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A method for retrieving the waveform of the pressure pulsations from the output of an electronic oscillometer

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ABSTRACT

In the most common version of an oscillometric blood pressure monitor, the output from the pressure transducer, *Y(t)*, is split into two parts, and used for separate determinations of the pressure inside the pneumatic cuff and its fluctuating part; the latter is derived by sending *Y(t)* to a high-pass filter (HPF) and amplifying the filtered part to obtain the oscillometric signal *O(t)*. Using a typical HPF-amplifier combination, we show that if *p(t)*, the pulsatile part of the cuff pressure, is defined to be a train of positive-going pulses, *O(t)* turns out to be rather close but not identical to d*p*/d*t*, and to demonstrate that one can easily retrieve *p(t)* from a record of *O(t)*. This means that, with a small modification, the instrument can provide both *p(t)* and d*p*/d*t*; the practical advantages of this demonstration are pointed out.

Keywords: Blood pressure, Oscillometry

1. INTRODUCTION

The oscillometric method of measuring blood pressure, which predates the discovery of the eponymous Korotkoff sounds, relies on examining only the pulsating part of the pressure in the pneumatic cuff used for occluding a suitably sized artery of the subject [1-7]. Even when the cuff pressure *P* is higher than the systolic blood pressure (*sbp*) and the underlying artery is occluded, the sensor used for measuring *P* registers small fluctuations in response to the arterial pulse. As the counterpressure applied through the cuff is slowly reduced from a suprasystolic level to a value lower than the diastolic blood pressure (*dbp*), or gradually raised from a subdiastolic to a suprasystolic value, the pressure fluctuations at first increase and then decrease. In the classical, non-electronic version of the technique, as practised, for example, by Hill [1] or by Erlanger [2], the operator had direct access, through the dial of an anaeroid manometer or a graphic record, to both the pressure signal and the pulsations (hereafter called p-pulses). The pioneers spent much ingenuity on finding the physical basis of the phenomenon, and on establishing criteria for deriving the values of the *sbp*, *dbp* and the mean arterial pressure (*map*) from the peak amplitudes of the p-pulses; the activity has come to be known as oscillometry or oscillotonometry. Though early variants of the technique, many of which relied on the use of a double cuff [3,4], failed to displace the auscultatory method, the introduction, a little over thirty years ago, of inexpensive piezoresistive pressure sensors [8] gave a new lease of life to oscillometry, and many commercial devices are now available for automated measurement of blood pressure.

In most oscillometric monitors, the cuff pressure is changed in a continuous manner, and it is important to state at the outset that the following discussion does not apply to the relatively uncommon design where the counterpressure is varied in a stepwise manner [9, 10]. The crucial step in the determination of the blood pressure involves filtering, usually through electronic hardware, in order to split the signal from the pressure transducer into a pulsatile part and a background trend of the slow reduction in the pressure within the cuff. The mode of operation of a typical electronic oscillometer has been described in one publication [5] as follows: "The counterpressure signal, monitored via a pressure tap located in the side of the compression chamber, was filtered using 0.1 Hz high-pass R-C filter to permit separate recording of the mean counterpressure and amplified pressure oscillations"; similar statements appear in other sources. The peak amplitudes of the electrical pulses at the output of the amplifier (hereafter called a-pulses) are used for deducing, with the aid of proprietary algorithms, the values of *sbp*, *dbp*, and *map*.

With the notable exception of a recent paper by Amoore [10], practitioners of electronic oscillometry seem to have paid no attention to the distortion introduced by the electronic circuitry. Considerations based on the frequency response of the high-pass filter and the frequency content of the pressure signal lead one to suspect that an a-pulse would resemble the time derivative of the corresponding p-pulse. This study was designed to answer two questions, whose practical importance will be discussed later. First, if one is using a typical filtering network for separating the oscillating part of the pressure signal from the slow trend, what is the relation between a p-pulse and the corresponding a-pulse? Secondly, is there a simple way to retrieve, from a record of a-pulses, the form of the causative p-pulses?

We stress here that, in the foregoing discussion, p-pulses have been defined to be positive-going, and note that these pulses can be isolated, with negligible distortion if one has access to contemporary computing facilities, by using software alone [11–13]. It will therefore be convenient to reserve the term oscillometry for measurements in which the low-frequency and high-frequency parts of the pressure signal are separated by means of electronic circuits; the phrase sphygmopiezometry will be applied to an approach where one records the output of the pressure sensor *in toto*, and uses software to resolve the output into a baseline and a train of p-pulses. Our task here is to show that an oscillometer (using a smooth variation in the counterpressure) can be easily adapted to provide a record of p-pulses.

2. EXPERIMENTAL DETAILS

The pressure sensor used in this study was a piezoresistive device (Freescale Semiconductors MPX5050DP). For obtaining the oscillometric signal, we used the circuitry presented by the manufacturer in an application note [7]; since there are some errors in the pin assignments in this document, our circuit is reproduced in **Figure 1**. The performance of the filter-amplifier combination as a function of input frequency is plotted in **Figure 2**. The static response of the pressure sensor was determined by using a water manometer, and the result came out to be in agreement (within the specified error limits) with the manufacturer's data. The step response of the sensor, and of the sensor-filter-amplifier combination, evaluated by manually disconnecting an inflated cuff from the input port, are illustrated in **Figure 3**; the shape of the pressure discontinuity (caused by the abrupt reduction in the pressure) is determined by the operator's agility, but the rate of fall of the output shows that the response is sufficiently fast for the purpose at hand.

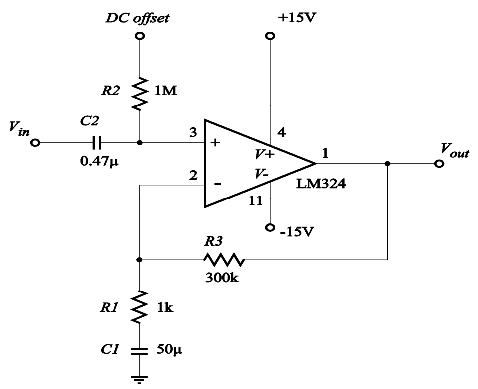

Figure 1. Circuit diagram of the oscillometric amplifier.

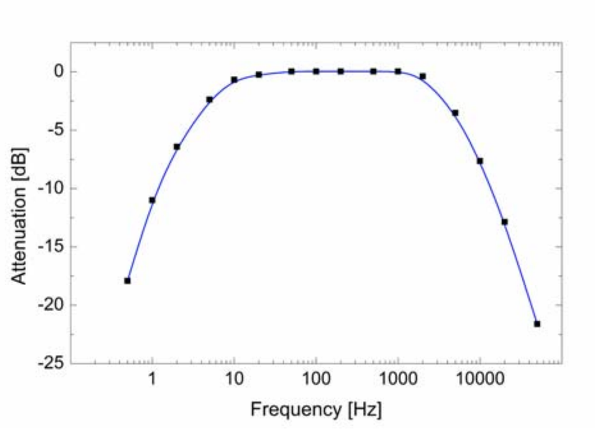

Figure 2. Frequency response of the filter-amplifier circuit.

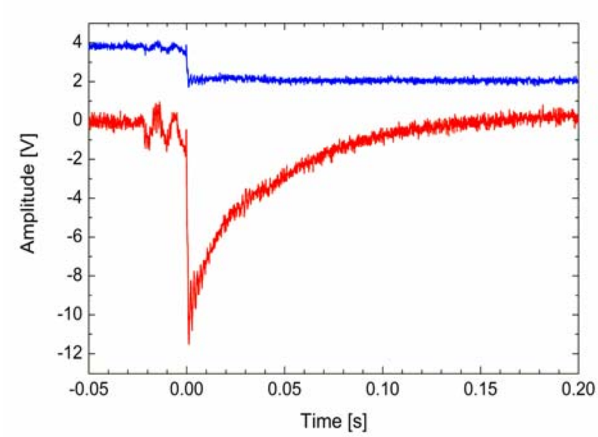

Figure 3. The output signal of the oscillometric amplifier (lower curve) as a response to a step-like change in its input (upper curve); the latter has been multiplied by a factor of 50, and displaced vertically in order to bring it within the frame.

The traditional method for occluding the brachial artery was used in this study; it entails wrapping a standard blood pressure cuff around the upper arm and inflating the cuff by compressing a rubber bulb. The rubber tube for reading the cuff pressure was connected to the input port of a piezoresistive pressure transducer (Motorola MPX 5050DP). Following the usual practice, the output Y of the pressure transducer was split into two parts, one of which was connected directly to a multi-channel analogue-to-digital converter (ADC), and the other to the input terminal of the oscillometric amplifier, whose output O was connected to a different channel of the ADC. In order to improve the signal-to-noise ratio, a high sampling rate was used (10^4 Hz for each channel), and the raw data were transformed to a less dense, smoother set (corresponding to a sampling rate of 10^2 Hz for each channel) by using the "decimate" function of MATLAB. In the following paper [13], an alternative to decimation has been presented, which amounts to replacing a set of r consecutive data points by their arithmetic mean. After decimation, the direct signal was converted into the cuff pressure P (in mm Hg).

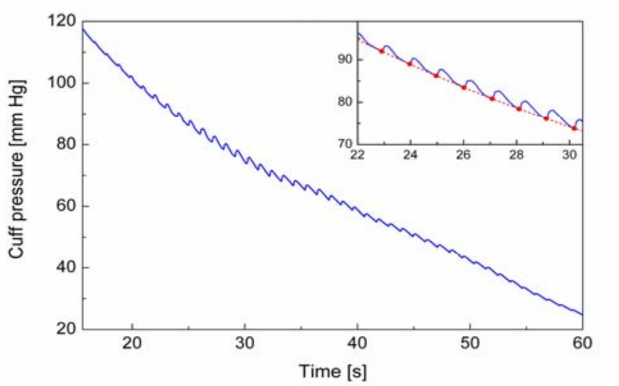

Figure 4. Plot of the direct output of the pressure sensor *vs* time (continuous line). The inset shows an enlarged portion of the main graph demonstrating the method of baseline subtraction. The local minima (filled circles) between each pulse were identified by a computer and interpolated to the whole region (dotted curve).

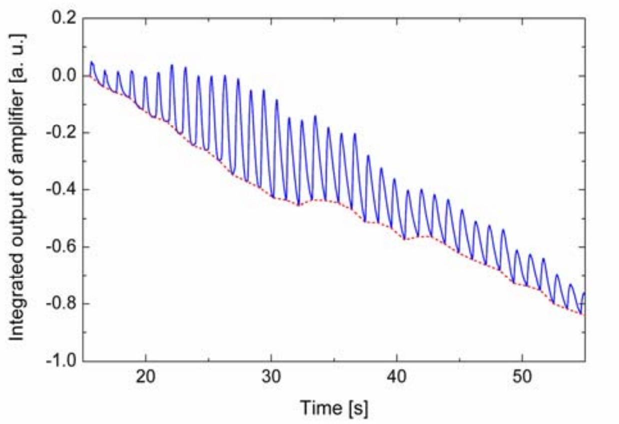

Figure 5. Plots of $N(t)$, the integral of the amplifier output (continuous curve) and $L(t)$, the baseline (dotted curve) obtained by passing a continuous curve through the minima of $N(t)$.

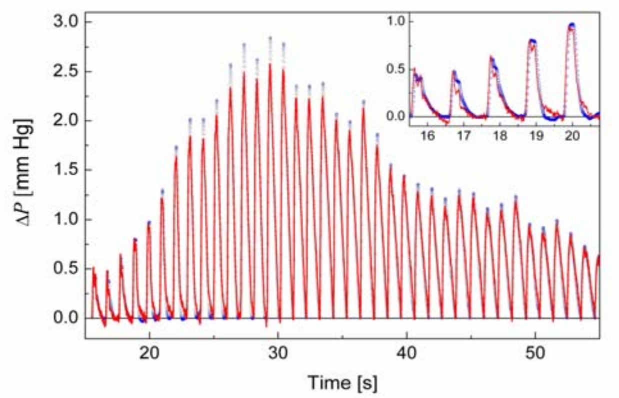

Figure 6. Plots of the pulsating part of the cuff signal (continuous curve) and the integral of the amplifier output signal after baseline subtraction (open circles). The inset shows the early part of the deflation phase (where the deviation between the two curves is most pronounced.

3. RESULTS

As stated above, acquisition of P and O is sufficient for the implementation of oscillometry, as currently practised [10]; the output P is plotted in **Figure 4**, while **Figure 5** shows, for reasons that will be explained shortly, the integral of O. Since we wish to establish the relation between O and the pulsating part of P, it was necessary to resolve P into two components, $P=p+b$, where b is a slowly declining base line and p a train of p-pulses (which would be non-negative in the absence of noise). The details of the method used for this resolution are described elsewhere [13]; the procedure, illustrated in the inset of **Figure 4**, involves finding the minima in P, and identifying b with an interpolated curve that passes through all the minima.

Once b and p become available, it is easy to calculate $s=\mathrm{d}b/\mathrm{d}t$ and $q=\mathrm{d}p/\mathrm{d}t$, and compare $O(t)$ with $\mathrm{d}P/\mathrm{d}t=s+q$. As the difference between $O(t)$ and $\mathrm{d}P/\mathrm{d}t$ is too small to be noticeable in a plot, we will adopt a different strategy-for scrutinizing the difference. Our main interest lies in recovering the p-pulses from the a-pulses; it turns out that this can be done by focussing attention on $N(t)$, the integral of $O(t)$. The discrepancy between $O(t)$ and q can be traced to the fact that, since s cannot be neglected, $\mathrm{d}P/\mathrm{d}t$ and $\mathrm{d}p/\mathrm{d}t$ cannot be identical. One finds, upon examining a plot of $N(t)$ against t, shown in **Figure 5**, that the minima in $N(t)$ are not close to zero, which would be the case if s were negligible; however, the blemish can be easily removed by constructing a base line $L(t)$ passing through the minima and subtracting its contribution from $N(t)$. As may be seen from **Figure 6**, the adjusted form of the integral, $J(t)\equiv N(t)-L(t)$, turns out to be in satisfactory agreement with $p(t)$, showing that the p-pulses can indeed be recovered from the a-pulses.

We conclude this section by listing the main steps involved in the procedure developed by us; departures from the standard version commence at the second step.

- Feed one part of the pressure signal to the amplifier circuit shown in **Figure 1** (or to a circuit with a similar dynamic response). Use the other part for recording the overall cuff pressure.
- Integrate $O(t)$, the output of the amplifier, and plot the integral $N(t)$ against t.
- Find the minima in the above plot and construct a smooth baseline, $L(t)$, passing through all the minima.
- Use the adjusted integral $J(t)\equiv N(t)-L(t)$ as a representation of the p-pulses.

4. CONCLUDING REMARKS

We have shown above that a small amendment in the processing of oscillometric data leads one to the contours of the p-pulses and their derivatives, a goal that has so far been attained only through sphygmopiezometry [11–13]. Since the advantages of acquiring these waveforms have been discussed by Brinton and co-authors [14], we will not dwell on this issue here.

With the amplifier circuit and the method of analysis described here, one can easily convert a standard sphygmomanometer into an oscillometer whose output has a known relationship with the shape of the p-pulses. There is at least one commercial instrument that allows the user to record both *P* and *O* [10]. This means that the time is now ripe for establishing reliable and device-independent criteria for deducing *sbp* and *dbp* from oscillometric data.

We conclude by drawing attention to another point of practical importance. The amplifier circuit used in this study follows the approach chosen by previous oscillometrists, but the data presented here indicate that an appropriately designed operational differentiator would perform equally well; if the cuff deflation (or inflation) is arranged to be a linear ramp [11, 12], d*P*/d*t* and d*p*/d*t* would differ only by a constant, making the task of baseline correction a trivial matter.

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