Oscillometric blood pressure measurements: A signal analysis

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Oscillometric Blood Pressure Measurements: a signal analysis

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Abstract. In this paper, the oscillometric waveform measured by automatic non-invasive blood pressure meters (NIBP) is analyzed by transforming the data from the time domain to the frequency domain. The signal’s spectrum of the oscillometric waveform is in current literature badly understood or explored. The only known link between the oscillometric waveform and the blood pressure is the maximum of the oscillometry’s envelope equalling the mean arterial pressure (MAP). This link is established under the assumption that the oscillometry is an AM-signal. Unfortunately, computing the MAP is difficult in practice due to the non-sinusoidal nature of the actual measured signals. In this paper, we construct the best AM-signal approximation of the oscillometry and explore its use to compute the MAP.

1. Introduction
One of the most popular medical instruments used at home is the automatic non-invasive blood pressure meter (NIBP). Most medicine cupboards contain one and a lot of people use it on a daily basis. A cuff is wrapped around the arm of the patient and inflated. Most classical automatic blood pressure meters are based on the oscillometric principle, which records the oscillations in the cuff pressure during deflation of the cuff. Out of this oscillometric waveform a mean arterial pressure (MAP) as well as a systolic and diastolic pressure is deducted. Each manufacturer of blood pressure meters has developed his proper algorithm which is most of the time patented. However, in general, the systolic and the diastolic pressure are defined as a certain percentage of the mean arterial pressure, [1]. The mean arterial pressure is defined as the maximum of the envelope of the oscillometric waveform. In many cases the oscillometric waveform has no clear envelop and determining the maximum is rather difficult and far from being accurate. Since the systolic and the diastolic pressure are defined as a certain percentage of the mean arterial pressure, it is important to determine this maximum very accurately or otherwise erroneous results will be obtained.

In order to be able to develop an accurate algorithm, it is mandatory to gain an extensive insight in the measurements. What kind of effects can explain the observed measurements? Can we eliminate all kinds of noise sources in order to ‘clean up’ the signals? Can we eliminate the effects of the blood pressure meter itself? Does the blood pressure behave like a linear or a nonlinear device-under-test?

The main problem arises due to the non-sinusoidal nature of the oscillometric measurements which makes it hard to define the maximum of the signal’s envelope. In this paper, we construct the best AM-signal approximation and assess its use to compute the MAP. In section 2 the experimental setup is described. Section 3 analyses the measurement results. Section 4 deals with the linearization of the blood pressure meter. Section 5 studies the question whether a linearization of the measurements is rich enough to describe the blood pressure. A conclusion is drawn in Section 6.
2. Experimental Setup
Measuring equals knowing! And developing new algorithms or models for whatever application requires accurate measurements as well as a solid insight in the measured data. Often too little information that is present in the data is used during signal processing due to the fact that many effects are simply overlooked.

2.1. Blood pressure meter
The automatic non-invasive blood pressure meter used for this project has been specially adapted so that the raw waveforms, i.e. the oscillometric waveform as well as the pressure curve, can be read through the USB port of the blood pressure meter. Since this device will be used on patients it is important that it behaves like a normal automatic blood pressure meter without additional wires or external printed circuit boards. The blood pressure meter samples the data at a frequency of 150 Hz.

2.2. Measurement campaign
In order to obtain measurement results that contain all different blood pressure types: hypertension, atherosclerosis, arrhythmia,…a large measurement campaign needs to be conducted. Therefore the blood pressure of 100 patients will be measurement by an automatic blood pressure meter as well as by the classical Korotkoff method [2], where a physician listens through a stethoscope to the Korotkoff sounds. This is referred to as the auscultatory method. In a first measurement, the oscillometric method will be used on the left arm and the auscultatory method on the right. After 5 minutes the measurement will be repeated but the arms will be switched. This is to omit the difference in blood pressure that exists between both arms. The patients will be selected so that no confounding effects among the patients are possible. The auscultatory measurement will be considered as the golden standard.

Before starting the large scale measurement campaign, a representative set of measurements is obtained through a small scale experiment. This small scale experiment consists of measuring the blood pressure on the right arm of 15 patients in rest by means of the oscillometric method. This experiment will allow us to get insight in the measured signals.

3. Analyzing the measurement results
3.1. What theory predicts...
In theory, the oscillometric waveform obtained from a blood pressure measurement should look like a modulated signal with a single carrier frequency, which represents the heartbeat. Figure 1 (a) simulated an ideal oscillometric waveform in time domain. The heartbeat in Figure 1 (a) was 54 beats per minute, the sampling frequency was 150 Hz, 2000 time domain samples were simulated and a DC offset of 1000 was used. In the frequency domain, this results in three spectral components, one which represents the carrier frequency (the heartbeat) and two sidebands which contain the information signal. Taking the envelope (gray curve in Figure 1 (a)) of the amplitude modulated signal returns the information signal. This is a concept that is well known in the telecommunication world.
Figure 1. Oscillometric waveform in theory: (a) time domain and (b) frequency domain

Basically, most of the automatic blood pressure meters compute the systolic and diastolic values from the envelope of the oscillometric waveform. Generally, there are two schools to pin-point the systolic and diastolic pressures: height-based or slope-based criterion.

The height-based method starts by computing the maximum of the envelope. The systolic and diastolic values are obtained as fixed ratios of the envelope’s amplitude with respect to its maximum. Different companies following this height-based criterion apply different ratios to avoid patent conflicts. Some researchers obtain different ratios based on different mathematical models of the oscillometric waveform: in [3] one defines a standard for the ratios as 40% and 60%, in [4] 59% and 72% and in [5] 50% and 80% were chosen for the systolic and diastolic pressures respectively. The slope-based criterion applies the derivative of the envelope of the oscillometric waveform with respect to the cuff-pressure to derive the systolic and diastolic values, [6].

3.2. In reality...

However, as often the case, theory is far from reality. Figure 2 shows the oscillometric waveforms measured in practice (sampling frequency is 150 Hz).

Figure 2. Measured oscillometric waveform: (a) time domain (b) frequency domain.

One can clearly see from these measurements that the carrier wave is not a single sine wave, but additional frequency components are present. This becomes more obvious when looking to the measurements in the frequency domain. Instead of three frequency components (carrier and both sidebands), the spectrum contains a second and a third harmonic of the carrier and the sidebands, as well as intermodulation products of the carrier and the sidebands. These are created by the nonlinear
behaviour of the blood pressure meter. The blood pressure meter can become nonlinear due to for example an amplifier that goes into compression or due to the valve that opens and closes.

The main problem that the different schools have in common is the need to compute the signal’s envelope. This might seem straightforward when looking at figure 1 but the measurement practice of figure 2 disagrees. The problem resides in the fact that the oscillometric waveform is not a single modulated sine wave. Besides the heart rate, the oscillations reveal artifacts such as nonlinearities. These artifacts make it impossible to compute the signal’s envelope by means of the Hilbert transform. To overcome this problem, one fits a smooth spline through the noisy maxima of the pulses, [7]. Hence, one obtains an envelope holding different local maxima and different points of inflexion. It is not straightforward to pin-point the systolic and diastolic values in neither of the two schools.

4. Linearization of the oscillometric waveform

Instead of fitting a smooth spline through the local maxima of the measured oscillometric waveform, we pursue a frequency domain approach. The theory implicitly assumes that the oscillometric waveform is an AM-signal with the heart rate as carrier frequency. Unfortunately, the measurements are disturbed by nonlinearities coming from the measurement device, the body itself and the non-sinusoidal amplitude modulation. To eliminate the influences of the nonlinearities, we take the frequencies in Figure 2 (b) at the first harmonic and its sidebands. Computing the inverse Fourier transform, will result in the ‘best’ AM-signal approximation for the measurements see Figure 3.

![Figure 3. Measured oscillometric waveform: Measurements (black), linear approximation measurements (gray), envelope of the gray curve (dashed black).](image)

In Figure 3, we computed the inverse Fourier transform of the first harmonic and its sidebands of the measured oscillometric waveform. This corresponds to an AM-signal as the theory predicts. Furthermore, we computed the envelope of the ‘best’ AM-signal of the measurements. The amplitude of the ‘best’ AM-signal does not match the measurements. This is not a problem to eventually determine the systolic and diastolic values, see more details in the final version. In Figure 3 only the first harmonic was used. In the final paper, we explore the influence of the other measured harmonics and the different included sidebands to the AM-signal approximation.

5. Validating the linearization

The only questions that remain are: Does it make sense to linearize the oscillometric waveform? Will the remaining envelope still be representative to calculate the mean arterial pressure? Are the nonlinearities triggered by the body or the measurement device?

The last question is a rather tough question to verify. It is clear that the nonlinearities come from both the body and measurement device. The body acts nonlinearly due to the fact that the heart beat is not a single sine-wave, besides this the amplitude modulation is not sinusoidal since the deflation of the cuff is performed step-wise. Nevertheless, removing these non-linearities is of profound interest since current literature reveals no knowledge how to interpret the higher harmonics observed in the signal’s spectrum. Thus, linearizing the signal provides a simple representation of the measurements.

To answer the first two questions a small-scale experiment is performed.
5.1. Experimental set-up
The automatic non-invasive blood pressure meter used for this project has been specially adapted so that the raw waveforms, i.e. the oscillometric waveform as well as the pressure curve, can be read through the USB port of the blood pressure meter. Since this device will be used on patients it is important that it behaves like a normal automatic blood pressure meter without additional wires or external printed circuit boards. The blood pressure meter samples the data at a frequency of 150 Hz.

A representative set of measurements is obtained through a small scale experiment. This small scale experiment consists of measuring the blood pressure on the right arm of 33 patients in rest by means of the oscillometric method. The patients will be selected so that no confounding effects among the patients are possible: mixed backgrounds, sex, age and expected blood pressure. This experiment will allow us to verify whether or not the mean arterial pressure obtained by using the ‘best’ AM-signal approximation is comparable to the MAP returned by the algorithm of the automatic blood pressure meter.

5.2. Arterial mean: an objective measure
In this paper we will focus on determining the mean arterial pressure, since this is a well defined value and the same for all automatic blood pressure meters, namely it is the pressure in the cuff that is observed at the time instant where the envelope of the oscillometric waveform is maximal. Comparing systolic and diastolic pressures is not a self-evident task since the criteria to determine these values differ for each blood pressure meter and is company confidential.

5.3. Statistical Analysis
The question that needs to be answered is whether or not the MAP-values obtained via the different approaches are comparable. An intuitive approach to compare the MAP-measurements of the NIBP and the best AM-signal approximation is by comparing the average or mean of the MAP-values. To assess this comparison a statistical hypothesis test is used. The null- and alternative hypotheses are given by,

$$\mathcal{H}_0 \equiv \mu_i = \mu_j \text{ subject to } \mathcal{H}_1 \equiv \mu_i \neq \mu_j$$

where $\mu_i$ denotes the expected value of either the NIBP ($i = 1$), the linearized waveform ($i = 2$) and the linearized waveform plus one intermodulation product ($i = 3$). In other words, the null-hypothesis $\mathcal{H}_0$ states that the MAP-values of the different algorithms are equal. The alternative hypothesis $\mathcal{H}_1$ states that there is a difference between the methods.

To investigate the validity of the null-hypothesis, we compute the boxplot of the different measurements. A boxplot provides an easy visualization of the probability density function.

![Boxplot for the MAP-data.](image)

The height of the box is representative for the variability of the median and the median is representative for $\mu_i$. Inspecting Figure 4 shows that a visual discrimination of the three methods is not possible, due to the fact that the medians of the different columns lie inside all three boxes. Hence, we
expect the differences among the methods to be small. Indeed, the 95% confidence interval for the difference $|\mu_1 - \mu_2|$ is $[3.8]$ mmHg. This interval is computed under the assumption that the measurements follow a Gaussian distribution. Hence this means that the true difference between the measured MAP values obtained by the blood pressure meter and the best AM-signal approximation lies between 3 and 8 mmHg with a confidence of 95%. However, during the blood pressure measurements the pressure in the cuff is not decreased in a linear way but in steps of 5 to 8 mmHg. Thus, no sufficient evidence is gathered that the linearized waveform is incapable of describing the gathered measurements.

6. Conclusion

In this paper, we discussed a seemingly simple modeling problem to identify the systolic and diastolic blood pressures. In literature most research is focused around determining the systolic and diastolic pressures. This paper studies the measurements in detail. We showed that the measurements are subjected to nonlinearities. The non-linearities implies the need of a difficult model for the oscillometric waveform, we advocate to remove them.

We presented a simple approach to remove the nonlinearities from the measurements by a frequency domain approach. The corresponding time-domain wave form can be seen as the ‘best’ AM-signal approximation of the measurements, which is what the theory predicts. A visual statistical analysis revealed no substantial evidence that the linearized waveform is not rich enough to allow deduction of the mean arterial pressure. Hence, the analysis suggests that the linearization can be used to extract the systolic and diastolic pressures from the best AM-signal which needs further examination.

References