing several key hemodynamic descriptors, such as the systolic time intervals (STI) and the cardiac output (CO). This measurement principle is based on the measurement of the thorax impedance variations (dZ/dt) that are influenced by airflow through the lungs, blood flow from the left ventricle to the aorta and lung perfusion. It is able to track the relative changes of stroke volume (SV) in healthy subjects and patients without valve diseases Gotshall *et al.* (1989). The assessment of the systolic time intervals
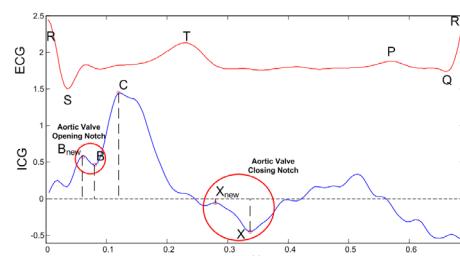

Figure1: Definition of characteristic points for aortic valve events in the Impedance Cardiogram. Points *B* and *X* are the traditional definitions for opening and closing events of the aortic valve. B_{new} and X_{new} correspond to the proposed definitions. Signal notches related to the opening and closing of the aortic valve are shown in circles.
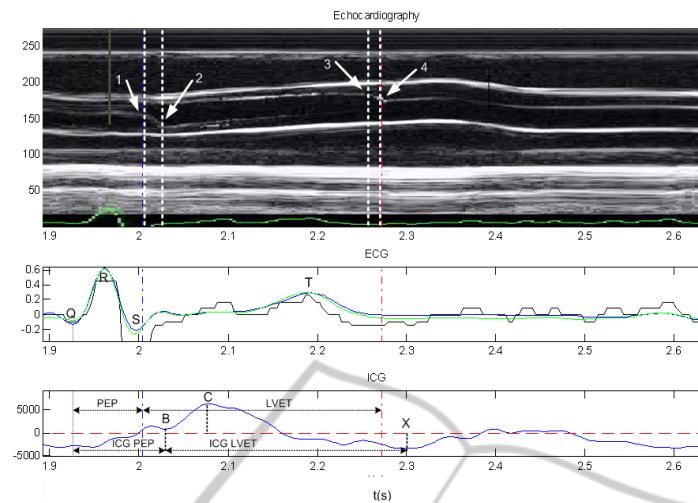
Figure2: Relationship between ICG characteristic points and aortic valve cusps movements. (top) Echocardiography M-mode; points 1 and 2, respectively, indicate the onset and the end of the movement of the aortic cusps during the opening movement of the valve; points 3 and 4, respectively indicate the onset and the end of the aortic cusps during the closing movement. (middle) ECGs captured by the different measurement modalities after synchronization. (bottom) Synchronized ICG signal with the echo.
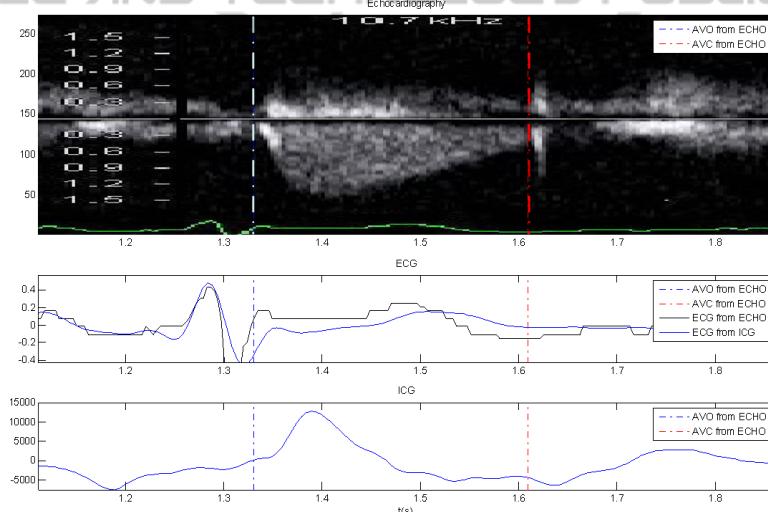

Figure 3: Relationship between blood ejection through the aortic valve and the ICG characteristic points. AVO and AVC represent aortic valve opening and closure, respectively. (top) Echocardiography Doppler-mode. (middle) ECGs captured by the different measurement modalities after synchronization. (bottom) Synchronized ICG signal with the Doppler Echo (top image).

as well as SV from ICG require the determination of the ICG's characteristic points, which are assumed to be correlated to the opening and closing of the aortic valve. The rationale in using ICG to measure the systolic time intervals is the assumptions that the notches of the dZ/dt signal (see fig. 1) are due to conduction changes of blood caused by changes in orientation of erythrocytes (Visser *et al.*, 1993) that can be directly related to the opening and closing events of the aortic valve. Namely, the so-called B

and X points are assumed to mark, respectively, the opening and the closing of the aortic valve. Using these reference ICG points, it is observed that the pre-ejection period (PEP) is defined by the time interval between the ECG's Q-peak and the ICG's B point, while the left ventricle ejection time (LVET) is defined as the time interval between the characteristic points B and X (see fig. 2).

As can be observed in fig. 1, the most common definitions of the B and X points assume that the B

point corresponds to the local minimum of the notch to the left of point C, while the X point corresponds to the time instant where the lowest ICG value occurs during the negative ICG signal section, to the right of the C point. Using synchronized echocardiography (clinical gold standard) with ICG (see fig. 2) suggests that the traditional definitions of B and X points do not correlate well to the exact opening and closing instants of the aortic valve, respectively. In fact, as was observed by Shyu *et al.* (2004) using pressure-volume (PV) loops, the X-point tends to occur substantially later than the E-point of the PV loop, which marks the closing of the aortic valve. The multi-modal graphical data provided by several authors (e.g. (Wang *et al.*, 1995)) seem to suggest that the ICG's B-point occurs after the onset of the opening movement of the aortic valve cusps. It should also be mentioned that some authors (e.g. (Reddy *et al.*, 1988), (Visser *et al.*, 1993), (Visser *et al.*, 1991)) define the onset of the aortic valve opening event at the zero-crossing point of dZ/dt prior to point C (variants exist where these points are measured at certain distances from this reference).

There have been several efforts to automate the detection of the ICG's characteristic points. Several algorithms rely on ensemble averaging to overcome artifacts in the ICG signal (Nagel *et al.*, 1986) related to baseline drift caused by respiration and movement artifacts. Because of heart rate variability, this technique tends to blur less distinctive events (particularly the B-point) making their detection more difficult. On the other hand, it comes at the expense of beat-to-beat variations, since ensemble averaging filters these out. In order to overcome these limitations, many authors suggest the use of filtering and adaptive thresholding techniques. Wang *et al.* (1995) use the spectrogram in different frequency regions to extract a salience measure of the characteristic points. A review on salience measure-based methods is reported in (Pandey and Pandey, 2005). Other authors exploit the wavelet transform (WT). The advantage of WT is that it decomposes the signal into different frequency bands or scales, while preserving and characterizing the regularities of the signal in those scales. Shyu *et al.* (2004) and Shuguang *et al.* (2005) explored the zero-crossings and local extremes to find the characteristic points in ICG in a particular scale.

In this paper we introduce a new definition for the characteristic points in ICG and an algorithm for their detection using a computationally simple and efficient method based on high order derivatives.

The basis for this new definition of the ICG's characteristic points is described in section 2.1. The details of the algorithm are introduced in section 2.2. A performance comparison with respect to the current clinical gold standard – the echocardiography – using state-of-the-art characteristic point definitions and detection methods and a commercial system is provided in section 3. Finally, in section 4, some main conclusions are presented and discussed.

2 METHODS

2.1 Characteristic Point Definition

There is evidence that the characteristic points considered in literature for ICG correspond only approximately to the events used to mark the systole and the diastole phases of the cardiac cycle, i.e. the movements of the aortic valve cusps. Heart valve movements are not instantaneous, but rather transitory processes that have their intrinsic dynamic. This is perfectly visible in fig. 2, where the ICG signal has been co-registered with an M-mode echocardiography of the aortic valve that enables to trace the aortic valve cusps movements. As can be observed, the opening movement of the aortic cusps is located at the notch of the ICG, to the left of point C. As depicted in fig. 1, this notch corresponds to a relatively large region of the ICG. The traditional definition of the B-point is at the base of the notch (see fig. 1 and fig. 2). However, from fig. 2 it is seen that physiologically this point does mark neither the onset nor the end of the cusps movement during its opening dynamics at the beginning of the systole. Synchronized ICG-echocardiographies suggest that these events occur earlier in time and tend to correspond, respectively, to the inflection point of the ICG curve, to the left of the maximum of the notch, and to a point near the notch's maximum.

To overcome the uncertainty induced by the dynamics of the cusps during the opening and closing of the aortic valve, the left ventricle blood ejection lobe is usually applied as a reference in clinical practice, which is measured using echocardiography in Doppler mode. Fig. 3 depicts the blood ejection lobe through the aortic valve measured using the echo-Doppler principle and co-registered with the ICG signal. As can be observed, the onset of the ejection lobe tends to be localized immediately before the ICG notch's maximum, i.e., an event that occurs noticeably earlier than the

classical B-point definition. This is the reference for the B point proposed in this paper (see point B_{new} in fig. 1).

Regarding the onset of the diastole phase of the heart cycle, a similar condition is observed. In ICG literature, the X-point is defined as the point that corresponds to the lowest ICG value of the first negative ICG signal section to the right of the C-Point. Using pressure-volume loops obtained through invasive measurement, Shyu *et al.* (2004) have noticed that this point typically occurs between 10ms and 50ms after the onset of the diastole. This is in accordance with the synchronized echocardiography-ICG measurements performed during this work. As can be observed in fig. 2, the onset of the aortic cusps closing movement tends to correspond to the local ICG maximum/start of the negative slope to the left of the X-point, while the end of the cusps movement is typically related to the ICG's inflexion point located between the mentioned maximum and the X-point. Not surprisingly, using the echo-Doppler echocardiographies (see fig. 3), it is observed that the end of the left ventricle ejection lobe corresponds to a point between the two aforementioned points. In this paper, the X-point will be assumed to be the onset of the descending part of the notch, to the left of the traditional X-point (see point X_{new} in fig. 1).

2.2 Characteristic Points Detection

Three main steps that target, respectively, the detection of the C, B and the X points of the signal form the proposed algorithm for ICG characteristic point detection using the definition proposed in the previous section. The algorithm operates on a beat-by-beat basis. For simplicity, it will be assumed that
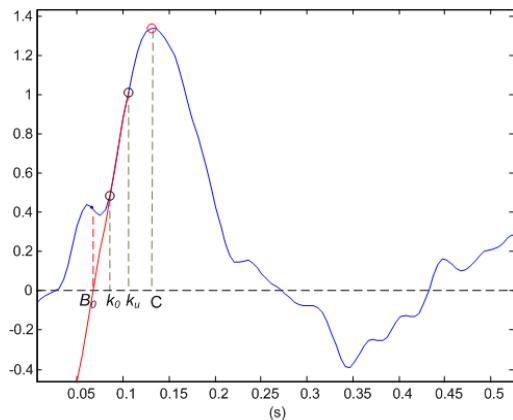

Figure 4: Illustration of the initial B0 estimation technique (vertical axis arbitrary scaled).
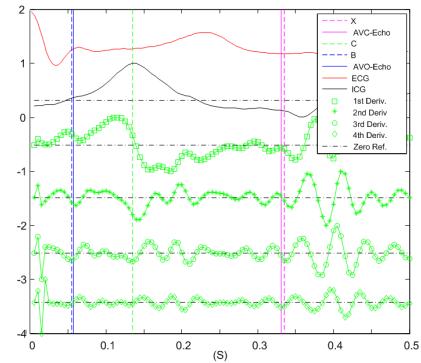

Figure 5: Illustration of B and X point detection method using high-order derivatives in an ICG signal with a subtle B-point notch. AVO-Echo and AVC-Echo define, respectively, the detected aortic valve opening and closing moments using echocardiography. Dashed vertical markers define B, X and C points detected using the described approach. Signals are arbitrarily scaled and translated.

the ICG signal included between two consecutive ECG R-peaks or Q-peaks is fed into the algorithm. The C-point corresponds to the most prominent component of the ICG and can be readily detected as the time instant where the maximum value of the ICG signal occurs.

The B-point is usually defined at the base of the notch to the left of the C-point (see fig. 1 and fig. 2). Regarding the notch, it is observed that it is not always well defined and, in many cases, is completely absent from the ICG signal. Therefore, the method proposed here first estimates the base of the notch (*Bo*). In a second phase the method verifies if a notch is present in the ICG signal under analysis. If a notch type salience is found in the ICG, the top of the notch is searched; otherwise the estimated base is adjusted according to the signal's morphology. The processing steps involve the computation of high-order derivatives, which amplify high frequency noise. In order to minimize high-frequency noise interference, in the proposed approach the impedance signal is low-pass filtered using a Butterworth filter with a cut-off frequency of 100Hz. This is motivated by the fact that a typical ICG signal exhibits spectral components up to this frequency range (Wang *et al.*, 1995). Zero-phase filtering is implemented, which involves filtering the signal in both the forward and backward directions, to eliminate phase distortion. The following steps form the actual procedure:

Step 1: In this step, a first estimate of the notch's base is performed using an adaptation of the procedure described by Onu *et al.* (2004). The first estimate of the B-point, *Bo*, is illustrated in fig. 4. It is obtained based on the intersection of the line fit of

the ICG points between 40% ($icg(Ko)$) and 80% ($icg(Ku)$) of the amplitude of point C with the horizontal axis (see fig. 4). In order to avoid underestimating Bo, its value is limited based on the physiological observation that the aortic valve opening typically occurs 30ms after the atria-ventricular (AV) valve closing (Tavel, 1967). As an approximate reference for the AV closing instant, the ECG's R-peak can be applied.

Step 2: This step is to check the existence of a detectable notch. In order to detect the presence of the notch, the method resorts to the second derivative of the ICG signal. Using the backward discrete derivative definition, the existence of a notch should lead to a (+,-,+,-) sign pattern of the second derivative to the left of the C-Point. If this second derivative sign pattern is found, then one might assume that a notch exists in the ICG signal. In this situation the B-point is defined by the first minimum of the 3rd derivative to the left of Bo. The use of this procedure enables the correct detection of the aortic valve opening moment for well-defined as well as for subtle notches (see fig. 5). For subtle notches, it is observed that there is no clear 1st derivative zero that can be applied to identify the top of the notch. The 2nd derivative is always negative due to the concavity of the notch's region around the local maximum; hence it is not straightforward to apply it directly for the notch's top identification task. However, the intended point corresponds to the minimum acceleration of the 1st derivative, i.e. a minimum of the 3rd derivative (see fig. 5). A similar approach has been followed by Chan *et al.* (2007) to identify characteristic points in the dichrotic notch of a Photoplethysmogram. If no sign pattern in the second derivative is detected, then no detectable notch exists. In this case, the B-point is assumed to be the first zero-crossing of the first derivative of the ICG to the left of Bo.

The third important event to be detected in the ICG is the X-point. In a well-defined ICG signal, it is observed that, using the traditional definition, the X-point corresponds to the lowest ICG value of the first negative ICG signal section to the right of the C-Point. In practice, due to noise and respiration artifacts, this might not be the case. Physiologically, it is observed that the T-wave of the ECG corresponds to the relaxation of the ventricles of the heart. Hence, the closing of the aortic valve is usually observed near the end of the T-wave. As a first estimate of the X-point, X_0, the lowest ICG negative minimum is taken in the interval

$RT \leq t \leq 1.75RT$, where RT represents the duration of the R-T ECG segment. As can be observed in fig. 2 and fig. 3, the actual closing of the aortic valve tends to be localized near the top of the first local ICG maximum to the left of X_0. This point can be readily detected both in well-defined and in less well-defined ICG signals using the local minimum of the 3rd derivative of the ICG to the left of X_0. The basis for using the 3rd derivative in this context is the same as for B point detection.

3 RESULTS AND DISCUSSION

17 volunteer students at the Centro Hospitalar de Coimbra have been asked to participate in the data collection study aimed at the simultaneous collection of ICG (a Niccomo device from Medis® was applied) and echocardiography (Siemens® Acuson CV70 device). A synchronous ECG with each of the above signals was also acquired and served as a reference signal for co-registration. The population was not balanced for gender (14 male and 3 female). The average heart rate during data collection was 72.94 ± 9.87 bpm. All subjects involved in this study did not have any known congenital or other heart disease. Regarding the main biometric characteristics of the population, they exhibited average age of 22.53 ± 3.81 years and average body mass index of 23.27 ± 2.15 Kg/m^2.

Table 1 and table 2 present the comparative analysis of the achieved results for B and X points detection, respectively, using five different methods on the common database. The database is composed by 564 heart beats with annotated aortic valve opening and 358 beats with annotated aortic valve closing moments using echocardiography as reference. Regarding the echocardiography mode, 213 beats were annotated in M-mode and 351 beats resorted to Doppler-mode. Values shown in table and table 2 have been found to be statistically relevant ($p<0.001$) using the Wilcoxon test (Gaussianity was assessed using the Kolmogorov-Smirnov test).

As can be observed, using echocardiography as reference, it is clear that the classical definitions of the systolic events in the ICG signal, i.e. the *B* and the *X* points, do not capture adequately the actual physiological opening and closing events of the aortic valve. In fact, all of the conventional ICG characteristic point identification methods exhibit significant biases with respect to the echocardiography reference in detecting both events.

Furthermore, it is observed that these biases differ substantially, leading to significant over or underestimations of PEP and LVET. This is clearly shown in table 3 where the impact on LVET estimation is summarized for all the considered methods. It should be observed that the statistics on PEP estimation are the same as the ones reported for point B (see table 1), given the definition of this systolic time interval.

From table 1 it is seen that Onu's algorithm (Onu *et al.*, 2004) is the most stable method in detecting the B-point using its classical definition. It exhibits the highest correlation with respect to the aortic valve opening and the lowest standard deviation of the error among the classical methods. Comparing the results achieved by this method in detecting the B and the X points, it is seen that the B point is measured with an average bias of 19.9 ms, while the X point exhibits a measurement bias of 34.6 ms (see table 2), hence, as is shown in table 3, these biases will not cancel out during LVET computation which is required for stroke volume assessment.

Table 1: Comparative analysis of beat-to-beat B point detection results with respect to echocardiography. Average error is defined by the average of $B-B_{Echo}$. The average absolute error is defined by the average of $|B-B_{Echo}|$, whereas SD is the standard deviation of $|B-B_{Echo}|$. All reported error and SD values are in *ms*. (*) Niccomo ICG device from Medis®. (**) Spearman Correlation (p<0.001).

	Proposed Method	Shyu *et al.*	Onu *et al.*	Nic*	Zero-Crossing
Av. Er.	5.8	11.4	16.5	9.8	-7.2
Av. Abs. Er.	12.4	21.1	19.9	19.3	23.96
SD	8.7	12.8	12.5	13.4	17.2
Correlation**	0.54	0.50	0.70	0.53	0.39

Table 2: Comparative analysis of beat-to-beat X point detection results with respect to echocardiography. Average error is defined by the average of $X-X_{Echo}$. The average absolute error is defined by the average of $|X-X_{Echo}|$, whereas SD is the standard deviation of $|X-X_{Echo}|$. All reported error and SD values are in *ms*. (*) Niccomo ICG device from Medis®. (**) Spearman correlation (p<0.001). (***) Pearson correlation (p<0.001).

	Proposed Method	Shyu *et al.*	Onu *et al.*	Nic*
Av. Er.	29.3	-59.9	14.2	-39.5
Av. Abs. Er.	32.2	61.9	34.6	44.1
SD	25.0	38.0	22.3	37.3
Correlation**	0.44	0.15	0.16***	0.22

Table 3: Comparative analysis of beat-to-beat LVET detection results with respect to echocardiography reference. The average absolute error is defined by the average of $|LVET-LVET_{Echo}|$, whereas SD is the standard deviation of $|LVET-LVET_{Echo}|$. All reported error and SD values are in *ms*. (*) Niccomo ICG device from Medis®. (**) (p<0.001).

	Proposed Method	Shyu *et al.*	Onu *et al.*	Nic*
Av. Abs. Er.	34.8	73.7	38.6	54.0
SD	38.0	43.3	24.4	41.8
Correlation**	0.36	0.05	0.14	0.33

As can be observed in table 1 and table 2, the aforementioned biases are significantly reduced using the new definitions proposed in this work for the B and X points. Regarding B-point identification, the proposed method achieves the smallest and most stable estimation errors among all algorithms, i.e. an absolute error of 12.4± 8.7 ms is obtained. This is 35.8% smaller compared to the smallest estimation error achieved by any of the remaining classical methods. Furthermore, as is depicted in fig. 6 (top),
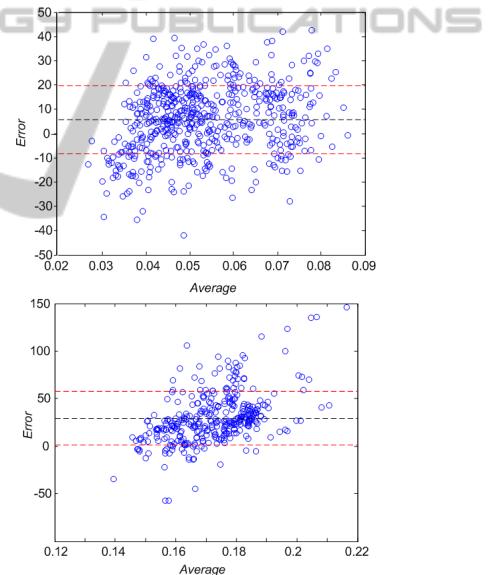

Figure 6: Bland-Altman bias plots of the estimated beat-to-beat B and X points with respect to the opening and closing of the aortic valve measured with echocardiography. Horizontal dashed lines represent mean error and mean error ± standard deviation of error, respectively. (*top*) B error distribution. Horizontal axis is defined by (RB+RAVO)/2, where RB and RAVO define, respectively, the time interval between the ECG's R-peak and the estimated B point, and the R-peak and the measured aortic valve opening moment. (*bottom*) X error distribution. Horizontal axis is defined by (RX+RAVC)/2, where RX and RAVC define, respectively, the time interval between the ECG's R-peak and the estimated X point, and the R-peak and the measured aortic valve closing moment.

the estimation error dispersion is not dependent on the actual value of B; it distributes evenly for a large range of B durations. Regarding the correlation coefficient, it is observed that the new method exhibits a smaller correlation compared to Onu's algorithm (0.54 vs. 0.70), although the dispersion of the estimations is significantly smaller for the new method. The reason for this is due to the fact that the ICG B-point notch is not always well defined or present in the signal. For Onu's method this is not very significant, since it does not rely on the notch to detect the B point (the reason for the performance of Niccomo's algorithm is unknown). Another reason for this lower correlation is noise. High-order derivatives are high-pass filters, which amplify high-frequency noise.

Regarding the definition of a marker for the detection of the onset of the aortic valve opening event, it is observed that the worst results were achieved using the zero-crossing principle. It exhibits a significantly larger absolute error as well as dispersion compared to the other marker definitions considered. This is due to the fact that (i) it is known that the zero line may change as a function of respiration (Reddy *et al.*, 1988) and (ii) the zero-crossing points tends to occur before the notch induced by the aortic valve opening event. In some situations this might induce that no zero-crossing exists in the *dZ/dt* signal between the ECG's R-peak and the C-point in the ICG.

Regarding the detection of the X point, which relates to the closing of the aortic valve, it is observed from the inspection of the results reported in table 2 that the identification errors are significantly higher for all methods compared to the performance achieved for B point detection. The reason for this is linked to the fact that typical ICG signals exhibit many minima to the right of the C-point. In many circumstances these minima are very similar in amplitude and, therefore, are very prone to noise interference. Nevertheless, it is seen that the proposed method has the lowest estimation error (32.2 ms) and the highest correlation (0.44) with respect to the annotated echocardiography. These results clearly show that the traditional definition of the X point does not correlate well to the closing of the aortic valve and that the proposed definition and algorithm significantly improves the estimation of the aortic valve closing moment. Moreover, fig. 6 (bottom) shows that the performance of the proposed method is stable for a significant range of systolic timings.

4 CONCLUSIONS

Based on synchronized echocardiography-ICG data, we have shown in this work that the classical definition of B and X points in the ICG exhibit a non constant bias and a reduced correlation to the physiological systolic events they are mend to capture, i.e. the opening and closing of the aortic valve. This might have a significant impact on the applicability of ICG in clinical practice, since it determines the accuracy of the most useful diagnosis variables - systolic time intervals, contractility and stroke volume that can be obtained using the signal. Currently, many researchers also use ICG to compensate for PEP in pulse transit time measurement (Payne *et al.*, 2006). The finding reported herein might also be significant in this context.

A new definition for the main systolic characteristic points in the ICG is suggested. These points minimize the offset with respect to the physiological events related to the left ventricle ejection. Based on these new definitions, an algorithm was introduced that enables a significant reduction in left ventricle ejection time estimation errors, while increasing its estimation stability, i.e. lowering the estimation error dispersion and increasing the correlation with respect to echocardiography based measurements. The algorithm enables the detection of the onset of left ventricle ejection with an average absolute estimation error of 12.4 ± 8.7 ms with a correlation coefficient of 0.54. This is about 35.8% smaller when compared to state of the art methods using the classical definition of the B-point. Regarding the detection of the end of the left ventricle ejection phase, the proposed algorithm performs significantly better compared to other state of the art methods. The detected characteristic points exhibit a much higher correlation (0.44) to the closing of the aortic valve than other competing methods (best achieved correlation 0.22). The average absolute detection error of this event (32.2 ± 25.0 ms) is higher compared to the performance achieved for the detection of the onset of the left ventricle ejection. Yet, it is smaller (in some cases almost 50% smaller) and less dispersed compared to state of the art methods. One might speculate that this might have a significant impact on the value of ICG in medical practice e.g. for cardiac output estimation. However, its clear demonstration probably requires a new study using thermo dilution as reference.

ACKNOWLEDGEMENTS

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