Central blood pressure from peripheral pulse measurements

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In this study we explore the possibility of obtaining BP information from PWV measurements. We have conducted an analysis with data from three individuals which unveils the existence of a clear connection between these two magnitudes. Moreover, this connection is in qualitative agreement with common existing models.

I. INTRODUCTION

With the increase in life expectancy, cardiovascular diseases have become one of the major causes of mortality. For long, it has been well-established that hypertension constitutes an important risk factor, and blood pressure (BP) measurements have been carried out for over 100 years. The most widely used technique for BP measurement used to consist in the use of a sphygmomanometer to determine brachial BP (BBP). However, different values of BP are obtained when measured on different sites of the body. In general, whereas diastolic BP (DBP) seems to be similar when measured on different sites, significant differences occur when dealing with systolic BP (SBP) and therefore with pulse pressure (PP), which is defined as the difference between SBP and DBP, with generally increasing values as we get further from the aorta (as explained by McEniery *et. al.* [1]). Recent evidence suggests that central BP (CBP) could be a better predictor of some cardiovascular complications, especially atherosclerosis and organ damage. Roman *et. al.* [2], in a study with 3520 participants, concluded that central PP (CPP) was more strongly related to atherosclerosis and carotid hypertrophy than brachial PP (BPP). A study conducted by Cremer *et. al.* [3] over 703 hypertensive participants with low cardiovascular risk concluded that 24-hour CPP measurement was a better predictor of cardiovascular events in this kind of patients than 24-hour BPP measurement. Pini *et. al.* [4], in a study with 398 over-65 participants, concluded that carotid BP better predicts cardiovascular events than BPP, also pointing in the direction of CBP being a better predictor than BBP. This growing evidence supports the use of CBP measurement to assess cardiovascular risk (without necessarily excluding BBP or other measurements).

In addition, different BP-lowering drugs, even if they have similar effect on BBP, may produce different outcomes on CBP, as shown by Williams *et. al.* [5], so that a good assessment of hypertension treatments would require both BBP and CBP measurements.

All these findings have led to a growing interest in the development of non-invasive techniques for CBP measurement. These techniques must be able to estimate CBP from indirect measurements. Some widely spread methods rely on pulse wave analysis. These methods consist on recording some parameters of the pressure waveform, such as pulse wave velocity (PWV), from which CBP is inferred. To obtain PWV, one option is to take measurements at two different sites of the body. These sites may be close to each other (see, for example, the device designed by Nabeel *et. al.* [6], in which the measurement sites are at a distance of 23 mm), or separated by a significant distance. In the latter case, carotid-femoral, carotid-brachial and carotid-radial measurements are common choices (the commercial SphygmoCor for PWV measurement, for example, relies on carotid-femoral measurement). The main advantage of a short separation device compared to long separation devices is that it makes it easier to have a precise measure of the blood traveling distance between the measurement sites, which are often selected on the same artery, whereas its main drawbacks are a greater uncertainty in time difference and possible interference effects. A second option is to use pulse measurements taking from some site in the body and compare them to the ECG signal. To obtain the CBP from the pressure waveform data, the transfer function method is commonly used. This method consists in considering the CBP and the pressure wave as the input and output, respectively, of a linear system. Under this assumption, CBP could be recovered from the pressure wave if we knew the transfer function. The different procedures using this method make some assumptions over this transfer function, but calibration is generally required for the procedure to work with each patient.

An important difficulty that arises when determining CBP is the fact that CBP obtained from a single measurement at clinical rest conditions does not seem to give a good estimate of through-day CBP. In this way, Burns *et. al.* [7] compared 24-hour measurements of BBP and CBP to single laboratory measurements in rest conditions, and found that, while laboratory measurements of BBP did provided a good estimate of through-day BBP, they tended to underestimate CBP against 24-hour measurements. Therefore, it seems that measurement of CBP through non-invasive techniques should be made through 24-hour repeated measurements to be reliable. Moreover, classical devices for blood pressure measuring, such as the sphygmomanometer, only provide an average value, not beat-by-beat data, so that they are not suitable for es-

timation of CBP from pulse wave analysis. This brings in the need for devices which allow the performance 24-hour beat-by-beat measurements. In addition, it would be convenient that these devices cause as little disturbance to the patient as possible, as, apart from the higher probability of patient rejection, such a disturbance could cause some alteration to the patient, and consequently affect the measurement (for example, it could disturb the patient's sleep). Thus, an alternative to disturbing devices (such as the commonly used cuff-based devices) should be investigated.

There are already some commercial devices for CBP measurement from pulse wave analysis. This includes the SphygmoCor and DiaTecne PulsePen for clinical measurement, and HealthSTATS B-Pro for 24-hour measurement. They all provide good estimations of CBP, but they all are extremely expensive nowadays, and, except for B-Pro, this devices are complex and must be managed by a professional.

In this study, we investigate the possibility of obtaining information about CBP (and BP in general) with non-intrusive techniques with an affordable device.

II. BACKGROUND

In this section we review some theory related to ECG and Impedance Pletysmography (IPG) measurements and how to derive blood pressure from these signals. The basic theory of ECG and IPG signals is extracted from Cuervo's Bachelor's Thesis [8].

The ECG signal is obtained from continuous measurement of the potential difference between different points on the body surface, which allows to obtain information from the heart polarization. The simplest version, which is the one which we used in this study, requires two measurement points (for example, the hands), from which a projection of the heart polarization vector is obtained. A schematic representation of a typical ECG signal portion corresponding to one beat can be seen in figure 1. The most easily recognizable feature in the signal is what is known as the QRS complex and corresponds to ventricular depolarization, which is followed by ventricular contraction. The time interval between the onset of the QRS complex and the ejection of blood from the ventricles is known as Pre-Ejection Period (PEP).

The IPG signal is obtained by measuring the resistance between two points of the body. Since the resistivity of the blood is significantly lower than that of the surrounding tissue, the resistance varies as the pulse wave goes through the measurement area giving rise to a variation in the arterial volume.

From the delay between some characteristic points of these two signals, we can get an estimate of PWV. For this purpose, the pulse transit time (PTT) is defined as the time difference between ventricular ejection and some fiducial point of the IPG signal (e.g. maximum or minimum). Since ventricular ejection is not an event that

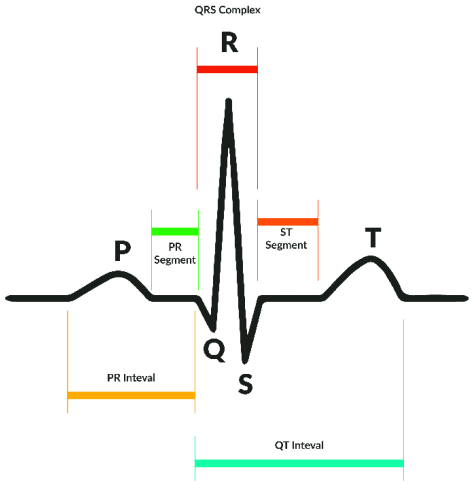

Figure 1. Schematic ECG signal with its characteristic points. From Miramontes *et. al.* [9].

can be easily identified in the ECG, the QRS complex is used instead. The time difference between the onset of the QRS complex (i.e. point Q) and the chosen fiducial point from the IPG signal is known as the Pulse Arrival Time (PAT). Observe that PAT is equal to PTT plus PEP. For commodity, however, the maximum of the QRS complex (i.e. point R) is commonly used instead of point Q.

The way in which the PWV relates to blood pressure is explained by Zhang *et. al.* [10]. We start with Moens–Korteweg equation:

$$\mathrm{PWV} = \sqrt{\frac{Eh}{2\rho R}}\,, \tag{1}$$

where E is the incremental elastic modulus of the blood vessel, h is the vessel wall thickness, ρ is the blood density and R is the inner vessel radius. On the other hand we have the empirical law

$$E = E_0 e^{a\mathrm{BP}}\,, \tag{2}$$

where E_0 and a are constants. From equations 1 and 2 and taking into account that PWV is inversely proportional to PTT, we deduce that BP is related to PTT through an equation of the form

$$\mathrm{BP} = \alpha \cdot \ln \mathrm{PTT} + \beta\,, \tag{3}$$

where α and β are constants. This is in fact a very simplified model; we have assumed that the pressure is constant both in time and through all the traveled length. However, it can be used to obtain reasonably accurate measurements of both SBP and DBP, as reported by Zhang *et. al.* [10]. To that end, coefficients α and β must be determined for both SBP and DBP for each individual. Moreover, they must be determined for a particular position of the body. The adjustment of these coefficients

Figure 2. Photograph showing the taking of a measurement.

can be done by simple linear regression, and requires the use of another BP measurement device. It is not especially important whether this other method provides only an average BP value through several seconds instead of continuous or beat-by-beat values, as we can simply use the mean of ln PTT through the measuring time for the linear regression. To obtain different pairs of values for the linear regression, the pressure is variated using different strategies, such as doing some kind of exercise or performing the Valsalva maneuver.

III. METHOD

The objective of the measurements was to investigate the variations of PTT due to exercise and the performing of Valsalva maneuvers.

The measurements were taken from a sample of 3 male individuals (ages 21-22). Each measurement consisted on recording ECG and IPG signals obtained during 1-2 minutes. Ballistocardiography (BCG) and tonometry signals were also recorded. The measurements were taken in standing position. The ECG signal was obtained from two electrodes on a handlebar that the individuals held during the measurements, whereas the IPG signal was measured from foot to foot through sensors located on a platform where the individuals stood for measurements. The BCG signal was also obtained from sensors at the feet.

We performed three measurements per individual. The first one was performed at rest. During the second measurement, the individuals were asked to alternate the performing of Valsalva maneuvers with resting periods. The third measurement was obtained immediately after a few minutes of intense exercise. In figure 2 we can see a picture showing how a measurement is taken.

The signals which we obtained were processed using the Pan-Tompkins algorithm. We used Matlab to process the signals. The codes were taken from Cuervo's Bachelor's Thesis [8].

To analyze the measurements, we plotted in each case the processed ECG signal against the processed ICG signal. We chose to use the R point of the ECG signal and the maximum of the IPG signal as the characteristic points to determine PAT. We measured PAT by manual exploration of some portions of the plotted signals (see figure 3).

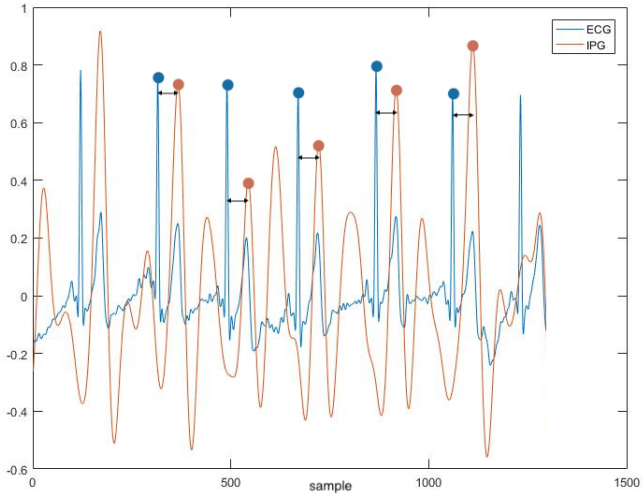

Figure 3. Characteristic points to determine PAT from ECG and IPG signals.

For the first measurement of each individual (the one taken in resting conditions) we simply chose a portion of the signal where 10 consecutive pulse signals could be clearly identified for both ECG and IPG and calculated PAT as the average of the PAT for these 10 consecutive pulses.

For the second measurement of each individual (when the Valsalva maneuvers were performed) we analyze a fragment of the signal corresponding to the performing of a Valsalva maneuver and the following recovering time.

For the third measurement of each individual, we chose different portions corresponding to 10 consecutive pulses at significantly separated times to study the evolution of PAT.

IV. ANALYSIS OF THE RESULTS

The results obtained for PAT at resting conditions can be found in table I.

Individual	PAT (ms)
1	257
2	315
3	330

Table I. PAT at resting conditions.

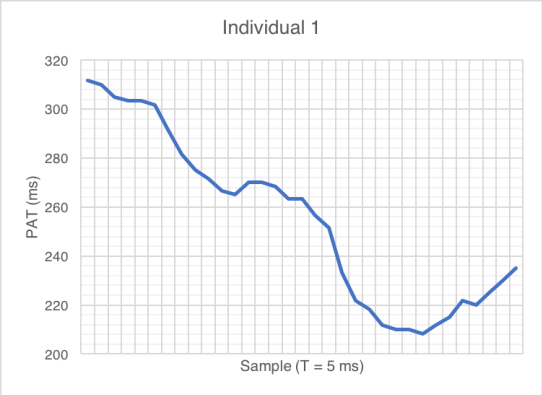

Figure 4. Evolution of PAT for individual 1 during and after the performance of a Valsalva maneuver.

In figures 4 and 5 we plotted the evolution of the obtained PAT for individuals 1 and 2, respectively, for a portion of the second measurement, corresponding to the performing of a Valsalva maneuver and the subsequent recovering time. Each value of the plotted signal results from averaging each measured value with the preceding and the following measured values, i.e.

$$x'_n = \frac{x_{n-1} + x_n + x_{n+1}}{3} .$$

As we can see in both graphics, the obtained PAT decreases during the performance of the Valsalva maneuver and it gradually returns to values at rest conditions afterwards. This agrees with the theoretical model exposed in section II: as a consequence of the Valsalva maneuver, BP increases, so that the elasticity of the arteries decreases and PWV increases.

In table II we can see the PAT obtained for each individual from the measurement taken after intense exercise. In the table we see two values per individual, the first one obtained from a portion towards the beginning of the recorded signal and the second one obtained from a portion towards the end of the recorded signal, in both cases from the average of 10 consecutive beats. As we can see, the obtained values are smaller than that obtained at resting conditions, which again agrees with the theoretical explanation in section II, as pressure increases with exercise. We can also observe that the second value of PAT is greater than the second one, showing the recovery after exercise.

We also conducted an analysis based on time differences using BCG instead of ECG. In this case, the minima of the BCG signal were used as the characteristic points to measure time differences. The qualitative behavior of these time differences turned out to be similar to that of PAT previously described.

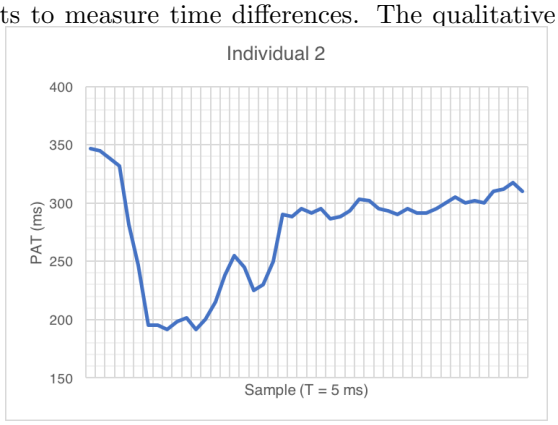

Figure 5. Evolution of PAT for individual 2 during and after the performance of a Valsalva maneuver.

Individual	PAT 1 (ms)	PAT 2 (ms)
1	212	228
2	267	285
3	301	312

Table II. PAT after exercise.

Apart from the measurements we have just analyzed, we also took some measurements using the DiaTecne PulsePen. This device allows to determine CBP from a set of peripheral measurements at different sites of the body. In particular, only as an example of how the device works, we took some measurements at the carotid. We could experience the difficulty of taking a good-quality signal with this kind of device, which adds to its obvious dependence on the managing by the operator.

V. CONCLUSION

From the performed measurements and the subsequent analysis, we can conclude that there exists an actual connection between PAT (and so PWV) and BP, pointing to the possibility of obtaining information about BP from PWV analysis. Moreover, this connection agrees qualitatively with the model exposed in section II. To determine the quantitative validity of this model, we would need a reference method to obtain BP values, both for adjusting the coefficients of the model and for checking the precision of the values of BP obtained from PAT measurements once these coefficients have been determined. This was beyond the aim of this study. Nevertheless, the research group/laboratory where we have made the measurements will begin a study to obtain those coefficients that relate the temporal changes with changes in pressure.

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