Comparison of Algorithms for Oscillometric Blood Pressure Estimation

This report is written mainly by Silu Chen during his M.Sc. thesis work at the University of Ottawa in 2011. Some changes are made by Miodrag Bolic

OBJECTIVES

* Identify main algorithms for oscillometric blood pressure estimation
* Identify main methods used in each step of the algorithms and understand their advantages and disadvantages
* Run the simulator to observe the results using provided database of BP measurements

CHAPTER CONTENTS

* Introduction to oscillometric algorithms
* Maximum amplitude algorithm
* Linear approximation algorithms
* Point of maximum/minimum slope
* Slope change algorithm
* Comparison of the algorithms

# Introduction

Large variety of methods were discovered that estimate blood pressure but these methods were scattered around many different publications or sources. Considering that oscillometric devices dominate the home blood pressure monitoring market, surprisingly little effort has been put forth to survey the underlying algorithms which are actually used to estimate blood pressure. A survey of the existing algorithms and methods will be presented in this chapter. The aim is to unite the diverse underlying algorithms and determine which algorithm is best for estimating SBP and DBP. Existing algorithms for blood pressure estimation are surveyed and assessed using a data set of 85 subjects. For each subject in this data set, oscillometric blood pressure will be estimated using the surveyed algorithms and compared to a set of nurse reference blood pressure readings obtained by auscultation. The algorithm or set of algorithms based on this data set is assessed.

# Overall Procedure

Estimation of SBP and DBP is performed based on an algorithm composed of several steps that processes this deflation curve. The individual steps of this algorithm have been proposed in many independent studies, but there exists a lack of unification between the existing methodologies. Given the deflation curve after an oscillometric recording, the procedure to estimate SBP and DBP may be generalized to the block diagram of Figure 1. This procedure can be broken down into the four steps, shown with rectangular boxes in Figure 1.

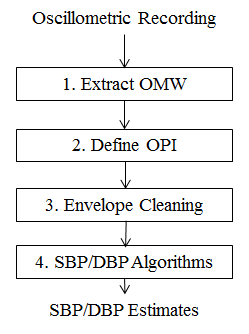


Figure 1. Block diagram for the proposed oscillometric blood pressure estimation algorithm.

Existing methods for steps 1 to 4 are quite diverse and varying. In the first step, extracting an OMW is necessary to identify pulsations that are caused by blood flow. The OMW should contain only the pulsations caused by the artery as it reacts to the decreasing cuff pressure. The downward trend relating to the cuff deflation should be removed to create the OMW. This can be performed by digital filtering (band pass [7], [8] or high pass [9]), analog filtering [3] or detrending [10], [11]. From the OMW, a definition of an OPI is then required as part of step 2. The OPI forms an envelope where points which correspond to SBP and DBP are located in later steps. The OPI can be taken as the height from baseline-to-peak, peak-to-peak, or area of each pulse [1], [10], [12], [13]. The OPI should form a locus, or envelope, for which cleaning techniques in step 3 are employed. This step is aimed at cleaning the envelope from any possible disturbances caused by noise or interference and is necessary for the algorithms later on in step 4 that estimate SBP and DBP values. Methods here include frequency domain filtering [7], [9] median filtering [14], moving average filtering [15]-[15] and curve fitting [18], [19]. These methods are intended to be a general purpose way rid the envelope formed by the OPI from noise or other interference. Afterwards, step 4 is performed where points that correspond to the SBP and DBP are found on the now cleaned envelope. Four known algorithms have been surveyed for this: the maximum amplitude algorithm (MAA) [3], [7]-[9], [12], [13], [15], [16], linear approximation algorithm (LAA) [22], points of maximum/minimum slope algorithm (MMSA) [12], [13], [23], [24], and slope change algorithm (SCA) [25]. Variations of these algorithms also exist, but these four represent the fundamental algorithms which others are based on. Finally, the SBP and DBP points on the cuff deflation curve to provide proper estimates of SBP and DBP in terms of mmHg.

Although a number of algorithms exist for estimating SBP and DBP, to the best of the author’s knowledge nobody has assessed or evaluated these different algorithms against each other. Some work that address the current state of oscillometric measurement techniques exist [1], [13], [26], [27], but the underlying algorithms behind these devices lack a more critical assessment. One objective of this chapter to fulfill this need and compare the different algorithms in each step of the procedure. This is important because further work on oscillometry requires an algorithmic procedure for oscillometric blood pressure estimation.

# Assessment of Oscillometric Algorithms

Algorithms for SBP and DBP estimation in oscillometric recordings will first be implemented and then assessed. These algorithms follow the diagram as shown in Figure 1. All algorithms for the four step blood pressure estimation procedure discussed in section I will be implemented and tested on the available data set. A typical deflation curve is shown in Figure 2. The remainder of the processing will work on this curve to eventually produce SBP and DBP estimates.



Figure 2. Typical cuff deflation curve.

## Extract OMW



Two main components comprise the deflation curve; the pressure from the deflating cuff and the pressure pulsations induced in the artery from the gradual deflation. The objective of this step is to extract these pressure pulsations, also known as oscillometric pulses [1], [3]. Over the duration of the recording, these pulses form a signal known as the OMW [27], but may also be referred to in some literature as the oscillogram [4], oscillometric pulse profile [9], oscillatory pressure curve [11], oscillometric signal [15], or simply as oscillation amplitudes [18]. The term OMW will be used here.

Methods to recover the OMW from the deflation curve consist of filtering [3], [7]-[9] and detrending [10], [11]. Filtering, either by band pass [7], [8] or high pass [3], [9], removes the frequency components that belong to the deflating cuff pressure. A band pass filter with cutoff 0.1 to 20 Hz is used here and the resulting OMW is shown in Figure 3 (a). Detrending is also used, where a line of best fit that represents the decreasing cuff pressure is subtracted from the deflation curve [10], [11]. Fitting the line requires locating the beginning of each individual pulse on the deflation curve and then joining these points. This trend line also produces an estimate of the decreasing cuff pressure [10], [11]. The main difference between detrending and filtering is that if the decreasing cuff pressure is properly estimated by detrending, then each pulse of the produced OMW should start at zero and at no point in the OMW should ever be negative. An example of the OMW extracted by this method is shown in Figure 3 (b).

## Define OPI



The OPI is a defined quantity that forms a locus, or envelope, where points which correspond to SBP and DBP are located. After the OMW is extracted, the OPI can be found by one of three methods. Methods in current literature compute the OPI as either the height of each pulse from baseline-to-peak, peak-to-peak or as the area under each pulse, which can be found by integration [1], [10], [12], [13]. Peak-to-peak and area values can be estimated after peaks are identified. The definition of baseline-to-peak values is vague because to the best of our knowledge, no strict definition of a baseline is ever provided. Here, it is assumed that the baseline is zero for the duration of the recording.

Three definitions of the OPI are applied to the OMW extracted by filtering, while only two definitions of the OPI are applied to the OMW extracted by detrending. The baseline-to-peak and peak-to-peak definitions applied to an OMW after detrending produce the same results, so the baseline-to-peak method here is redundant and ignored. Figure 4 shows the three different OPI calculations on a single pulse for an OMW extracted by filtering. Simpson’s rule was used to find the discrete area in Figure 4(c).



Figure 3. OMW extracted by (a) filtering and (b) detrending.



Figure 4. OPI extracted by (a) Baseline to peak, (b) Peak to peak, (c) Area

Here, the area is calculated for each pulse to produce an OPI. The start and end of each pulse on the OMW is taken as the troughs. Evaluation of the extraction methods and OPI definitions is the goal here. Five signals are available at this point, three defined OPI values from the filtered OMW and two defined OPI values from the detrended OMW.

## Envelope Cleaning



Much like other signals, the OMW can be corrupted by noise and interference, some of which are from natural physiological processes and some of which are caused by external factors. These include movement or cardio-respiratory interactions. Here, methods will be discussed which reduce these disturbances so that algorithms in step 4 of the procedure may be applied to estimate SBP and DBP. Since the envelopes formed by the OPI should follow a distinct characteristic, the role of envelope cleaning is to re-shape a corrupted envelope, regardless of what the source of the irregularities may be. Algorithms specifically designed to target one type of disturbance also exist. For example, algorithms based on an external sensor and adaptive filtering work especially well for the elimination of motion artifacts **Error! Reference source not found.**, but they add complexity and only target this specific disturbance. In this chapter, the focus of envelope cleaning is on less intensive, general purpose methods that clean the envelope.

Two simple filtering methods have been proposed to help get rid of artifacts and interference: median filtering and moving average filtering. Median filtering is a nonlinear filter which is often applied to image processing because of its strong ability to preserve edges and remove impulse noise. In blood pressure, median filtering has shown to work well in removing spurious points caused by possible motion artifacts [14]. Median filters replace each sample by the median value of it and its neighboring samples.

Moving average filters also work by considering a window for each point, except instead of replacing a point with the median point of the window, the mean of all the points in the window is used. These are a type of non-causal finite impulse response (FIR) filter. The moving average filter can also be thought of as a LPF with a cutoff dependent on the window size. Windows lengths that have been previously used in moving average filtering for this purpose can depend on the size of the width of the pulses [15] or are a fixed length nine-point window for a 128 Hz sampled system [16].

Another known technique to clean the envelope is curve fitting [19]-[21]. Curve fitting is the process of constructing a line or curve through the points of interest that has the best fit. The curve is defined by a mathematical function with variables that are adjusted. Best fit is in terms of least squared error between the points of interest and the curve produced after fitting. Current literature fits the envelope by a Lorentzian [19] or Gaussian function [21].

Fitting is performed by constructing either a Gaussian or Cauchy-Lorentzian function that best fits the given data. These functions are defined by a set of input parameters, such as mean, variance and amplitude. The set of inputs that minimize the sum of squares between the fitted curve and the data is known as the least squares best fit.

Existing literature uses symmetric Gaussian and Lorentzian functions to fit the envelope [19]-[21]. However, the OMW envelope is not always symmetric so, in this chapter, asymmetric functions are also proposed and implemented. An asymmetric Gaussian function can be constructed with different standard deviation and amplitude to the left and right side of its mean:

|  |  |  |
| --- | --- | --- |
|  |  |  |

To the left side of the mean, *µ*, this function has a standard deviation and amplitude, and *A1*. To the right side of the mean, this function has a standard deviation and amplitude, and *A2*. This gives the function asymmetric properties, as two different distributions are used to construct the function. At the point where *x = µ*, it can be shown that *A1* = *A2*.

Another function, which exhibits properties of an asymmetrical Gaussian function, is also implemented which is built by summing two Gaussian functions. This function has been implemented for OMW in [20] and is expressed here:

|  |  |  |
| --- | --- | --- |
|  |  |  |

This is simply two Gaussian functions with different mean, standard deviation and amplitude summed together. Second, the Lorentzian function is implemented [21]. Similar to the above, an asymmetric representation of this function may be expressed by:

|  |  |  |
| --- | --- | --- |
|  |  |  |

This function will exhibit Lorentzian distribution on both sides of the mean, but with different standard deviation and amplitude. Again, at the point where *x = µ*, it can be shown that *A1* = *A2*. Also, like the Gaussian implementation, two Lorentzian functions can also be summed up. This function has not previously been used for curve fitting an OMW, but it combines the idea of using a Lorentzian function presented in [21] with the idea of summing up two functions like the one used for Gaussian distributions in [20]. Two Lorentzian functions, with different mean, amplitude and standard deviation, are summed as follows:

|  |  |  |
| --- | --- | --- |
|  |  |  |

All four of these functions are implemented and evaluated. Minimization to produce the least square error is performed in MATLAB by Levenberg-Marquardt optimization.

## SBP/DBP Algorithms



Information regarding a subject’s blood pressure is embedded on the cleaned envelope formed by the OPI. Blood pressure is estimated by applying algorithms that determine points on the envelope that correspond to the SBP and DBP. Four known algorithms, which may be divided into two different approaches: height based and slope based, were analyzed. Height based algorithms include the most popular MAA [3], [7]-[9], [12], [13], [15], [16], and the lesser known LAA [22]. Slope based approaches include the well-known MMSA [12], [13], [23], [24], and SCA [25]. The SCA is a yet to be published algorithm. Height based algorithms depend on locating the mean arterial pressure (MAP) first. This will be addressed first before the four algorithms are discussed.

MAP is defined as average arterial blood pressure of an individual. For intra-arterial blood pressure measurements, it is estimated as the average of the total arterial pressure during one cardiac cycle [8]. As opposed to the SBP and DBP, this quantity is not commonly returned by blood pressure monitors but empirical methods do exist to approximate the MAP. From the SBP and DBP, the MAP may be calculated by [7]:

|  |  |  |
| --- | --- | --- |
|  |  |  |

In oscillometric measurements, the widely accepted method to estimate the MAP is by finding the maximum point on the OPI [3]. In certain cases, the MAP has also been taken as 95% of the maximum point on the diastolic side [8]. An actual pressure value in mmHg can then be estimated by locating this point on the deflating cuff curve. When looking at the OMW, the point which corresponds to the SBP typically lies to the left of the MAP and the points which corresponds to the DBP lies to the right of the MAP. Thus, when considering the OMW plotted against time, it is said that the MAP divides the OMW into two regions: the systolic region and the diastolic region.

### Maximum Amplitude Algorithm

The MAA is the most popular oscillometric algorithm for determining blood pressure [15]. As shown in Figure 5, this algorithm operates by first finding the point on the envelope corresponding to the mean arterial (MAP) [8]. The right side of the maximum point of the envelope is the diastolic side and the left side is the systolic side. In Figure 5, this point corresponds to amplitude *A*. Predetermined systolic and diastolic characteristic ratios, *rs* and *rd*, are then used to find the points that correspond to SBP and DBP. The systolic ratio can reportedly range from 0.45 to 0.73 and the diastolic ratio may range from range from 0.69 to 0.83 [7]. These ratios seem to differ between devices as well. Some have also adopted dynamic ratios that change depending on the subject’s MAP [9]. Regardless of what ratio is chosen, the point corresponding to SBP can be found by multiplying the height of the MAP point with the systolic ratio, *A⋅rs*. The resulting amplitude can then be located on the systolic side of the envelope to produce the SBP point. The same can be done for the point corresponding to the DBP, by multiplying the height of the MAP with the diastolic ratio, *A⋅rd* and locating the point on the diastolic side of the envelope.

### Linear Approximation Algorithm

Similar to the MAA, the LAA also operates by using the heights of the envelope and also requires predefined systolic and diastolic characteristic ratios [22]. This algorithm works by approximating the envelope with a pair of linear lines of best fit based on the peaks of all the oscillometric pulses. A pair of lines is first approximated, one for peaks 1, 2 and another for peaks 3 to N, where N is the total number of peaks. Next, another pair of lines is approximated, one for peaks 1 to 3 and another for peaks 4 to N. This procedure continues until a pair of lines for peaks 1 to N – 2 and peaks N – 1 and N is found. For each pair of lines, it is assumed that the one produced by the first set of the peaks should have positive slope and represent the systolic side, whereas the one produced by the second set of peaks should have a negative slope and represent the diastolic side. If some artifacts or interference causes any approximated line to have the opposite slope, then it and its paired line are removed from analysis. Each iteration should then produce a valid pair of lines that have an intersection point. Intersection points from all the produced pairs of lines are compared and the highest intersection point is taken as the initial MAP.

To eliminate any artifacts or interference, the procedure is performed again, but this time only with peaks that are greater in amplitude than half the initial MAP point. All remaining points after this elimination are then again fitted for pairs of linear lines of best fit. The same procedure as before is performed, except N now represents a lesser number of peaks than before. After each iteration, a pair of lines should be produced, each with a corresponding intersection point. The highest intersection point is taken as the final MAP and the pair of lines that produce this intersection is used to locate SBP and DBP. The line on the left with positive slope is the final systolic line and the line of the right with negative slope is the final diastolic line. The amplitude of the MAP point is multiplied by the corresponding systolic or diastolic characteristic ratio to produce points that are located on the final systolic and diastolic lines, respectively. These points are the final systolic and diastolic points. **Figure 6** shows the implementation of this algorithm with the final pair of lines of best fit illustrated. The amplitude corresponding to the MAP is *A* and the systolic and diastolic ratios are *rs* and *rd*. By using linear approximations, this algorithm provides another layer of artifact reduction. The LAA was developed by Medero in a 1996 US patent [22] and has not been found in any other known literature.

### Points of Maximum/Minimum Slope Algorithm

Unlike the previous two algorithms, the MMSA considers the slope of the envelope rather than the heights [12], [13], [23], [24]. Here, the systolic point is found as the point on the envelope where the slope of the envelope is at its maximum and the diastolic point is where the slope of the envelope is at its minimum. As shown in **Figure 7**, these two points can be found by taking the derivative of the signal. Since the derivative represents the slope of the line tangent to each point on the signal, the point where slope is maximum also correspond to the maximum of the derivative signal and the point where slope is minimum also corresponds to the minimum of the derivative signal. Overall, the MMSA is arguably the second most well-known algorithm, just behind the MAA [1].

### Slope Change Algorithm

The SCA finds the points on the envelope where the slope changes, or the inflection points. Although no published literature regarding this algorithm exists, [25] argues that it is based on the physiology of blood pressure. It is hypothesized that the envelope may be split into 4 distinct regions, based on slope. The location of the intersection of these regions are taken as the systolic, MAP and diastolic points. The four regions S1 to S4 are:

* S1: From the beginning of the reading to the systolic point where no blood flow passes under the cuff but oscillations are present because the radial artery pulsations are transmitted to the proximal side of the cuff.
* S2: From the systolic point to the MAP where blood flow is no longer occluded and starts flowing into the arm.
* S3: From the MAP point to the diastolic point where blood flow is turbulent and the artery under the cuff is free from occlusion.
* S4: From the diastolic point to the end of the procedure where the radial artery is no longer occluded.

This algorithm differs from the previous slope based algorithm in that it looks for inflection points on the envelope, which is when the derivative of the signal is equal to zero, rather than the maximum and minimum points. The algorithm is illustrated in **Figure 8**.

## SBP/DBP Estimation

Actual systolic and diastolic pressure values must be extracted after their corresponding points are located on the envelope. This is performed by mapping the points determined to be SBP and DBP on the envelope back to the cuff deflation curve, as shown in Figure 5 to **Figure 8**. After locating the points on the envelope which correspond to the SBP and DBP, actual pressure values are found by mapping these points to the deflation curve. Pressure values in mmHg are returned to the subject, which are the estimated SBP and DBP.



Figure 5. MAA implementation.



Figure 6. LAA implementation.



Figure 7. MMSA implementation.



Figure 8. SCA implementation.

# ANALYSIS OF THE ALGORITHMS

Oscillometric blood pressure data was acquired using an automated digital blood pressure monitor (UFIT® TEN-10) from Biosign Technologies Inc. This is a wrist device that plugs into a PC through USB and samples at a rate of 100 Hz. The device returns two waveforms, the deflating cuff pressure and the discrete derivative of the pulse pressure, which are used to determine the OMW. A data set of 85 healthy subjects, whose oscillometric blood pressure was recorded using the UFIT, was provided by Biosign and used to assess the above mention oscillometric algorithms. Oscillometric blood pressure was recorded for these subjects according to SP10 standard, which is established to provide safe practices for automated sphygmomanometer performance evaluation. This procedure consists of 5 oscillometric blood pressure recordings performed by the BP device with 5 nurse blood pressure measurements in between them. First, an oscillometric recording was performed, and then a one minute break followed. After the break, two trained nurses measured blood pressure. Another one minute break followed this, where then another oscillometric recording is performed and the procedure is continued again for a total of 5 trials. For each subject, 5 oscillometric recordings along with 5 sets of two nurse measurements are obtained. The nurse measurements are all performed by auscultation and used as a reference reading for the oscillometric recordings. If the two nurses differ by over 5 mmHg in SBP or DBP, the recording is discarded and repeated. Out of the 85 subjects, 84 underwent this 5 trial recording procedure and 1 underwent only 4 trials of recordings instead.

In order to present a concise summary of these results, the results are presented qualitatively as MODERATE, GOOD or VERY GOOD in Table 1 to Table 3. Table 1 shows the performance of the different ways to perform steps 1 and 2 of the algorithm: extract an OMW and define the OPI. Respectively, the ratings MODERATE, GOOD and VERY GOOD correspond to blood pressure estimation improvement of less than 5 mmHg, between 5 to 7 mmHg and greater than 7 mmHg with reference to the nurse readings. Table 2 and Table 3 show the performance of envelope cleaning methods. Table 3 shows the results for envelope cleaning methods where curve fitting with a sum of two functions has been combined with median or moving average filtering. For these results, the ratings MODERATE, GOOD and VERY GOOD correspond to blood pressure estimation improvement of less than 1 mmHg, between 1 to 2 mmHg and greater than 2 mmHg. These performance ratings are all assessed from the Biosign data set.

Table 1. Performance of different OPI definitions and two OMW extraction methods

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **OMW Extraction Method:** | **Filtering** | | | **Detrending** | |
| **OPI Defined** | **P2B** | **P2P** | **Area** | **P2B/P2P** | **Area** |
| **Performance** | MODERATE | GOOD | VERY GOOD | GOOD | VERY GOOD |

Table 2. Performance of envelope cleaning methods.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Cleaning Method** | **Median Filter** | **MA Filter** | **Sum Two Lorentz** | **Sum Two Gaussian** | **Asymm. Lorentz** | **Asymm. Gauss** |
| **Performance** | MODERATE | GOOD | VERY GOOD | VERY GOOD | GOOD | MODERATE |

Table 3. Performance of envelope cleaning methods that combine two methods.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Cleaning Method** | **Median Filter** | | **Moving Average Filter** | |
| **Sum Lorentz** | **Sum Gaussian** | **Sum Lorentz** | **Sum Gaussian** |
| **Performance** | VERY GOOD | VERY GOOD | VERY GOOD | VERY GOOD |

The final step, consisting of four algorithms for oscillometric blood pressure estimation is evaluated. For the procedure used here, filtering is used for step 1, the area based OPI is used for step 2 and a combination of moving average filtering followed by curve fitting by a sum of two Gaussian functions is used for step 3. An evaluation of these four algorithms is shown in Table 4, where for each trial, the mean absolute error (MAE) and standard deviation (STD) between estimated blood pressure and nurse blood pressure readings is presented. It can be seen here that the CHA performs the worst, while the MAA and LAA (height based algorithms) perform best. It is worth mentioning that the algorithms may perform differently for each subject. That is, someone whose nurse reading may vary with their MAA estimation by over 20 mmHg may still be within 5 mmHg for the MMSA. It is difficult to choose one algorithm over another because they rely on two different fundamental approaches. Moreover, choosing one algorithm over the other may eliminate important physiological features that might otherwise be useful. A potential future work might be to determine which algorithm performs best on which subject and why.

Table 4. Estimated MAE and STD in mmHg between estimated SBP and DBP and nurse readings for all algorithms over 5 trials.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Trial 1** | | **Trial 2** | | **Trial 3** | | **Trial 4** | | **Trial 5** | |
|  |  | **MAE** | **STD** | **MAE** | **STD** | **MAE** | **STD** | **MAE** | **STD** | **MAE** | **STD** |
| **MAA** | **SBP** | 7.94 | 7.01 | 7.07 | 6.77 | 7.11 | 5.43 | 7.94 | 6.96 | 6.4 | 6.96 |
| **DBP** | 7.65 | 7.72 | 7.05 | 7.31 | 6.53 | 5.96 | 7.26 | 7.21 | 6.84 | 7.79 |
| **LAA** | **SBP** | 7.73 | 7.29 | 8.14 | 10.77 | 7.37 | 5.79 | 7.46 | 6.51 | 7.09 | 7.86 |
| **DBP** | 6.78 | 5.99 | 7.98 | 8.62 | 6.7 | 4.92 | 6.71 | 5.15 | 5.96 | 5.82 |
| **MMSA** | **SBP** | 9.88 | 8.41 | 9.13 | 8.1 | 9.87 | 7.54 | 9.66 | 7.17 | 9.75 | 7.83 |
| **DBP** | 7.21 | 5.76 | 7.74 | 9.677 | 6.75 | 5.5 | 6.78 | 5.53 | 6.93 | 5.56 |
| **CHA** | **SBP** | 15.67 | 9.26 | 15.4 | 8.13 | 15.88 | 8.87 | 15.55 | 8.43 | 15.88 | 8.58 |
| **DBP** | 7.61 | 5.66 | 7.74 | 9.32 | 6.97 | 5.47 | 7.08 | 5.55 | 7.17 | 5.38 |

# Conclusion

A variety of algorithms exist to determine the SBP and DBP from the oscillometric method. Although literature examines oscillometric devices from the perspective of a black box approach, no work has been done to examine the quality of the underlying algorithms. The work here surveyed and evaluated the different algorithms to assess performance in the estimation of blood pressure. Various algorithms for oscillometric blood pressure estimation were implemented and validated on a data set. This allowed the entire oscillometric blood pressure estimation method be evaluated and the results showed one particular set of algorithms that stood out. The algorithm which produced the lowest error between the estimated blood pressure and the reference readings here is to extract the OMW by filtering, and then use the area defined OPI. The preferred envelope cleaning method consists of a moving average filter, followed by Gaussian curve fitting.

# References

1. K.G. Ng, C.F. Small, “Survey of Automated Noninvasive Blood Pressure Monitors,” *Journal of Clinical Engineering*, vol. 33, Dec. 1994, pp. 452-475.
2. W.A. Littler, B. Komosuoglu, “Which is the Most Accurate Method of Measuring Blood Pressure?,” *American Heart Journal*, vol. 117, Mar. 1989, pp. 723-728.
3. M. Ramsey III, “Blood Pressure Monitoring: Automated Oscillometric Devices,” *Journal of Clinical Monitoring and Computing*, vol. 7, Jan. 1991, pp. 55-67.
4. G.A. van Montfrans, “Oscillometric Blood Pressure Measurement: Progress and Problems,” *Blood Pressure Monitoring*, vol. 6, Dec. 2001, pp. 287-290.
5. M.A. Hasan, T.A. Thomas, C. Prys-Roberts, “Comparison of Automatic Oscillometric Arterial Pressure Measurement with Conventional Auscultatory Measurement in the Labour Ward,” *British Journal of Anaeshesia*, vol. 70, Feb. 1993, pp. 141-144.
6. C.M. Masi, L.C. Hawkley, E.M. Rickett, J.T. Cacioppo, “Respiratory Sinus Arrhythmia and Diseases of Aging: Obesity, Diabetes Mellitus and Hypertension,” *Biological Physiology*, vol. 74, Feb. 2007, pp. 212-223.
7. L.A. Geddes, M. Voelz, C. Combs, D. Reiner, C.F. Babbs, “Characterization of the Oscillometric Method for Measuring Indirect Blood Pressure,” *Annals of Biomedical Engineering*, vol. 10, Nov. 1982, pp. 271-280.
8. H. Sorvoja, R. Myllyla, P. Karja-Koskenkari, J. Koskenkari, M. Lilja, A. Kesaniemi, “Accuracy Comparison of Oscillometric and Electronic Palpation Blood Pressure Measuring Methods Using Intra-Arterial Method as a Reference,” *Molecular and Quantum Acoustics*, vol. 26, 2005, pp. 235-260.
9. J.C.T.B. Moraes, M. Cerulli, P.S. Ng, “Development of a New Oscillometric Blood Pressure Measurement System,” *IEEE Computers and Cardiology*, Hannover, Germany, Sep. 1999, pp. 467-470.
10. V. Jazbinsek, J. Luznik, Z. Trontelj, “Non-Invasive Blood Pressure Measurements: Separation of the Arterial Pressure Oscillometric Waveform from the Deflation Using Digital Filtering,”*IFBME Proceedings of EMBEC’05*, Prague, Czech Republic, Nov. 2005.
11. J.N. Amoore, “Extracting Oscillometric Pulses from the Cuff Pressure: Does it Affect the Pressures Determined by Oscillometric Blood Pressure Monitors?,” *Blood Pressure Monitoring*, vol. 11, Oct. 2006, pp. 269-279.
12. A. Ball-llovera, “An Experience in Implementing the Oscillometric Algorithm for the Non-Invasive Determination of Human Blood Pressure,” *Proceeding of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Cancun, Mexico, Sep. 2003.
13. G. Gersak, V. Batagelj, J. Drnovsek, “Oscillometric Virtual Instrument for Blood Pressure Measurement,” *XVIII Imeko World Congress*, Rio de Janeiro, Brazil, Sep. 2006.
14. P. Shaltis, A. Reisner, H. Asada, “Calibration of the Photoplethysmogram to Arterial Blood Pressure: Capabilities and Limitations for Continuous Pressure Monitoring,” *27th Annual International Conference of the IEEE/IMBS*, Shanghai, China, Sep. 2005.
15. P.D. Baker, D.R. Westenskow, K. Kuck, “Theoretical Analysis of Non-Invasive Oscillometric Maximum Amplitude Algorithm for Estimating Mean Blood Pressure,” *Medical and Biological Engineering*, vol. 35, May 1997, pp. 271-278.
16. J.Y. Lee, J.K. Kim, G. Yoon, “Digital Envelope Detector for Blood Pressure Measurement Using an Oscillometric Method,” *Journal of Medical Engineering & Technology*, vol. 26, May 2002, pp. 117-112.
17. S. Colak, C. Isik, “Fuzzy Pulse Qualifier,” *Proceeds of the 23rd International Conference of the North American Fuzzy Information Processing Society*, Banff, Canada, June 2004, pp. 850-853.
18. C.T. Lin, S.H. Liu, J.J. Wang, Z.C. Wen,”Reduction of Interference in Oscillometric Arterial Blood Pressure Measurement Using Fuzzy Logic,” *IEEE Transactions on Biomedical Engineering*, vol. 50, Apr. 2003, pp. 432-441.
19. L.T. Hersh, B. Friedman, R. Medero, “Method for Oscillometric Blood Pressure Determination Employing Curve Fitting,” US Patent 5 704 362, Jan. 6, 1998.
20. H. Chunbao, L. Lingjiao, “Technique Research and System Design of Ambulatory Blood Pressure Monitoring,” *8th Internation Conference on Electronic Measurement Instruments*, Xian, China, Jul.-Aug. 2007, pp. 669-672.
21. C.H. Nelson, T.J. Dorsett, C.L. Davis, “Method for Noninvasive Blood-Pressure Measurement by Evaluation of Waveform-Specific Area Data,” US Patent 4 889 133, Dec. 26, 1989.
22. R. Medero, “Determination of Oscillometric Blood Pressure by Linear Approximation,” US Patent 5 577 508, Nov. 26, 1996.
23. J. Erlanger, “Studies in Blood Pressure Estimations by Indirect Methods I. The Mechanism of the Oscillatory Criteria,” *American Journal of Physiology*, vol. 39, 1916, pp. 401-446.
24. W.T. Link, “Method of and Appatus for Determining the Diastolic and Systolic Blood Pressure of a Patient,” US Patent 4 712 563, Dec. 15, 1987.
25. J. Jilek, “Physiology of Oscillometric Blood Pressure Measurement,” unpublished.
26. H. Sorvoja, R. Myllyla, “Noninvasive Blood Pressure Measurement Methods,” *Molecular and Quantum Acoustics*, vol. 27, 2006, pp. 239-264.
27. J. Jilek, T. Fukushima, “Oscillometric Blood Pressure Measurement: The Methodology, Some Observations and Suggestions,” *Biomedical Instrumentation & Technology*, vol. 39, May. 2005, pp. 237-241.