# Algorithm for Real-Time Pulse Wave Detection Dedicated to Non-Invasive Pulse Sensing

Ivo Iliev[1], Bistra Nenova[1], Irena Jekova[2], Vessela Krasteva[2]

[1]Technical University, Sofia, Bulgaria
[2]Institute of Biophysics and Biomedical Engineering, Bulgarian Academy of Sciences, Sofia,Bulgaria

## Abstract

*This study presents a simple algorithm for pulse wave PW detection dedicated to real-time pulse sensing devices in an emergency. Two basic principles are implemented – identification of extrema by time-amplitude criteria, and validation of the most prominent rising edges preceding the systolic peak according to criteria for slope and similarity to neighbors within 4 s. The pilot version of the algorithm (Matlab implementation) is developed and tested over independent subsets of arterial pressure PW signals from MGH/MF waveform PhysioNet database. Referring to ECG-synchronized beat annotations, the following performance is reported for the test set: positive predictivity PPV=96.4 %, sensitivity Se=98.9 % (443116/447983) for normal beats, Se=92 % (5522/6004) for supraventricular beats, Se=78.7 % (2834/3603) for premature ventricular beats, Se=97 % (27691/28547) for paced beats. The algorithm is also implemented in a prototype with photoplethysmographic (PPG) sensor for detection of carotid pulse from the neck region. It has been validated on 10 volunteers for whom ECG and PPG signals with duration of 10 s are superimposed to confirm 100 % coincidence between QRS and detected PWs. The results prove that the presented method is a reliable tool for non-invasive pulse sensing in an emergency.*

## 1. Introduction

The pulse wave (PW), induced on each artery or vena by blood circulation, provokes three coherent events: blood flow (flow pulse), blood pressure change (pressure pulse) and extension of transverse profile (volume pulse) [1]. The PW typical morphology has a steep rising edge during systole and a falling edge with a dicrotic notch, followed by a dicrotic peak, concerned with diastole and wave reflections from the periphery. The PW contour is influenced by physiological conditions and diseases [2].

Studies with different levels of PW contour analysis are published, including detection of systolic peak [3-6], PW onset [7] and additionally dicrotic notch/peak [8, 9].

The systolic peaks are identified by detection of all PW extrema and consecutive validation of candidates by filtering adapted to the heart rate and rank-based features estimation [3] or analysis of the refractory period between detected local maxima [4]. Studies suggest improvement of the PW signal quality by pre-processing techniques based on wavelet cascaded adaptive filtration for baseline wander correction [5], moving averaging and template matching for smoothing of high-frequency fluctuation [6].

Considering that the strategy of only peak detection is inappropriate for studying PW velocity and delay after QRS, Zong et al [7] propose an algorithm to determine the PW onset by conversion of arterial blood pressure in a slope sum function and subsequent adaptive thresholding.

PW morphological analysis is used as a technique for assessing different vascular diseases. Detection of all fiducial points (onset, systolic peak, dicrotic notch/peak) is provided by more detailed evaluation of PW contours [8, 9]. The offline algorithm [8] incorporates information about the heart rate, amplitude and interbeat intervals to identify the locations of the different components on the intracranial pressure. The method in [9] calculates the derivative of arterial blood pressure to detect pairs of maximal inflection and zero-line crossing points which are then backwards validated as systolic peak and pulse onset according to combinatorial amplitude and interval criteria. The dicrotic notch is then detected right away.

Palpation of the carotid pulse is the traditional method for assessment of circulation in unresponsive cardiac arrest victim and any single determination of carotid pulselessness is the diagnostic step that immediately leads to the initiation of cardiopulmonary resuscitation. As advocated in resuscitation guidelines, the time for a single pulse check is limited to <10 s for healthcare providers and not recommended for lay rescuers [10]. The main consideration is the limited reliability of pulse palpation for confirming presence or absence of circulation.

This study aims at providing a tool for fast detection of carotid pulse in an emergency, including a simple algorithm for PW analysis embedded in a prototype with photoplethysmographic sensor. The algorithm is tested on annotated database with large excerpt of arrhythmias.

## 2. Materials and methods

### 2.1. Database

This study uses the publicly-available Massachusetts General Hospital/Marquette Foundation (MGH/MF) Waveform Database of PhysioNet [11, 12], representative for a large excerpt of physiologic and pathophysiologic states seen in 250 stable and unstable patients in critical care units, operating rooms, and cardiac catheterization laboratories. Individual electronic recordings include 3 ECG leads and 5 hemodynamic signals (arterial pressure, pulmonary arterial pressure, central venous pressure, respiratory impedance, and airway CO2) sampled at 360 Hz, 12-bit, with supporting ECG-synchronized beat annotations, diagnosis and treatment history. All 250 recordings (duration from 12 min to 86 min) have been visually inspected to extract episodes with noise-free arterial pressure pulse wave signal (ART) and non-interrupted beat annotations, taking the eligible signals in full-length but limited to no more than 30 min per patient. Out of all 250 patients, 48 recordings are excluded due to: missing beat annotations or missing ART signal. The remaining 202 recordings are separated into training set (12 files, mgh001-mgh012) and independent test set (190 files, mgh013-mgh250), with a total duration of 05h:50min and 90h:07min, respectively.

The heartbeats, included into the training and test sets (Table 1) are classified in 4 types, according to the beat annotation scheme of the MGH/MF Waveform database:

- *N-beats* – normal beats;
- *S-beats* – supraventricular beats, including premature or ectopic atrial or nodal beats;
- *V-beats* – premature ventricular contractions;
- *P-beats* – paced beats.

Table 1. Number of beats with corresponding beat-type annotation (*N,S,V,P*), included in training and test sets.

| | *N*-beats | *S*-beats | *V*-beats | *P*-beats |
|---|---|---|---|---|
| Training set | 27917 | 324 | 177 | 4031 |
| Test set | 447983 | 6004 | 3603 | 28547 |

### 2.2. Pulse wave detection algorithm

Details of the algorithm for PW detection are introduced in a previous study of the authors [13]. A short description of the basics concepts is presented below:

- *Preprocessing filtration*: The PW is processed in a narrow pass-band (0.5-5.5 Hz), considering that details of the waveform shape are less important than the robust identification of pulsations in noisy environments. A real-time filter is embedded as an adaptation of the averaging technique in [14].
- *Identification of extrema*: Pairs of maximums and minimums over the pulse waveform are detected according to two simple criteria: (1) absolute amplitude >50µV (2) distance between pairs >200ms.
- *Validation of rising edges according to slope criteria:* Each pair of extrema is validated if it belongs to the most distinguished rising slope of the pulse waveform before the systolic peak, verified according to basic requirements: (1) slope duration >40ms; (2) slope amplitude >5% of the signal range.
- *Validation of rising edges according to similarity to neighbours:* Each pair of extrema is compared to neighbours following criteria for slope similarity: (1) difference between 2 slope amplitudes <10%; (2) difference between 2 slope durations <33%. PW is validated if the number of similar slopes is greater than the number of dissimilar slopes, both evaluated for neighbouring rising edges within 4 s.

### 2.3. Implementation in a prototype

The presented algorithm has been embedded in a microcontroller-based prototype dedicated for fast non-invasive detection of PW in an emergency (Figure 1). The PW signal is acquired via reflective photo-plethysmographic (PPG) sensor, including: an emitting module (2 green LEDs at 520 nm, working in pulsed mode with an option for intensity adjustment) and a photodetector (photodiode current source followed by a synchronized demodulator). Special caution is paid on suppression of environmental noises, such as movement artifacts, interference from ambient light, interference induced in the high resistance (≅1 MΩ) feedback of the photodetector, and residual electromagnetically induced noises. The schematic includes hardware filters – low pass at 12 Hz and high-pass at 0.5 Hz, the latter removing the constant component, so that the pulsatile component is subsequently amplified. The digital PW signal, the PW detection instants, together with one lead ECG (acquired by an external module) are transmitted via Bluetooth to a central processing unit for successive performance study.

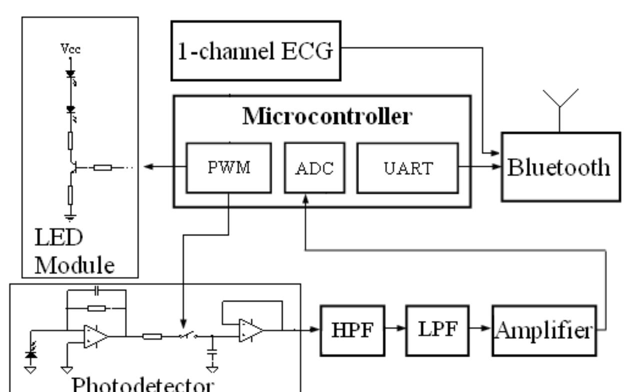


Figure 1. Block diagram of PW detector with PPG sensor.

# 3. Results

The pilot version of the PW detection algorithm is developed in Matlab 7.5 (MathWorks Inc.). The training and test process on MGH/MF database adopts the reference QRS-synchronized beat annotations (time of beat occurrence and beat type). Following the AAMI guidelines [15], the sensitivity (Se, fraction of beat annotations for which PW is detected) and the positive predictive value (PPV, fraction of PW detections which correspond to beat annotations) are calculated to evaluate the performance of PW detection algorithm:

$$Se = TP/(TP+FN)\,,\;\; PPV = TP/(TP+FP)\,,$$

where TP is the number of correctly detected PW; FP is the number of erroneously detected PW; FN is the number of missed PW. To match beat annotation to PW detection, a window is defined within 600 ms after beat annotation label or up to next beat annotation, considering the natural delay of mechanical contraction after QRS.

The PW detection performance is presented in Table 2, where Se is evaluated separately for N, S, V, P-beats, and PPV is calculated for all types of annotations. Examples of detected and missed PWs (Figure 2) suggest that shortened preceding RR-interval can limit the amplitude of PW below a reasonable detection level. Difference in distributions of preceding and following coupling RR-interval for detected vs. missed PWs (for V and S-beats, typically behaving with irregular RR-intervals) is confirmed by Student t-test (Table 3).

Table 2. Evaluation of PPV and Se for different beat types, as included in the training and test sets.

| | | N-beats | S-beats | V-beats | P-beats |
|---|---|---|---|---|---|
| | PPV | Se | Se | Se | Se |
| Training set | 99.9 % | 99.9 % | 96.9 % | 42.9 % | 99.8 % |
| Test set | 96.4 % | 98.9 % | 92.0 % | 78.7 % | 97.0 % |

Table 3. Mean±standard deviation of preceding and following RR intervals compared for the groups of missed vs. detected PWs after S, V-beats in the test set. *(p<0.05): significant differences are highlighted.

| Beat type (detected/ missed) | RR interval | Detected mean±std (ms) | Missed mean±std (ms) | p-value |
|---|---|---|---|---|
| S-beats | Preceding RR | 569±505 | 437±82 | <0.001* |
| (5522/482) | Following RR | 658±510 | 643±162 | 0.517 |
| V-beats | Preceding RR | 553±148 | 457±77 | <0.001* |
| (2834/769) | Following RR | 571±212 | 794±229 | <0.001* |

The algorithm running in the device is validated on 10 volunteers for whom the PPG sensor is applied on the neck region for detection of carotid pulse. PW detection instants are paired to QRS in the reference ECG channel. Visual inspection confirms 100 % coincidence (Figure 3).

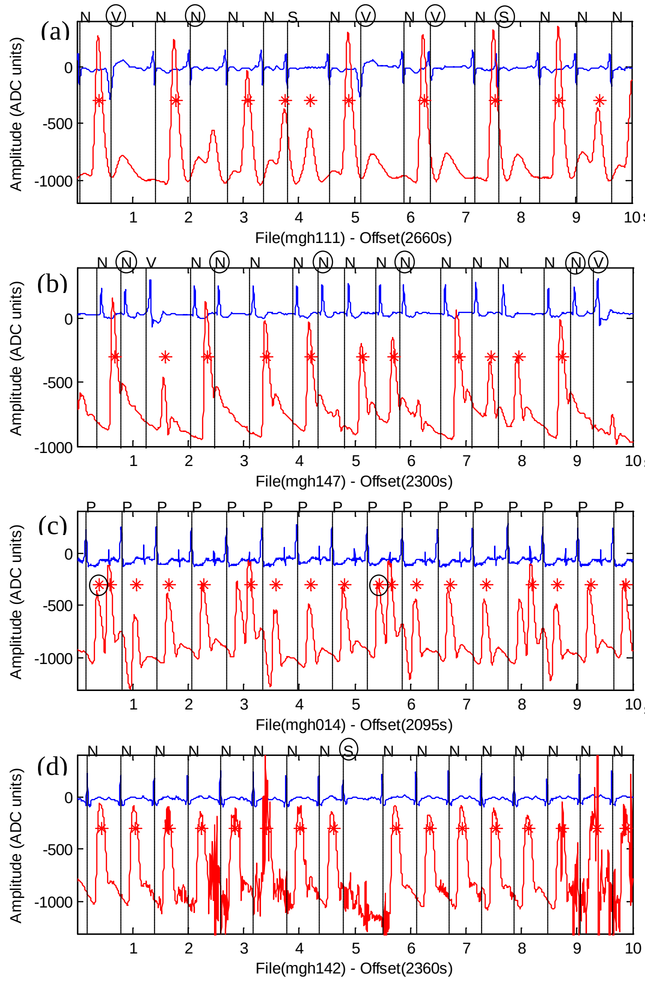


Figure 2. Ten-second episodes from MGH/MF database, showing ECG (top trace), ART (bottom trace), reference beat annotation labels and PW detection instants ('*' marks). Normally, after each beat annotation, a PW detection mark is seen, except for the errors: missed PWs (enclosed in circle annotation labels) and false positives (enclosed in circle detection marks).

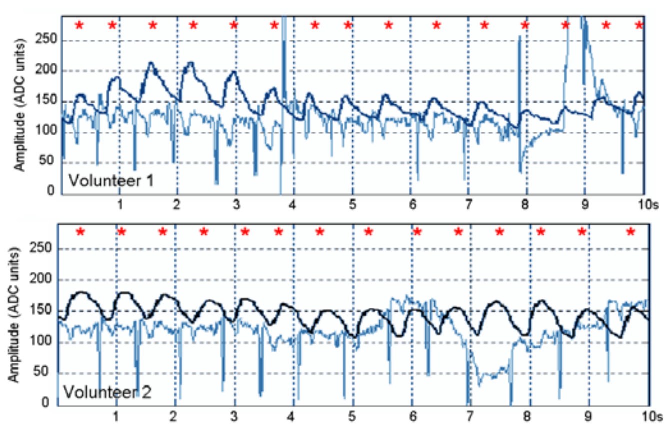


Figure 3. Ten-second recordings (8-bit) of ECG and PPG (from the neck) acquired by the prototype from two volunteers. The PW detection instants are shown by '*'.

## 4. Discussion and conclusions

This study presents a simple algorithm for PW detection dedicated to real-time pulse sensing devices in an emergency. Two basic principles are implemented – identification of extrema by time-amplitude criteria, and validation of the most prominent rising edges preceding the systolic peak according to criteria for slope and similarity to neighbors within 4 s pre-history. The pilot version of the algorithm has been developed and tested over independent subsets of arterial pressure PW signals from MGH/MF waveform PhysioNet database with different pathologies, using the reference beat annotations of large excerpt of N, S, V and P-beats. Sensitivity of 98.9 % and 97 % is achieved for normal and paced beats in the test dataset, however, the PW detection for supraventricular and ventricular ectopic beats is less accurate at 92 % and 78.7 %, respectively. Direct comparison to performances of published algorithms [3, 7, 9] is limited as others use different test databases and report a common Se for all beat annotations above 99 %.

Our observations indicate that the problematic detection of PW after S and V-beats is frequently due to low amplitude or missing PW (Figure 2a,d), that is suggested to be a natural consequence from a small stroke volume after shortened RR-interval. This phenomenon is also observed for irregular N-beats (Figure 2b). We show that the duration of preceding RR-interval could be considered as a significant predictor of PW detection ability with mean value for missed vs. detected cases of 437±82 ms vs. 569±505 ms (S-beats) and 457±77 ms vs. 553±148 ms (V-beats), $p<0.05$ (Table 3). The duration of the coupling RR-interval is also shown to be a significant predictor of PW detection sensitivity with 571±212 ms vs. 794±229 ms ($p<0.05$) for missed vs. detected V-beats.

Although the training of the PW detection algorithm achieves positive predictivity of 99.9 %, the test dataset, including a broad spectrum of pathologies, predisposes towards more false positives with PPV=96.4 %. Such an example is shown in Figure 2c, where some P-beats are provoking paired waves in the PW contour that could mislead to false positive PW detections. Apart from false positives due to specific PW contour in pathologic states, the example in Figure 2d demonstrates a good robustness against high-frequency noise secured by the restricted pass-band (<5.5 Hz) of the pre-processor filtering.

The application of the algorithm in a prototype with PPG sensor provides a tool for non-invasive pulse sensing in an emergency. The portable PW detector produces a real-time audio feedback after each detected PW which is a prompt indicator for confirming presence or absence of circulation within <10 s. Although the initial testing on 10 volunteers in a normal sinus rhythm confirms the adequate work of the algorithm on PPG signals from the neck region, data from more cardiac patients shall be collected for final validation of the device reliability.


## Acknowledgements

This study has been supported in part by the National Science Fund of Bulgaria, project ДДВУ02/18.


## References


[1] Korpas D, Halek J, Dolezal L. Parameters describing the pulse wave. Physiol Res 2009; 58: 473-9.

[2] O'Rourke MF, Pauca A, Jiang XJ. Pulse Wave Analysis. Br J Clin Pharmacol 2001; 51:507-22.

[3] Aboy M, McNames J, Thong T, Tsunami D, Ellenby M, Goldstein B. An automatic beat detection algorithm for pressure signals. Trans Biomed Eng 2005; 52:1662-70.

[4] Navakatikyan M, Barrett C, Head G, Ricketts J, Malpas S. A real-time algorithm for the quantification of blood pressure waveforms. Trans Biomed Eng 2002; 49: 1662-70.

[5] Xu L, Zhang D, Wang K, Li N, Wang X. Baseline wander correction in pulse waveforms using wavelet-based cascaded adaptive filter. Comput Biol Med 2007; 37:716-31.

[6] Chang KM, Chang KM. Pulse rate derivation and its correlation with heart rate. J Med Biol Eng 2009; 29:132-7.

[7] Zong W, Heldt T, Moody G, Mark R. An open-source algorithm to detect onset of arterial blood pressure pulses. Comp in Card 2003; 30:259-62.

[8] Aboy M, Crespo C, McNames J, Goldstein B. Automatic detection algorithm for physiologic pressure signal components, Proc 2nd Joint EMBS/BMES Conference 2002: 196-197.

[9] Li BN, Dong MC, Vai MI. On an automatic delineator for arterial blood pressure waveforms. Biomed Signal Proc and Control 2010; 5: 76-81.

[10] Berg R, Hemphill R, Abella B, Aufderheide T, Cave D, Hazinski M, et al. 2010 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care, Part 5: Adult Basic Life Support. Circulation 2010;122:S685-S705.

[11] Welch JP, Ford PJ, Teplick RS, Rubsamen RM. The Massachusetts General Hospital-Marquette Foundation Hemodynamic and Electrocardiographic Database - Comprehensive collection of critical care waveforms. J Clin Monitoring 1991;7:96-7.

[12] The Massachusetts General Hospital/Marquette Foundation (MGH/MF) Waveform Database, URL: http://physionet.org/physiobank/database/mghdb/

[13] Nenova B, Iliev I. An automated algorithm for fast pulse wave detection. Bioautomation 2010; 14:203-16.

[14] Tabakov S, Iliev I, Krasteva V. Online digital filter and QRS detector applicable in low resource ECG monitoring systems. Ann Biomed Eng 2008; 36:2065-76.

[15] ANSI/AAMI CE57: Testing and Reporting Performance Results of Cardiac Rhythm and ST Segment Measurement Algorithm. AAMI Recommended Practice: American National Standards Institute, Inc. 1998.



Address for correspondence.

Vessela Krasteva
Institute of Biophysics and Biomedical Engineering
Acad. G. Bonchev str., bl.105, 1113, Sofia, Bulgaria
vessika@biomed.bas.bg