Recognition of dicrotic notch in arterial blood pressure pulses using signal processing techniques

J Bethanney Janney¹, G Umashankar¹, S Krishnakumar¹, H Chandana², L Caroline Chriselda²

¹, ² Department of Biomedical Engineering, Sathyabama Institute of Science and Technology, Chennai, India

E-mail: jannydoll@gmail.com

Abstract. The Physiological condition of cardiovascular system is analyzed by arterial blood pressure pulse wave. The arterial pulse wave displays the genetic traits of the heart, average records of a heartbeat and variation in pressure as the heart spouts blood. This pulse monitoring is a standard process used to assess the cardiovascular system’s medical history. A waveform of the Arterial blood pressure usually involves a systolic level, diastolic occurrence, and dicrotic spike and dicrotic notch. The cardiac cavity contracting and relaxing leads to systolic and diastolic blood pressure respectively. The dicrotic notch which is a drop on the down slope shows systole termination and depicts the aorta closure of successive backward stream. The position of the dicrotic notch throughout the cardiac activity differs as per the duration of aortic closure. Dicrotic notch plays an essential part in sclerosis, occlusion, stenosis, arterial spasm and erythromelalgia diagnostic test.

Hence Discrete Wavelet transform is utilized in this proposed work to examine and assess the dicrotic notch.

1. Introduction

The pulse appearing in the blood pressure wave during the diastolic phase called dicrotic notch. The abrupt decrease in pressure preceding systolic contraction is the Dicrotic Spot. This decrease is triggered by blood pumping back into the arteries while the valve has been in the closure period [1]. Because some of the blood approaches the cardiac system, cardiac circulation also leads to this decrease of pressure. The dicrotic spot shows the termination of the systole and reflects the contraction of the aortic valve and the resulting regressive flow. In the conduction system, the position of the dicrotic spot differs as per the pacing of aortic closure. In context, for patients with hypovolemia, arterial closure is disrupted. Subsequently, for hypovolemic patients the dicrotic spot takes place further lower on the dicrotic arm. As arterial pressure is assessed at distal locations in the arteries the dicrotic spot remains elevated on the dicrotic arm as well. Before the start of the next systemic upstroke, diastolic pressure is calculated. The opposing perspective is that in an arterial blood pressure waveform, the dicrotic spot will not explicitly refer to the aortic pressure incisura [2].

An amount of blood is pushed into the aorta once the heart contracts, pressuring it to absorb this additional blood volume. Then blood is forced from the aorta via the arteries while the valve walls begin to recover. Throughout each heartbeat, this mechanism of contraction and getting back to normal continues when blood flows via the arteries [3, 4].
The Figure 1 depicts the events of the pulse waveform, Where S is an aortic pulse-wave starting point where the aorta releases as well as the left ventricular blood is expelled. P is a percussion wave that is triggered linearly by LV eruptions that maximize the arterial wall. T is a projected tidal wave mostly from tiny blood vessel. The end-point of the systolic process is C (Incisura), and hence the aorta is closed.

Figure 1. Arterial pressure waveform

Figure 2. Classification of Dicrotic Notch

the Figure 2 indicates several pulse waveforms with different clinical findings [5, 6]. Smooth or non-existent notch indicates dehydration of the patient. Decreased notch indicates high pressure of the pulse. In cardiopulmonary valve failure, a flattened notch is sometimes observed. Through accordance to intrinsic vascular resistance, the degree of dicrotic fall-off is the amount during which the arteriolar path traces decreases from end-systole to initial diastole shifts. The fall-off time becomes significant in patients with severely decreased vascular resistance. Owing to the dramatically decreased pressure in the arterial system, this happens too eventually as the end-systole exits. The aortic signal looks thin and elevated in this clinical condition. Dicrotic fall-off rates are significantly elevated in patients with increased vascular resistance, like main artery stenosis etc.

2. Related Works
Balmer et al. (2020) developed a latest end systole detection system for dicrotic notch-less aortic signal. The search feature employs the probabilistic model of beta distribution as a weighting factor and was adaptive based on past end systole positions of heart rate. Utilizing dicrotic notch positions from continuously assessed aortic pressure, forward predicted through pulse transit time (PTT) towards the more distal pressure signal, a validation method is established. The subsequent average difference ± acceptance parameters suggest the effectiveness of the algorithms designed [7].

Md. Sayed Tanveer and Md. Kamrul Hasan et al. (2019) presented a new ANN-LSTM signal framework for a deep model of blood pressure prediction. Without providing additional technical features, the framework was suitable for extracting the required features. The presented method matched the AAMI norm for BP estimation. Grade A has been attained in the BP efficiency evaluationfor both SBP and DBP [8].

Omkar Singh and Ramesh Kumar Sunkaria et al. (2017) suggested a reliable solution by defining fiducial points in stimuli of systolic blood pressure that used empirical wavelet analysis to detect the systolic peak and the origin of the stimulus of blood pressure. This approach was using empirical wavelet analysis to determine the basic frequency of the blood pressure signal and used the mix of the blood pressure signal and the predicted frequency to identify the starting point and systolic peak [9].

Omkar Singh and Ramesh Kumar Sunkaria et al. (2016) introduced by a particular technique
for initiation and systolic peak detection in EWT-based ABP. The algorithm is evaluated on numerous perspectives of differing archives for monitoring blood pressure. In order to improve the precision rate, sensitivity and successful predictivity were observed [10].

Sanjeev Nara, Mandvinder Kaur and Kundan Lal Verma et al. (2014) suggested a dynamic notch recognition algorithm for the identification of PPG dicrotic notches determined by non-invasive photoplethysmography sensors and a visual tool that calculates relative changes in blood flow. The proposed algorithm was implemented in MATLAB with the aid of the self-developed Graphic User Interface (GUI) [11].

3. Materials and Methods
A waveform of the Arterial blood pressure usually involves a systolic level, diastolic occurrence, dicrotic spike and dicrotic notch. The cardiac cavity contracting and relaxing leads to systolic and diastolic blood pressure respectively. The dicrotic notch which is a drop on the down slope shows systole termination and depicts the aortic valve closure and successive backward flow. The position of the dicrotic notch throughout the cardiac activity differs as per the duration of aortic closure. Dicrotic notch plays an essential part in sclerosis, occlusion, stenosis, arterial spasm and erythromelalgia diagnostic test. Therefore, in this proposed work discrete wavelet transformation is used to analyse and assess the dicrotic notch in the form of aortic pulse wave [12]. Using sensor composed of multiple channels arterial wave information is processed and a computer is utilized to capture the required data for future analysis. The uniform peer group of 22 patients has been evaluated utilizing two distinct Haar and Daubuechies4 (db4) wavelet transformation [13]. The proposed system's structure is shown in Figure 3.

![Figure 3. Block diagram of suggested system](image-url)
3.1 Wavelet Transform

A wavelet is basically a small pulse that focuses energy on time to provide a method for examining transient, non-stationary or time-varying events including a wave shown in Figure 4.

![Wavelet Function](image)

Figure 4. Wavelet Function

A signal can also be measured simultaneously as a function of $f(t)$ and illustrated as a linear decomposition of the sums, the coefficient and function elements. In the development of the wavelet, the two-parameter method is built meaning that it has a double sum and two-index factors. The Discrete Wavelet Transform $f(t)$ is called the collection of frequencies. The extension of the Wavelet pattern maps a time varying function into a coefficient sequence almost just like the Fourier series is doing with the four inherent properties. The expressions of singularities, the presentation of local base functions to allow functional methods adaptive to function homogeneities, also have the unrestricted base property for a number of function classes to include a broad range of signals. The source signal 1-D, 2-D, 3-D in the wavelets is transformed utilizing pre-specified wavelet coefficients. The wavelets are orthogonal, biorthogonal and multiwavelets [14].

3.2 Discrete Wavelet Transform

The Wavelet Sequence is only a sampled form of CWT and, focusing on the necessary precision, its simulation will occupy a significant amount of time and effort. A simple Wavelet Transform calculation is found to yield the Discrete Wavelet Transform that is centered on sub-band labeling.

3.3 Filter bank Tree

At various frequencies, the signal to be evaluated is processed via filters with specific cut off frequency. The wavelet transformation is altered to a filter bank tree by means of decomposition and reconstruction as shown in Figure 5 and Figure 6.

![Filter bank tree of Decomposition](image)

![Filter bank tree of Reconstruction](image)

Figure 5. Filter bank tree of Decomposition  Figure 6. Filter bank tree of Reconstruction
As shown in Figure 5, the transform is determined by subsequent low pass and high pass filtering of the discrete time series. This is also the methodology for Mallat. In the figure, the array x[n], where n is an integer, signifies the signal. G0 represents the low pass filter, whereas the high pass filter is marked by H0. The high pass filter generates precise details d[n] at each step, whereas the low pass filter correlated with the carrier signal creates generalized approximations, a[n].

The half band filters emit signals comprising merely twice the frequency band for each decomposition step. At a frequency of ω radians, the original signal will be sampled, thus removing half of the samples without data loss. This 2-decimation halves the time resolution, as only half the sample size now reflects the entire signal. Therefore, the low pass filtering of the half band eliminates half of the frequencies and hence halves the resolution, the decimation twice the size by 2.

The coefficients a[n] and d[n] obtained with this method provide indefinitely great time precision at longer wavelengths, while at shorter wavelengths, the frequency resolution appears randomly better. Before the target amount is achieved, the sorting and decimation step is performed. The highest number of decimated grades will rely on the signal length. The actual digital signal DWT was further derived by integrating each of the last decomposition levels [15, 16].

3.4 Methodology

The Pulse waveform is recorded using a multi-channel acquisition system and stored in PC. Signal processing and parameter extraction were carried out in Matlab [17]. The dicrotic notch of 22 subjects was analyzed.

- The discrete data is loaded into the Matlab. ABP signal is plotted using the loaded data.
- The first derivative of the ABP signal is taken to detect the abrupt changes in the pulse waveform.
- The differentiated pulse waveform is introduced to the Discrete Wavelet Transformation.
- As a result of the aortic valve closure, the dicrotic notch is found in the arterial pressure waveform.
- Dicrotic notch diagnosis is non-trivial since the pressure pulse might well be distorted of interference and in patients who are weak. It could diverge drastically from standard.
- By using wavelets of the 1st order derivative of the pressure waveform, the dicrotic notch can be identified as its notch position can be defined and the unique frequency bands of the pulse do not intersect.
- To decrease unnecessary interference, the arterial blood pressure pulse is pre-processed using a low pass filter.
- Then, by finding the highest and lowest of the pressure waveform respectively, the model identifies both the systolic high point and endpoint diastole, using the zero crossing of the 1st derivative all over the points, for each heart rate.
- At increasing levels, the system proceeds to measure the wavelet coefficients until the limit in the wavelets, identifying the notch position, appears during two successive measurements at a same point in time.
- By finding the successive limit over two continuous levels of the wavelet transformation, accurate and complete dicrotic notch analysis of the arterial blood pressure pulse was achieved.

4. Results and discussion

The proposed method used db4 wavelet, and Haar wavelets to detect and analyze the dicrotic notch. The approach employs the 1st order differential of the pre-processed ABP pulse signal for dicrotic notch recognition. The method initially computes the 1st order differential of the processed ABP pulse. The time series of the 1st order differential was further smoothed using
the low pass filters. The system then identifies the end diastole and the systolic high point to locate the dicrotic notch by finding the highest and lowest of the pressure waveform simultaneously, utilizing the first derivative's zero crossing all over the peaks, per heart rate. The method proceeds to calculate the wavelet transformation at increasing scales until the peak in the transformation of the wavelet, identifying the notch location at the same point in time over 2 consecutive scales.

The results in the following figures were obtained by using db4 wavelet, and Haar wavelets methods. The ABP (arterial blood pressure) signal and its derivative are shown in the Figure 7. The 1st, 2nd, 3rd level decomposition using dB4 wavelet is displayed in Figure 8, Figure 9 and Figure 10.

**Figure 7.** ABP signal and its derivative wavelet

**Figure 8.** 1st level decomposition using dB4 wavelet

**Figure 9.** 2nd level decomposition using dB4 wavelet

**Figure 10.** 3rd level decomposition using dB4 wavelet
In Figure 11 and Figure 12, the decomposition of the 4th level using the dB4 wavelet and the Haar wavelet is shown. It is observed from the process that the Haar wavelet is able to precisely locate all the dicrotic notches than the dB4 wavelet.

**Figure 11.** 4th level decomposition dB4 wavelet

**Figure 12.** 4th level decomposition Haar wavelet

**Table 1.** Duration of pulse and Dicrotic Notch

| Name of the Subject | Age | Sex | Systolic Duration (sec) | Dicrotic notch duration (sec) |
|--------------------|-----|-----|-------------------------|------------------------------|
| X1                 | 19  | F   | 0.27                    | 0.10                         |
| X2                 | 19  | F   | 0.28                    | 0.10                         |
| X3                 | 19  | M   | 0.3                     | 0.09                         |
| X4                 | 20  | M   | 0.27                    | 0.11                         |
| X5                 | 19  | M   | 0.28                    | 0.10                         |
| X6                 | 19  | M   | 0.27                    | 0.12                         |
| X7                 | 20  | M   | 0.29                    | 0.11                         |
| X8                 | 20  | M   | 0.26                    | 0.11                         |
| X9                 | 20  | M   | 0.27                    | 0.13                         |
| X10                | 20  | F   | 0.26                    | 0.10                         |
| X11                | 20  | F   | 0.29                    | 0.12                         |
| X12                | 34  | F   | 0.27                    | 0.11                         |
| X13                | 37  | F   | 0.28                    | 0.13                         |
| X14                | 38  | M   | 0.30                    | 0.14                         |
| X15                | 40  | M   | 0.27                    | 0.14                         |
| X16                | 44  | M   | 0.31                    | 0.15                         |
| X17                | 32  | M   | 0.27                    | 0.12                         |
| X18                | 34  | M   | 0.29                    | 0.14                         |
| X19                | 38  | M   | 0.30                    | 0.18                         |
| X20                | 37  | M   | 0.27                    | 0.14                         |
| X21                | 38  | F   | 0.26                    | 0.13                         |
| X22                | 41  | F   | 0.29                    | 0.16                         |
The effectiveness of suggested algorithms is evaluated on several research datasets available from Physio Net, fantasia dataset, MIMIC dataset [18] and challenge 2014 computers in cardiology training set. A team of skilled cardiologists were able to manually annotate the BP pulses. Via such a well-annotated dataset, the delineator can then be thoroughly evaluated in relation to systolic peaks, onset and dicrotic notch. Therefore, if the variation is within ±2 observations between the position observed and the ground truth, the system considers it more as correctly predicted (i.e., True Positive). Table 1 shows the duration of systolic and dicrotic Notch. Eventually, two standard reference metrics were used to validate the assessment: Sensitivity (SEN) and Positive Predictivity (PPRE) [19].

\[
\text{SEN} = \frac{TP}{TP + FN} \quad (1)
\]

\[
\text{PPRE} = \frac{TP}{TP + FP} \quad (2)
\]

Where, TP is the proportion of true positives, FN is the proportion of false negatives, and FP is the proportion of false positives. Table 2 presents the average performance of the two algorithms. The Haar and Daubuchies (db4) algorithm efficiency is contrasted with arterial blood pressure pulse delineator ground truth. The Haar wavelet provides a much better efficiency, as observable from Table 2.

| Algorithm          | Sensitivity SEN (%) | Positive Predictivity PPRE (%) |
|--------------------|---------------------|-------------------------------|
| Haar Wavelet       | 98.87               | 98.78                         |
| Daubuchies4 (db4)  | 94.53               | 94.41                         |

5. Conclusion
The proposed algorithm detected dicrotic notch in the Arterial Blood Pressure waveform to analyse the physiological changes in the cardiovascular system. The DWT algorithm included the technique of decomposition and reconstruction to define the ABP waveform frequency resolution and band width. Two distinct wavelet transforms, namely Haar and Daubuchies4 (db4), were tested for a number of individuals, which provided strong evidence that the Haar method is better in detecting the dicrotic notch than the db4 method. Although both the methods are useful in analyzing the dicrotic notch, Haar wavelet gave good results, and this work can be extended by using other wavelets to analyze the dicrotic notch. Implementation of the present method discussed for real time application is great task.

6. Acknowledgments
The sincere gratitude to the Sathyabama Institute of Science and Technology, Department of Biomedical Engineering, Chennai for providing the necessary support to successfully finish this research.

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