Comparison of central systolic pressure estimates obtained from ultrasound images and applanation tonometry

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Abstract. Current non invasive assessment methods to estimate central pressure are based on the use of arterial tonometry: directly on the carotid artery or using a mathematical transfer function applied to the radial artery waveform. The first one is not recommended in obese patients or in the presence of carotid plaques, whereas the use of a unique transfer function to different population has been questioned. In this work we evaluated two alternative methods to assess systolic local arterial blood pressure: 1) from the analysis of B-mode carotid diameter waveforms (SBP\textsubscript{Dia}) and 2) from the radial artery pressure waveform using an n-point moving average filter (SBP\textsubscript{Rad}), and we estimated the accuracy of both when compared to direct carotid tonometry (SBP\textsubscript{Ton}). In 20 asymptomatic subjects (49±11 years, range: 38-73; pulse pressure: 53±9 mmHg, range: 36-70), SBP\textsubscript{Ton} was 132±13 mmHg (range 115-154) and correlated significantly with SBP\textsubscript{Dia} (R=0.96, p<0.05) and with SBP\textsubscript{Rad} (R=0.93, p<0.05). Mean difference between SBP\textsubscript{Dia} and SBP\textsubscript{Ton} was 0.85±4.0 mmHg, and 0.18±5.0 mmHg between SBP\textsubscript{Rad} and SBP\textsubscript{Ton}, independent of pressure levels. In conclusion, both alternative methods were found to allow an accurate and precise estimation of systolic local arterial pressure, when compared to direct carotid tonometry.

1. Introduction

Estimation of central blood pressure has gained increased attention over the past few years, based on evidence that central pressure may more accurately predict cardiovascular damage when compared to brachial pressures [1,2,3]. Current non invasive assessment methods are based on the use of arterial tonometry: directly on the carotid artery [4] or using a mathematical transfer function applied to the radial artery waveform to transform it into a central waveform [5,6]. In both cases, a calibration procedure is required, assuming that mean arterial pressure (MAP) is nearly constant throughout the large artery tree and that diastolic pressure does not change substantially [7]. Direct carotid tonometry requires a trained operator and is not recommended in obese patients.
or in the presence of carotid plaques. By other side, the use of a unique transfer function to be applied to different population has been questioned [8].

A recent study, propose to derive central systolic pressure from the radial artery pressure waveform using an n-point moving average filter [9]. This method, which is simple and avoid the use of a transfer function, showed an excellent correlation and agreement when compared to directly measured aortic root systolic pressures at cardiac catheterization [9]. Another approach, is to derive pressure waveforms from arterial distension waves obtained from echographic images [10,11]. In a recent study, we evaluated the validity to assess systolic local arterial blood pressure using B-mode ultrasound image analysis and the implementation of an iterative calibration model. This method was found to allow an accurate and precise estimation of systolic local arterial pressure, with an underestimation error of ~ 2% independent of pressure levels, when compared to carotid and femoral arterial tonometry [12]. Therefore, the aim of this study was to evaluate in a general population these two alternative methods to assess systolic local arterial blood pressure, 1) from the analysis of B-mode carotid diameter waveforms, and 2) from the radial artery pressure waveform using an n-point moving average filter, and to estimate the accuracy of both when compared to direct carotid tonometry.

2. Material and methods

2.1. Study subjects

Non invasive study was performed in 20 (12 men, 8 women) asymptomatic subjects ranging in age from 38 to 72 years old (mean 49±11 years). Measurements were performed after 15 min rest period in a temperature-controlled environment. In order to ensure similar haemodynamic conditions, for each arterial segment, echographic and applanation tonometry recordings were performed consecutively, with a separation time of about 3 minutes. Systolic (SBP_{bra}) and diastolic (DBP_{bra}) brachial blood pressure values were determined in the arm by sphygmomanometer procedure (supine position), between echographic and tonometer recordings. Hypertension was defined by blood pressure of 140 and/or 90 mmHg or above and/or presence of hypertensive medication. Left carotid arterial waveforms were assessed by experienced sonographer physicians with high-resolution B-mode echography (ATL HDI 5000, Miami Lakes, EE.UU) using a 7.5-MHz probe. Briefly, a sequence of B-mode images of at least 10 seconds were transferred to a computer, and digitized for offline analysis using an automated computerized system (Hemodyn4M®, Oxitech, Argentina). In order to obtain the diameter waveform, the sequences of images were analyzed automatically frame by frame. The anterior and posterior walls were detected. After analyzing the overall sequence, the software yielded as output, the internal diameter waveform, which was calculated as the difference between the far and near wall movement. Arterial pressure waveforms were obtained at the left radial and left carotid arteries by applanation tonometry using a Miller pen-type tonometer (SPT 301, Millar Instruments, Houston, Texas, USA) and a dedicated hardware and software system [12]. The instantaneous pressure waveforms of at least 10 cardiac cycles were digitized every 2 ms and stored on the hard disk of a PC for off-line post processing.

2.2. Data analysis

MAP was estimated at the upper arm using SBP_{bra} and DBP_{bra} values, as 38% of pulse pressure above diastolic pressure [13,14,15]. For each tonometry signal an average waveform was constructed of at least five beats. The carotid waveforms were calibrated by assigning the corresponding DBP_{bra} to the minimum value and the resulting brachial MAP to the average value. The peak of the calibrated carotid (SBP_Car_Tonometer) artery waveforms were considered as the reference systolic value.
The radial waveforms were calibrated first by assigning the corresponding DBP_{tra} to the minimum value and the resulting brachial MAP to the average value. Then a 125 moving average point filter was applied [9], and the peak of the resulting filtered signal was considered as the systolic estimates (SBP_{Rad_tonometer}).

![Figure 1. Typical example of carotid tonometer waveform (in black) and radial tonometer waveform (in gray) after calibration procedure. Radial waveform after applying a 125 point moving average filter appears superimposed.](image)

The diameter waveforms (D) were calibrated using an exponential approach proposed by Vermeersch et al [11]. Briefly, it is assumed that pressure (P) and arterial cross-section (A) are related by an empirically derived exponential function. The derived pressure waveform is calibrated to DBP_{tra} and MAP by iteratively changing a wall rigidity coefficient (\( \alpha \)). The peak of the calibrated carotid waveform (SBP_{Car_Diameter}) was considered as systolic value. See figure 2.

\[
A(t) = \frac{\pi \cdot D(t)^2}{4}, \quad \alpha = \frac{A_j \cdot \ln\left(\frac{SBP_{Car}}{DBP_{tra}}\right)}{A_j - A_d}
\]

![Figure 2. Iterative exponential calibration approach. A(t): carotid cross-section, \( A_s \) and \( A_d \): systolic and diastolic carotid cross-section, \( P(t) \): estimated carotid pressure waveform, \( \overline{P(t)} \) : average value, \( \alpha \): wall rigidity coefficient](image)
Values are presented as mean ± standard deviation. Differences were compared with paired t-test and the relationship between variables was evaluated by linear regression and Bland and Altman analysis. A value of p<0.05 was considered statistically significant

3. Results
Subject’s characteristics are shown in table 1.

| Table 1. Subjects characteristics |
|----------------------------------|
| (n=20)                           |
| Mean±SD | Min | Max |
| Age (years) | 49 ± 11 | 38 | 72 |
| Body Mass Index (Kg. m⁻²) | 27 ± 3 | 23 | 33 |
| Sex (male,%) | 58 |  |
| SBPbra, mmHg | 139 ± 12 | 117 | 155 |
| DBPbra, mmHg | 86 ± 12 | 61 | 108 |
| PPbra, mmHg | 53 ± 9 | 36 | 70 |
| Hypertensión, % | 63 |  |

Mean carotid systolic pressure value obtained with direct carotid tonometry was 132±14 mmHg. There were no significant differences between SBP_Ca_Diameter and SBP_Ca_Tonometer values (p=ns, paired t-test), and between SBP_Ca_Tonometer and SBP_Rad_Tonometer values (p=ns, paired t-test).

Figure 4 (left panel) shows carotid SBP estimated by exponential B-mode calibration method plotted against carotid SBP estimated by tonometry. The two methods correlated significantly (R=0.96, p<0.05). In figure 4 (right panel), the difference between direct carotid tonometry and echocardiography-derived pressure estimates is plotted against the average of the two methods. The mean difference between the two methods was 0.85±4.0 mmHg, whereas the range of the limits of agreement (mean ± 2 standard deviation) was -7 to 9 mmHg, showing no trend with increasing pressure levels.

Figure 4. Left: carotid SBP by the exponential diameter calibration method plotted against carotid SBP by the direct tonometer method (n=20). Right: Bland and Altman plots. The dotted line is the mean difference and the dashed lines represent the mean ± two times SD.
Similarly, figure 5 (left panel) shows SBP estimated by the radial calibration method plotted against carotid SBP estimated by tonometry. The mean difference between direct carotid tonometry and radial-derived pressure estimates was 0.18±5.0 mmHg, whereas the range of the limits of agreement (mean ± 2 standard deviation) was -10 to 10 mmHg, showing no trend with increasing pressure levels.

\[ y = 0.9423x + 7.7964 \]
\[ R^2 = 0.8674 \]

**Figure 5** Left: SBP derived from calibrated radial waveform after moving average filter plotted against carotid SBP by the direct tonometer method (n=20). Right: Bland and Altman plots The dotted line is the mean difference and the dashed lines represent the mean ± two times SD

4. Discussion

In this study, we investigated the validity of using two approaches to estimate systolic local arterial blood pressure: from the analysis of B-mode carotid diameter waveforms and from the radial artery pressure waveform using a 125 point moving average filter. Due to the impossibility to obtain a direct measurement of aortic root pressure using an invasive procedure, direct carotid tonometry was used as reference method. Carotid tonometer waveforms were calibrated according to the procedure proposed by Kelly and Fitchet [7], using brachial diastolic and mean arterial pressures. Instead of deriving MAP from brachial tonometry, in this study MAP was computed as 38% of pulse pressure above diastolic pressure. Recently we showed that such value in the formula introduced an error of only 0.1% in mean brachial pressure estimation resulting in an error of 0.2% in systolic carotid estimates, independent of pulse pressure levels [13,14].

Calibrated radial pressure waveforms were filtered using a 125 point moving average filter. This number was established according to Williams et al, who determined that one quarter of the tonometer sampling frequency (in this case 500 Hz) most accurately defined the value of central systolic pressure [9]. In general, this alternative method was relatively simple to implement. We found no significant differences between SBP_Rad and SBP_Ton methods. The mean difference was only 0.18 mmHg, and 95% of the differences were less than two standard deviations, showing no trend.

Using calibrated diameter distension waveforms instead of tonometric waveforms avoids the technical difficulties and required operator skills associated with direct carotid applanation tonometry. Moreover, it use is not limited to superficial arteries. Several studies showed a very good agreement in systolic values, when comparing direct carotid tonometry with linearly or exponentially calibrated diameter distension waveforms [4,10,11,12]. However, compared to linear calibration, exponential calibration significantly improves the pressure estimation [10,11,12]. We found no significant differences between SBP_Dia and SBP_Ton methods. The mean
difference was only 0.85 mmHg, and 95% of the differences were less than two standard deviations, showing no trend.

In summary, our results showed that the two alternative methods presented good accuracy within the acceptability limits of the AAMI criteria (differences <= 5 ± 8 mmHg). However, the results were obtained in a small sample and without severely hypertensive patients. It is therefore necessary to perform more studies, including a higher number of patients to confirm the results here found.

5. Conclusion
The two alternative methods used based on exponentially calibrated B-mode carotid diameter and on radial tonometry after application of a moving average filter, were found to allow an accurate and precise estimation of systolic local arterial pressure, when compared to direct carotid tonometry.

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