Biomedical Signal Processing and Control 5 (2010) 76–81

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Short communication

On an automatic delineator for arterial blood pressure waveforms

Bing Nan Li [a,b,*], Ming Chui Dong [a,c], Mang I. Vai [a]

[a] Department of Electrical and Electronics Engineering, University of Macau, Taipa 1356, Macau
[b] NUS Graduate School for Integrative Science and Engineering, National University of Singapore, Kent Ridge 117456, Singapore
[c] Institute of Systems and Computer Engineering of Macau, Taipa 1356, Macau

ARTICLE INFO

Article history:
Received 12 December 2008
Received in revised form 4 June 2009
Accepted 5 June 2009
Available online 3 July 2009

Keywords:
Arterial blood pressure waveforms
Cardiovascular system
Dicrotic notch detection
Pulse contour analysis

ABSTRACT

Arterial blood pressure waveforms contain rich pathophysiological information; hence receive much attention in cardiovascular health monitoring. To assist computerized analysis, an automatic delineator was proposed for the fiducial points of arterial blood pressure waveforms, namely their onsets, systolic peaks and dicrotic notches. The presented delineator characterizes arterial blood pressure waveforms in a beat-by-beat manner. It firstly seeks the pairs of inflection and zero-crossing points, and then utilizes combinatorial amplitude and interval criteria to select the onset and systolic peak. Once a new beat is settled, the delineator seeks the derivative backward to locate the dicrotic notch in the preceding beat. In a nutshell, the delineator is based on the combinatorial analysis of arterial blood pressure waveforms and their derivatives. Three open databases, with an additional subset database, were utilized for delineator validation and performance evaluation. In terms of beat detection, the delineator achieved an average error rate 1.14%, sensitivity 99.43% and positive predictivity 99.45%. As to dicrotic notch detection, it performed well with an error rate 6.83%, sensitivity 96.53% and positive predictivity 96.64%.

1. Introduction

Blood circulation is a summation of the steady and kinetic flows in the cardiovascular system. The kinetic blood flow contains both quasi-periodic fluctuations, due to the rhythmic heart beating, and non-periodic fluctuations due to the incidental vascular oscillation [1]. It is convenient to monitor kinetic blood circulation indirectly by pressure waveforms at peripheral accessible sites, for example radial artery. Arterial blood pressure (ABP) waveforms are actually modulated by two distinct components, namely cardiac pressure signaling and iterative pulse wave reflection [2]. Moreover, they are also subject to many other modulating factors, such as blood volume, arterial compliance, and peripheral resistance. In clinical medicine, the dynamic blood pressure collected during hemodynamic monitoring has been confirmed with rich pathophysiological information of cardiovascular system [3–5], where the interested messages consist of blood pressure values, cardiac rhythms and pulse waveforms. In addition, it has been proposed more than once to infer various cardiovascular parameters, such as cardiac output, arterial compliance and peripheral resistance, from noninvasive ABP waveforms by mathematical modeling [6–9]. The methods for pulse contour analysis are generally built on their morphological characteristics as well as rhythmic information. It is thus necessary to report the fiducial points of ABP waveforms accurately.

The morphological characteristics of an ABP waveform are closely related with the hemodynamic behaviors of blood circulation. Its onset and steep upstroke (Fig. 1a) should be attributed to aortic valve opening for blood ejection. Nevertheless, the systolic peak reflects the integrated behaviors of cardiac blood ejection and arterial wave reflection [2]. Before blood runoff in vasculature, there is generally a dicrotic notch indicating the closure of aortic valve. In reality, ABP waveforms are often contaminated by various noises and artifacts, which could be due to instrumental unreliability or measuring inconsistency. As a consequence, on the one hand, substantial attention is continuing on the better instrumentation for measuring noninvasive ABP waveforms for cardiovascular health monitoring [10–12]. On the other hand, the effective and robust delineators are pursued to attack noises and artifacts for subsequent pulse contour analysis.

Many beat detectors have been reported for characterizing ABP waveforms in the literatures [13–18]. What inspired our works in this paper is due to the following facts. In the first aspect, those reported detectors paid major attention on either systolic peaks [17,18], the onsets [16], or dicrotic notches [13–15] only. There are comparatively fewer systems and algorithms dedicated to the full delineation of ABP waveforms [10]. In the second aspect, most of them merely accounted for pathological alternations [14,15] or

* Corresponding author at: Vision and Image Processing Lab, E4A, #05-03, 3 Engineering Drive 3, National University of Singapore, Singapore 117576. Tel.: +65 65166332.
E-mail addresses: me@bingoon.org (B.N. Li), dmc@inesc-macau.org.mo (M.C. Dong), fstmiv@Umac.Mo (M.I. Vai).

1746-8094/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.bspc.2009.06.002

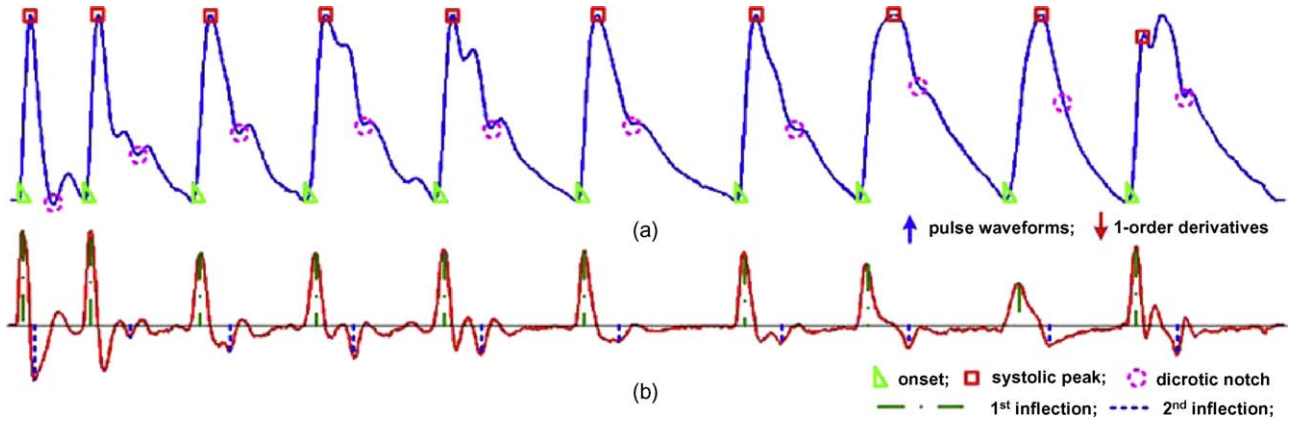

Fig. 1. Synthetic ABP waveforms and their derivatives.

physiological diversities [13,17,18]. However, the recorded ABP waveforms often suffer from instrumental unreliability and measuring inconsistency, too. In the third aspect, their validation and performance evaluation was based on small datasets, which were from selected patients and with limited number of beats only [13–15,17,18]. In particular, it is difficult to evaluate those systems and algorithms by their proprietary datasets.

An automatic delineator, hereafter termed as PUD (PUlse waveform Delineator), is proposed in this paper to report the onsets, systolic peaks and dicrotic notches of ABP waveforms as a whole. It is evaluated in different large-scale databases that embody various pathophysiological complexity, instrumental unreliability and measuring inconsistency in real-world ABP waveforms. Furthermore, the evaluation will be carried out on both invasive and noninvasive ABP waveforms, unlike those only by aortic pressure waveforms [14,15], invasive [17] or noninvasive ABP waveforms [13,18]. The rest of this paper is organized as follows: the methods and design considerations for ABP waveform characterization are elucidated in the second section; the third section is devoted to system evaluation and result analysis; the last one is for concluding remarks.

2. Methods

Full characterization of ABP waveforms is much more challenging than beat detection. For instance, it is acceptable for beat detectors to take systolic peaks as a reference. However, the onsets and the ends of ABP waveforms, due to their weak amplitudes, are generally more susceptible to noises and artifacts [19]. Moreover, different from the QRS complexes in electrocardiograms (ECGs), the spectra of systolic and diastolic complexes in ABP waveforms are overlapped substantially. In other words, the band-pass filters are applicable to ECG beat detection, but not enough for ABP waveform delineation. In addition, the durable measuring process unavoidably introduces various noises and artifacts, such as the notorious baseline wander [18], into ABP waveforms. A competent delineator has to take all of the above challenges into account.

The beat detectors usually make use of combinatorial filters to enhance systolic peaks while attenuating other components, noises and artifacts, and then report the locations of systolic peaks in ABP waveforms [16–18]. Such kind of information is helpful for pulse rate or heart rate analysis [20]. However, as mentioned above, pulse contour analysis relies on both morphological characteristics and rhythmic information. Not only the systolic peaks but also the onsets and dicrotic notches should be reported for computerized pulse contour analysis. The authors in reference [16] proposed a windowed and weighted slope sum function to extract the onsets of ABP waveforms, and claimed its accuracy 99.31% on 368,364 beats with reference to ECG annotations and 96.41% on 39,848 beats with reference to manual annotation. In reference [13], there was a dicrotic notch detector built on analyzing the first- and second-order derivatives of ABP waveforms. Evaluated on a small dataset (373 beats from 8 patients), its performance was claimed as 96.25%. The authors in references [14,15] proposed an innovative method for dicrotic notch detection. Instead of direct analysis of pulse waveforms, they utilized a simplified windkessel model to derive flow waveforms, and took the first negative dip of flow waveforms as a dicrotic notch. It was evaluated on both normal and arrhythmia patients with good performance. However, they concentrated on invasive aortic signals only, and pointed out the potential issues if extended to ABP waveforms. In particular, a series of physiological parameters, including characteristic impedance, arterial compliance and peripheral resistance, are necessary for their models and algorithms. Unfortunately, such parameters are not available in most cases.

In a nutshell, the combinatorial derivative analysis, with widespread applications [10,13,18], yet seems promising for ABP waveform characterization. The proposed delineator in this paper is theoretically similar to that in reference [13]. Nevertheless, we concentrated on the combinatorial analysis of ABP waveforms and the first-order derivative only. In addition, more decision logics were introduced to cope with pathophysiological complexity and instrumental unreliability in large-scale ABP waveforms. The authors in references [10] and [18] have mentioned part of the ideas, but did not carry out the systematic analysis.

2.1. Onsets and systolic peaks

It has been proved that any singularity in the differentiable signals must correspond to a pair of inflection and zero-crossing points in their derivative [21], as a matter of fact, which has been applied to ECG delineation [19]. The presented delineator is principally based on critical point detection in the derivative of ABP waveforms, too. Fig. 1b depicts both concepts of inflection and zero-crossing points well for ABP waveform characterization. Note that, in the derivative, the onset of an ABP waveform is related to a zero-crossing point before a maximal inflection, while the systolic peak is related to a zero-crossing point after that inflection.

Fig. 1 illustrates several common ABP waveforms as well as their derivatives. The presented delineator has to firstly seek the candidate zero-crossing points in the derivative. Nevertheless, various noises and artifacts often distort the raw ABP waveforms, and hereby introduce many aliasing points into their derivatives. To suppress noises and artifacts, it is a useful strategy to refine the raw signals with band-pass filters [15–18]. As the derivation itself is equivalent to a high-pass filter, the delineator manipulates the

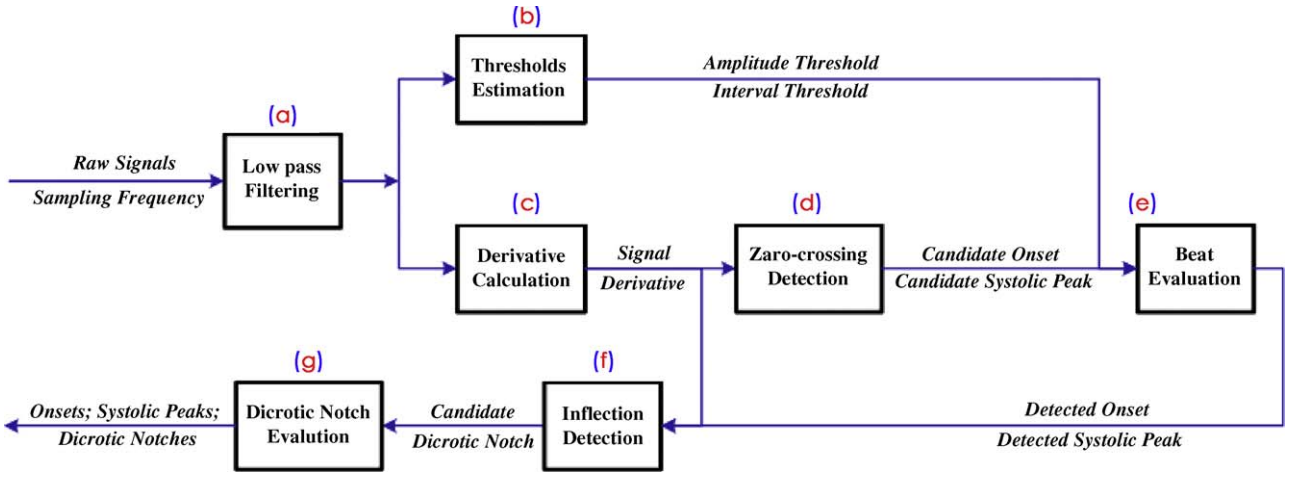

Fig. 2. Flowchart of the proposed ABP waveform delineator.

raw ABP waveforms by a 3-order low-pass Bessel filter only (Fig. 2a).

The one-order amplitude differences are utilized to approximate the derivative of filtered ABP waveforms (Fig. 2c). Before formal characterization, the delineator has to estimate the amplitude and interval thresholds adaptively (Fig. 2b). It firstly segments the filtered ABP waveforms into multiple equal divisions (i.e., each division with equal waveform samples), and then applies a selective window (e.g., with the duration of 2 s) to the beginning of each division. Within those windows, the amplitudes and pulse rates are hereby estimated and averaged as the initial thresholds. Then, the delineator manipulates ABP waveforms and their derivatives in a beat-by-beat manner (Fig. 2d–g). It firstly seeks the derivative for the pairs of inflection and zero-crossing points (Fig. 2d). For onsets and systolic peaks, the delineator is interested in the zero-crossing points before and after the maximal inflection (1st inflection in Fig. 1b) in each beat of waveform derivative. The delineator then goes back to ABP waveforms, and evaluates those candidate onsets and systolic peaks in accordance with both amplitude and interval thresholds (Fig. 2e). If qualified, the delineator proceeds to dicrotic notch detection. Otherwise, it will adjust the thresholds and step backward to the searching window again.

2.2. Dicrotic notches

The onset in each beat of ABP waveform manifests the beginning of blood ejection from the heart to the aorta. On the contrary, the dicrotic notch indicates the end of blood ejection or the closure of aortic valve. Consequently, the systolic complex reflects the information of cardiac function as well as vascular condition, but the diastolic complex tells more about the latter. In other words, for effective pulse contour analysis, it is necessary to accurately report the dicrotic notches in advance [6,7]. However, the iterative pulse wave reflections [2], due to pathophysiological alteration, often diversify dicrotic notches. As a consequence, the real-world dicrotic notches often vary substantially in terms of their positions and morphologies. Sometimes they even degenerate to an incisura in ABP waveforms. The preceding Fig. 1 partially manifests the challenges in dicrotic notch detection.

The onset and systolic peak of an ABP waveform are related to the zero-crossing points in the derivative. Between those zero-crossing points, there are one or more local extreme points corresponding to the inflections, which indicate the behaviors of acceleration and deceleration. To locate a dicrotic notch, the presented delineator resorts to the critical points in ABP waveform derivatives, too. It is assumed there should be a dicrotic notch, or at least an incisura, after each systolic peak. Therefore, once a new beat of ABP waveform is detected, the delineator will step back for a dicrotic notch right away. If the interval between two beats is qualified, its one tenth (or 40 ms, whichever is shorter) and one half (or 400 ms, whichever is shorter) are utilized to define a temporary searching window [10,13,15]. The delineator is interested in the pairs of inflection and zero-crossing points within that window (Fig. 2f). A few rules of thumb have been defined for final selection of those candidate dicrotic notches. In general, it is sound to take the first zero-crossing point after the secondary inflection (2nd inflection in Fig. 1b) as the dicrotic notch (Fig. 2g). In some special cases, there is no such zero-crossing point at all. Then the delineator settles an empirical point as the dicrotic notch, for example, the point in one third of the temporary searching window (or 200 ms after the systolic peak, whichever is shorter) [13,25]. Note that such empirical setting is possibly subject to further modification in practice.

3. Evaluation and results

One of the major factors that inspired our works in this paper is the reproducibility of ABP waveform delineators and their evaluation. In general, the authors reported their detectors with performance evaluation in a small dataset only. For instance, the dataset in reference [13] merely had 373 beats from 8 patients. The authors in reference [14,15] evaluated their dicrotic notch detector on the data from experimental animals and selected patients. The case was similar in reference [18]. As mentioned above, it is generally difficult to reproduce them. A few investigators have noticed that problem [16,17]. The authors in reference [17] set up a benchmark database, CSL (http://bsp.pdx.edu), and made it openly accessible for beat detector evaluation. CSL contains two 60 min recordings of ABP waveforms. In particular, there are three sets of annotations in that database: two by medical experts and the other one by the beat detector proposed in reference [17]. Such well-annotated database is definitely contributive to detector evaluation. However, the selected recordings, merely from two patients, are not enough to reflect the artifacts and pathophysiological complexity of ABP waveforms. On the contrary, the authors in reference [16] built up their onset detector based on a large-scale database from PhysioNet (http://www.physionet.org) [22].

Open accessibility and authoritative annotation are two essential criteria determining the eligibility of benchmark databases. The Fantasia database (http://www.physionet.org/physiobank/database/fantasia/) at PhysioNet is aimed to reflect the age-related alterations in cardiovascular physiological signals [23]. There are twenty 120 min recordings of physiological signals

collected from two cohorts of youths and elders. Other than noninvasive ABP waveforms, all recordings contain a set of synchronously-sampled ECG signals with approved beat annotations. In contrast, the Polysomnographic database (SLP) (http://www.physionet.org/physiobank/database/slpdb/), from PhysioNet too, is a collection of physiological signals recorded during sleep [24]. It is oriented to the evaluation of chronic obstructive sleep apnea syndrome, and the effects of medical intervention. There are over 80 h polysomnographic recordings from 16 subjects aged from 32 to 56. Each recording contains the synchronously-sampled invasive ABP waveforms as well as the ECG signals with approved beat annotations. Above two databases, together with the CSL in reference [17], were selected for delineator evaluation in this paper.

It is noteworthy that, in above open databases, there are no reference annotations for dicrotic notches. Hence a new database, hereafter termed as SFM (Subset of the First Minute of arterial pulse waveforms), was built with approved annotations of the onsets, systolic peaks and dicrotic notches of ABP waveforms. It contains totally 36 pieces of ABP waveforms excerpted from the first minute recordings in Fantasia and SLP databases. The ABP waveforms in SFM were manually annotated by a group of trained engineers, and then submitted to medical experts for their approval. By means of such well-annotated database, it is then possible to fully evaluate the delineator with regard to the onsets, systolic peaks and dicrotic notches.

Two benchmark parameters, sensitivity *Se* as in (1) and positive predictivity P^+ as in (2), were adopted for quantitative evaluation of the presented ABP delineator:

$$Se = \frac{\mathrm{TP}}{(\mathrm{TP} + \mathrm{FN})} \tag{1}$$

$$P^{+} = \frac{\mathrm{TP}}{(\mathrm{TP} + \mathrm{FP})} \tag{2}$$

where TP stands for the number of true positives, FN for the number of false negatives, and FP for the number of false positives. Therefore, *Se* indicates the percentage of detected true beats to overall beats of ABP waveforms, while P^+ calculates the percentage of detected true beats to all beat annotations. In addition, the evaluation was based on the error rate as in (3), too.

$$\mathrm{error} = \frac{(\mathrm{FP} + \mathrm{FN})}{(\mathrm{TP} + \mathrm{FP})} \tag{3}$$

3.1. Evaluation of beat detection

All databases were utilized for performance evaluation with regard to beat detection in ABP waveforms. It is convenient to directly compare the reported systolic peaks with both manual annotations and reference detections in the CSL database (Fig. 3a). For instance, a threshold 8 ms was designated to admit the

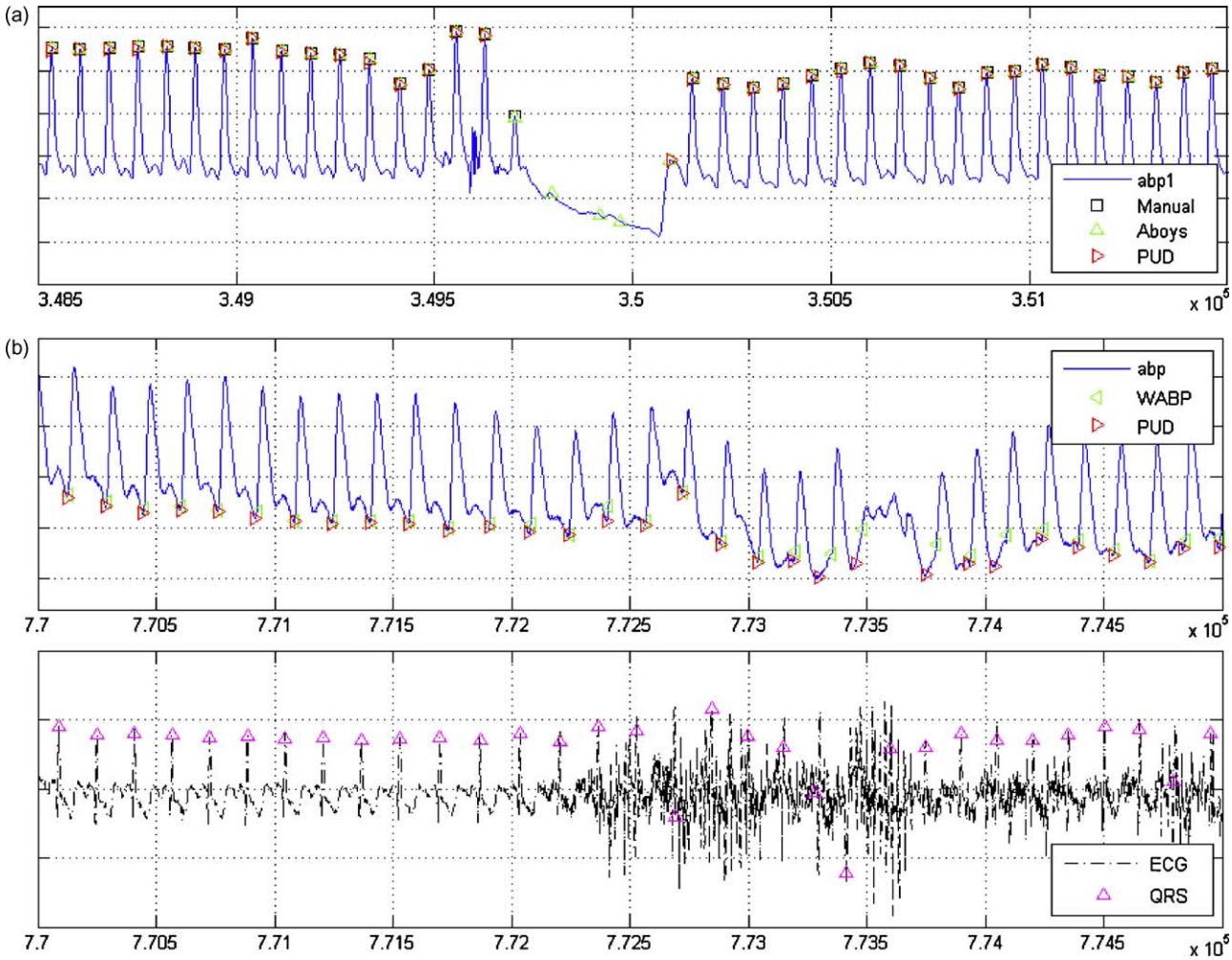

Fig. 3. Evaluation of beat detection in open databases. (a) Data segment: CSL/abp1 (348501:351500); performance evaluation with regard to both manual (black square) and computerized (green up triangle) references; note the robustness of the presented ABP waveform delineator (b) data segment: SLP/slp04 (770001:775000); performance evaluation with regard to computerized ABP (green left triangle) and ECG (magenta up triangle) references; note the difference between ABP and ECG due to physiological artifacts.

Table 1
Overall performance of the presented delineator on beat detection.

Database	Annotations	Detector	TP	FP	FN	Error (%)	*Se* (%)	P^+ (%)
CSL (systolic peaks)	13079	PUD	13055	21	24	0.34	99.82	99.84
		Aboy et al., 2005	13053	49	26	0.57	99.80	99.63
Fantasia (onsets)	137830	PUD	135748	24	2082	1.56	98.29	99.98
		Zong et al., 2003	136389	2418	1441	2.78	98.95	98.26
SLP (onsets)	318412	PUD	315823	17	2589	0.83	99.19	99.99
		Zong et al., 2003	317890	1601	522	0.66	99.84	99.50

Table 2
Overall performance of the ABP waveform delineator in SFM database.

	Annotations	TP	FP	FN	Error (%)	*Se* (%)	P^+ (%)
Onsets	2564	2563	33	4	1.43	99.96	98.73
Systolic peaks	2564	2561	34	6	1.54	99.88	98.69
Dicrotic notches	2564	2475	86	89	6.83	96.53	96.64

delineator results as TP or reject them as FP or FN. In terms of Fantasia and SLP databases, nevertheless, there are merely the reference onsets of ABP waveforms by an open-source algorithm [16]. Fortunately, the approved ECG annotations in those databases may serve as a corrective reference for performance evaluation in a beat-by-beat manner (Fig. 3b). In other words, the status of delineator results was judged by visual inspection. If the ABP waveform is clear and there is corresponding ECG annotation, a beat detection was considered as TP or FN based on its presence or absence. Otherwise, it was considered as FP if there is no clear ABP waveform or no ECG annotation.

The performance of beat detection in terms of CSL, Fantasia and SLP databases were summarized in Table 1. The presented delineator exhibits competitive performance against those up-to-date beat detectors. It is noteworthy that, besides fair error rates and sensitivities, the presented delineator always leads to a higher positive predictivity P^+. In fact, during ABP characterization, the delineator takes both amplitude and interval criteria into account, which makes it comparatively conservative to admit a new beat of ABP waveform (Fig. 3). In other words, its results are more reliable for subsequent pulse contour analysis.

In addition, the time discrepancies between manual annotations and the detected fiducial points may be defined as a function of Δt, by which it is possible to further evaluate the delineator's accuracy [16]. Here the CSL database was adopted again due to its manual annotations (Fig. 3a). The delineator reported 5678 and 7398 beats for the two recordings, among which 5666 and 7389 beats were approved matching with manual annotations. The Δt for the first recording is 4.87 ± 12.94 ms (ms), and for the second one is 5.46 ± 10.22 ms. If a confidence interval is defined as the Δt

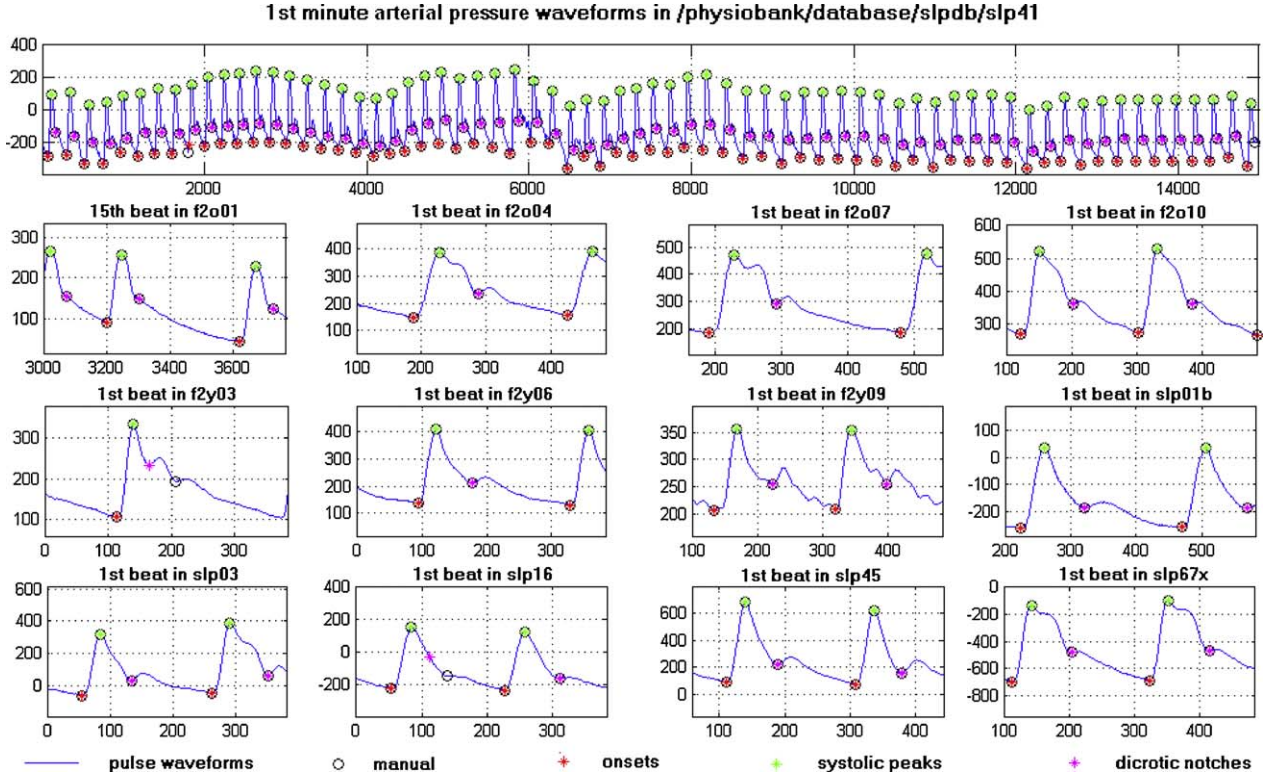

Fig. 4. Overall performance of the presented ABP waveform delineator in SFM database (top: Performance evaluation on a complete 1 min segment of ABP waveforms; down: Performance evaluation on different types of ABP waveforms).

equal to or less than 8 ms (i.e., ±1 sampling period), then in CSL database, 99.68% and 99.95% beat annotations of the presented delineator are within such confidence interval.

3.2. Evaluation of dicrotic notch detection

In terms of dicrotic notch detection, the performance evaluation was based on a selective database SFM only. There are 2564 beats of ABP waveforms with approved annotations, including those for dicrotic notches. Again, the confidence interval was limited within ±8 ms. In other words, a reported dicrotic notch was considered TP only when it did not deviate from manual annotations over ±8 ms, namely one sampling period. Otherwise, it was assigned to FPs. The delineator eventually reported 2561 dicrotic notches, 2475 of which were deemed TPs. The performance indices of dicrotic notch detection, including error rate (6.83%), sensitivity (96.53%) and positive predictivity (96.64%), are a little worse than those of beat detection. The detailed results may refer to Table 2 and Fig. 4. It is noteworthy that, as shown in Fig. 4, those empirical dicrotic notches are sometimes not consistent with the manual references. However, the overall performance has been fairly good for computerized pulse contour analysis.

4. Discussions and conclusion

ABP waveforms contain plenty of pathophysiological information of cardiovascular circulation system. It is thus a tradition of interest to measure and analyze ABP waveforms in cardiovascular health monitoring. Accurate delineation of their fiducial points is a prerequisite step for pulse contour analysis; hence computerized delineation is by no means a novel idea. However there are still few delineators reported for the onsets, systolic peaks and dicrotic notches of ABP waveforms as a whole. In particular, the previous validation and performance evaluation were generally based on small datasets, but not large-scale databases. As a matter of fact, the large-scale databases often encompass more types of pathophysiological complexity, instrumental errors and measuring artifacts. It hereby imposes more challenges on the reliability and the generalization of ABP waveform delineators.

In this paper, we presented an ABP waveform delineator to report their fiducial points, namely the onsets, systolic peaks, and dicrotic notches. Three open databases, reflecting real-world artifacts and pathophysiological complexity in ABP waveforms, were selected for performance evaluation. As to beat detection, no matter onsets or systolic peaks, the delineator achieved the average error rate 1.14%, sensitivity 99.43% and positive predictivity 99.45%. Furthermore, a subset database with approved manual annotations was built to evaluate dicrotic notch detection. In terms of dicrotic notch detection, the delineator performed well with the error rate 6.83%, sensitivity 96.53% and positive predictivity 96.64%. In summary, the presented delineator is able to characterize ABP waveforms with elegant performance.

As there are approved manual annotations, it is safe to claim the delineator performance in CSL and SFM databases. On the contrary, performance evaluation in terms of Fantasia and SLP databases was referred to their ECG annotations. In fact, such strategy has been adopted by Zong et al. in reference [16] too. However, we should bear in mind that it is not safe to evaluate the delineators of ABP waveforms with ECG annotations only. Although recorded synchronously, the physiological signals usually suffer from different noises and artifacts. As shown in Fig. 3, ECG annotations occasionally do not correspond to effective ABP waveforms. Therefore, in spite of our careful proofreading, it is possible that current results still contain a few statistical errors. Nevertheless, the results presented here do serve as a reference for future works.

Acknowledgments

The authors would like to thank the anonymous reviewers for their comments, which are helpful to improve this paper. This work was partially supported by the Macau Science and Technology Development Fund (Grant No.: 007/2006/A1 and 014/2007/A1), and in part by the Research Committee of University of Macau (Grant No: RG071/04-05S/DMC/FST and RG061/06-07S/VMI/FST).

References

[1] T.M. Laleg, E. Crepeau, M. Sorine, Separation of arterial pressure into a nonlinear superposition of solitary waves and a windkessel flow, Biomedical Signal Processing and Control 2 (3) (2007) 163–170.
[2] W.W. Nichols, M.F. O'Rourke, McDonald's Blood Flow in Arteries: Theoretical Experimental and Clinical Principles, 4th ed., Arnold, London, UK, 1998.
[3] Z.X. Fei, Contemporary Sphygmology of Chinese Medicine, People's Medicine Publishing House, Beijing, CN, 2003.
[4] Z.C. Luo, S. Zhang, Y.M. Yang, Engineering Analysis of Pulse Waveforms and its Clinical Applications, Science Press, Beijing, CN, 2006.
[5] A. Aboukhalil, L. Nielsen, M. Saeed, R.G. Mark, G.D. Clifford, Reducing false alarm rates for critical arrhythmias using the arterial blood pressure waveform, Journal of Biomedical Informatics 41 (2008) 442–451.
[6] J.N. Cohn, S. Finkelstein, G. McVeigh, D. Morgan, L. LeMay, J. Robinson, J. Mock, Noninvasive pulse wave analysis for the early detection of vascular disease, Hypertension 26 (1995) 503–508.
[7] E.R. Rietzschel, E. Boeykens, M.L.D. Buyzere, D.A. Duprez, D.L. Clement, A comparison between systolic and diastolic pulse contour analysis in the evaluation of arterial stiffness, Hypertension 37 (2001) e15–e22.
[8] J.I. Davies, A.D. Struthers, Beyond blood pressure: pulse wave analysis–a better way of assessing cardiovascular risks? Future Cardiology 1 (2004) 69–78.
[9] A. de Sá Ferreira, J.B. Filho, I. Cordovil, M.N. de Souza, Three-section transmission-line arterial model for noninvasive assessment of vascular remodeling in primary hypertension, Biomedical Signal Processing and Control 4 (1) (2009) 2–6.
[10] G. Gratze, J. Fortin, A. Holler, K. Grasenick, G. Pfurtscheller, P. Wach, et al., A soft package for non-invasive, real-time beat-to-beat monitoring of stroke volume, blood pressure, total peripheral resistance and for assessment of autonomic function, Computers in Biology and Medicine 28 (1998) 121–142.
[11] P. Dupuis, C. Eugene, Combined detection of respiratory and cardiac rhythm disorders by high-resolution differential cuff pressure measurement, IEEE Transactions on Instrumentation and Measurement 49 (3) (2000) 498–502.
[12] B.N. Li, B.B. Fu, M.C. Dong, Development of a mobile pulse waveform analyzer for cardiovascular health monitoring, Computers in Biology and Medicine 38 (2008) 438–445.
[13] M.I. Oppenheim, D.F. Sittig, An innovative dicrotic notch detection algorithm which combines rule-based logic with digital signal processing techniques, Computers and Biomedical Research 28 (1995) 154–170.
[14] S.A.A.P. Hoeksel, J.R.C. Jansen, J.A. Blom, J.J. Schreuder, Detection of dicrotic notch in arterial pressure signals, Journal of Clinical Monitoring 13 (1997) 309–316.
[15] A. Donelli, J.R.C. Jansen, B. Hoeksel, P. Pedeferri, R. Hanania, J. Bovelander, et al., Performance of a real-time dicrotic notch detection and predication algorithm in arrhythmic human aortic pressure signals, Journal of Clinical Monitoring and Computing 17 (2002) 182–185.
[16] W. Zong, T. Hedlt, G.B. Moody, R.G. Mark, An open-source algorithm to detect onset of arterial blood pressure pulses, Computers in Cardiology 30 (2003) 259–262.
[17] M. Aboy, J. McNames, T. Thong, D. Tsunami, M.S. Ellenby, B. Goldstein, An automatic beat detection algorithm for pressure signals, IEEE Transactions on Biomedical Engineering 52 (2005) 1662–1670.
[18] L. Xu, D. Zhang, K. Wang, N. Li, X. Wang, Baseline wander correlation in pulse waveforms using wavelet-based cascaded adaptive filter, Computers in Biology and Medicine 37 (2007) 716–731.
[19] J.P. Martinez, R. Almeida, S. Olmos, A.P. Rocha, P. Laguna, A wavelet-based ECG delineator: evaluation on standard databases, IEEE Transactions on Biomedical Engineering 51 (2004) 570–581.
[20] P.S. McKinley, P.A. Shapiro, E. Bagiella, M.M. Myers, R.E. DeMeersman, I. Grant, R.P. Sloan, Deriving heart rate variability from blood pressure waveforms, Journal of Applied Physiology 95 (2003) 1431–1438.
[21] S. Mallat, W.L. Hwang, Singularity detection and processing with wavelets, IEEE Transactions on Information Theory 38 (1992) 617–643.
[22] A.L. Goldberger, L.A.N. Amaral, L. Glass, M.H. Jeffrey, C.I. Plamen, G.M. Roger, et al., PhysioBank, PhysioToolkit, and PhysioNet: components of a new research resource for complex physiologic signals, Circulation 101 (2000) e215–e220.
[23] N. Iyengar, C.K. Peng, R. Morin, A.L. Goldberger, L.A. Lipsitz, Age-related alterations in the fractal scaling of cardiac interbeat interval dynamics, American Journal of Physiology (Regulation, Integration and Comparative Physiology) 271 (1996) R1078–R1084.
[24] Y. Ichimaru, G.B. Moody, Development of the polysomnographic database on CD-ROM, Psychiatry and Clinical Neurosciences 53 (1999) 175–177.
[25] M.O. Poliac, Beat onset detector, USA Patent (No. 5720292) 1998.