Effects of External Pressure on Arteries Distal to the Cuff During Sphygmomanometry

Meir Nitzan*, Chaim Rosenfeld, A. Teddy Weiss, Ehud Grossman, Amikam Patron, and Alan Murray

***Abstract*—The aim of this study was to examine the effect on distal arteries of external pressure, applied by upper arm sphygmomanometer cuff. Photoplethysmographic (PPG) signals were measured on the index fingers of 44 healthy male subjects, during the slow decrease of cuff air pressure. For each pulse the ratio of PPG amplitude to its baseline (AM/BL) and its time delay $(\Delta \mathrm{TD})$ relative to the contralateral hand were determined as a function of cuff pressure. At cuff pressures equal to systolic blood pressure, pulses reappeared with the pulse time delay in the cuffed arm significantly greater than in the noncuffed arm, with $(\Delta \mathrm{TD})(\mathrm{mean} \pm \mathrm{SD}) 150 \pm 31$ ms $(p < 0.001)$. At cuff pressures equal to diastolic blood pressure $(81 \pm 12\ \mathrm{mmHg})$, $\Delta \mathrm{TD}$ was 42 ± 19 ms $(p < 0.001)$, and at 50 mmHg, which is below diastolic blood pressure, $(\Delta \mathrm{TD})$ was still significantly positive at 6 ± 9 ms $(p < 0.001)$. AM/BL relative to its initial value rose at cuff pressures between systolic and diastolic blood pressure, then deceased to 0.6 ± 0.41 $(p < 0.001)$ at diastolic blood pressure and 0.54 ± 0.24 $(p < 0.001)$ at 50 mmHg. The changes in $(\Delta \mathrm{TD})$ and AM/BL can be interpreted as originating from changes in the compliance of conduit arteries and small arteries with cuff inflation and deflation.**

***Index Terms*—Arterial blood pressure, arterial compliance, photoplethysmography, pulse wave velocity.**

I. INTRODUCTION

IN 1886, Riva-Rocci introduced the pressure cuff for the measurement of systolic blood pressure by the detection through palpation of the pressure pulse distal to the cuff. Later, Korotkoff described the sounds, which originate from the artery under the cuff when the cuff pressure is between systolic and diastolic blood pressure (SBP and DBP) and are the basis for auscultatory sphygmomanometry. Due to the high clinical significance of arterial blood pressure measurement the Korotkoff sounds and their relationship to sphygmomanometry were thoroughly investigated. However, only few studies dealt with the hemodynamic changes in the arteries distal to the cuff, which were caused by the fast inflation and the consequent slow deflation of the pressure cuff.

For cuff pressure above SBP value the pressure pulses disappear due to the collapse of the artery under the cuff, and this effect can be used as a means for SBP measurement: the cuff pressure at which the pulses reappear during the deflation period equals SBP [1]–[5]. The appearance of the distal pressure pulses can be detected indirectly, using Doppler ultrasound or photoplethysmography (PPG), which measure the oscillations in blood velocity or tissue blood volume, respectively, and are induced by the blood pressure pulses.

For cuff pressure between DBP and SBP, the artery under the cuff is closed when arterial blood pressure is below the cuff pressure and open when arterial blood pressure is greater than the cuff pressure. Since the pressure pulse can propagate distal to the pressure cuff only when arterial blood pressure is greater than the cuff pressure, the amplitude of the pressure pulse is expected to be lower than that of the pressure pulse without cuff pressure. In addition, the start time of the systolic increase of the pressure pulse distal to the cuff is delayed relative to that of the pressure pulse in the contralateral limb or relative to the corresponding electrocardiography (ECG) R-wave [6]–[8]. The time-delay measurement was used for the assessment of DBP by finding the external pressure at which the time-delay disappears, since only external pressure higher than DBP can cause arterial closure. However the method is not accurate, mainly due to the fact that positive time-delay has been found even for cuff pressure values lower than DBP [6], [7], showing that the cuff inflation induces hemodynamic changes in the blood vessels under and distal to the cuff, and this effect is superimposed on the arterial closure mechanism.

The aim of the current study is to investigate the effect of the fast inflation and the consequent slow deflation of the pressure cuff on the PPG signal distal to the cuff. The changes in PPG time-delay and PPG amplitude, induced by the external pressure are interpreted as originated from the changes in the compliance of the arteries distal to the pressure cuff caused by the external pressure exerted by the cuff: the PPG amplitude depends on the compliance of the small arteries under the PPG probe and the PPG arrival time depends on the compliance of the conduit arteries. The changes in PPG time-delay and PPG amplitude during cuff deflation can be used as a potential tool, which may offer complementary information on arterial compliance, a physiological parameter of high clinical merit, due to its relationship to atherosclerosis and hypertension.

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TABLE I
MEAN, SD AND RANGE OF VALUES FOR THE SUBJECT CHARACTERISTICS

	Mean	SD	Range
AGE (y)	46	17	18-77
DBP (mmHg)	81	12	54-110
SBP (mmHg)	130	19	101-175
PP (mmHg)	49	12	25-78

II. MATERIALS AND METHODS

A. *Subjects*

PPG examinations were performed on 44 male nonsmoker subjects aged 18–77 years. The subjects were nondiabetic, with no known cardiovascular disease, except hypertension. Table I displays for all subjects the mean, SD and range of age, DBP, SBP, and pulse pressure $(= \mathrm{SBP}-\mathrm{DBP})$.

The subjects were asked to refrain from drinking coffee and alcohol two hours before the examination. After a rest period of 10 min, they were seated for the examination, with their hands laid on the table. Room temperature was 21 °–24 °C.

B. *Measurements*

The PPG signals were recorded from the index fingers of the two hands, using the infrared light-sources and photodetectors of two pulse-oximeter probes (Oxisensor N25, Nelcor), and the signal was high-pass filtered. The high-pass filtered PPG signals and the PPG signals before the high-pass filtering were both sampled (250 samples/s) by an analogue-to-digital card (16 bit) and digitally stored for further processing. We used the unfiltered signals for baseline and for the amplitude measurements and the high-pass filtered PPG signals for time-delay measurements.

A pressure cuff was applied on one of the arms, and an electronic pump raised the air pressure to 200 mmHg, then the air pressure was gradually reduced at a rate of 2–3 mmHg/s. The shape of the pressure/time curves was similar for all examinations. The cuff air pressure was measured both by a mercury manometer and by a piezoelectric transducer, and the signal of the latter was digitized and stored as for the PPG signal. Two trained observers determined SBP and DBP simultaneously and independently by auscultatory sphygmomanometry, using a double stethoscope. SBP and DBP were taken as the average of the readings of the two observers.

C. *Analysis*

After the recording, the PPG signal was smoothed by means of a moving average of 11 points (including 5 points on either side of the current point) of equal weight, and analyzed for the detection of the minimum and maximum of each pulse. The pulse minimum was identified as the sampling point at which the value of the smoothed PPG signal was lower than that for the 10 adjacent sample points on either side, and the maximum was similarly defined. Also, by demanding a minimum period of 400 ms between the maximum and the subsequent minimum, any notch following the PPG peak was eliminated. The smoothing procedure changed the amplitude by less than 4%, with negligible difference of the amplitude change between different PPG pulses.

For each pulse, the values of the pulse baseline BL (the pulse minimum), its amplitude AM and their ratio AM/BL were derived. AM/BL is proportional [9] to the arterial blood volume increase in the tissue under the PPG probe, which is induced during systole by the pulse pressure and is therefore strongly related to the pulse pressure.

The time-delay between two PPG pulses was not determined from the minima of the pulses, because the slope in the PPG signal in the neighborhood of the minimum is low, and even low noise can influence the determination of the pulse minimum time. In order to determine the time-delay with higher accuracy we used a fiducial point on the fast rising section of the PPG pulse. The baseline BL and the amplitude AM for each pulse were first derived. Then the time the PPG signal reached the value of $\mathrm{BL}+0.1$ AM was determined for both fingers and their difference TD was calculated, representing the time-delay in the start of the PPG pulse in the finger distal to the cuff (see Fig. 1). In order to eliminate the initial time-delay difference which is not related to the external pressure, the time-delay difference before the pressure application (TD_0) was subtracted from TD and $\Delta\mathrm{TD} = \mathrm{TD} - \mathrm{TD}_0$ was taken as the time-delay due to the cuff pressure.

The two PPG values, AM/BL and $(\Delta\mathrm{TD})$, were determined for each pulse during the deflation period, as a function of the cuff pressure. Then for each subject seven PPG characteristics were derived: $(\Delta\mathrm{TD})$ at cuff pressure values of SBP, DBP and 50 mmHg; AM/BL at its maximum $(\mathrm{AM/BL_{MX}})$ and at cuff pressure of DBP and 50 mmHg; and cuff pressure value at $\mathrm{AM/BL_{MX}}, \mathrm{P_{CMX}}$.

D. *Statistical Analysis*

In order to test the hypotheses that $(\Delta\mathrm{TD})$ is different from zero at cuff pressure values of SBP, DBP, and 50 mmHg, the Student t-test was used. Similarly the Student t-test was used for the evaluation of the hypotheses that AM/BL at its maximum and at cuff pressures of DBP and 50 mmHg differ from the value of AM/BL before the pressure application.

The correlation between two parameters was assessed by linear regression analysis. $\mathrm{P} < 0.05$ was considered statistically significant.

III. RESULTS

A. *Pulse Appearance at Systolic Blood Pressure*

When the cuff air pressure was increased to 200 mmHg the PPG pulses disappeared in all subjects, and reappeared during cuff deflation. Fig. 1(a) and (b) shows the PPG signals distal to the cuff and in the contralateral hand for cuff pressures in the neighborhood of SBP and DBP. In Fig. 2 the curves of the PPG in the sensor distal to the cuff and the cuff pressure are shown as a function of time for one of the subjects. During the increase of the cuff pressure the PPG pulses disappeared, and they returned when the cuff pressure decreased to below the SBP value.

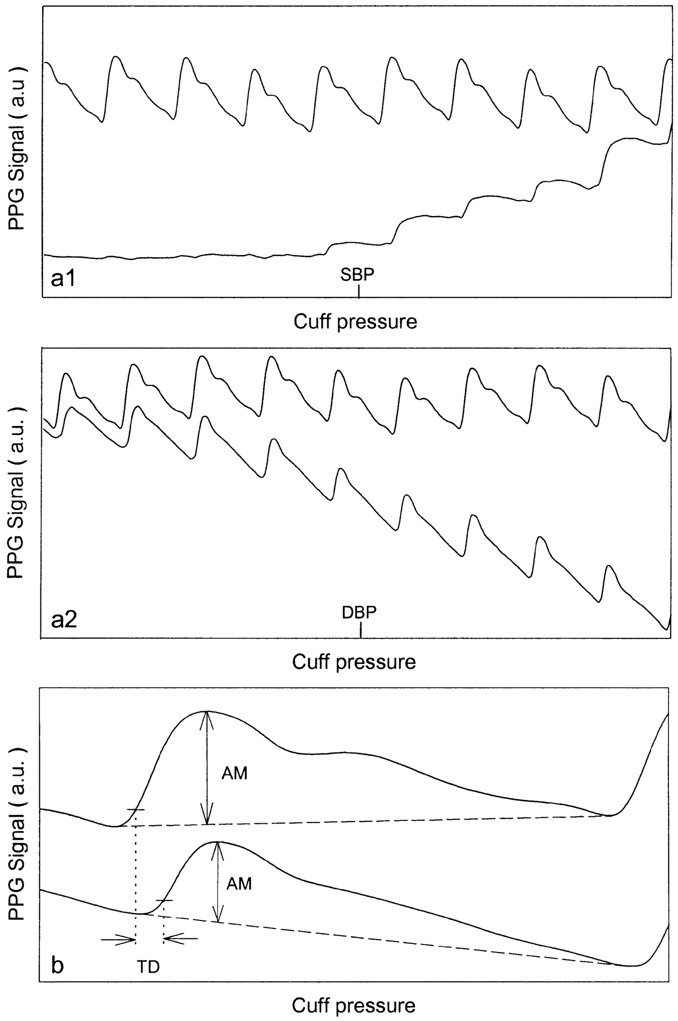

Fig. 1. The PPG pulses in the hand distal to the cuff (below) and in the contralateral hand (above) of one of the subjects for cuff pressure values (a1) in the region of SBP and (a2), (b) in the region of DBP. Note the time-delay TD between the two PPG onsets. The dashed lines indicate the time when the PPG signal is $\mathrm{BL} + 0.1$ AM.

The value of SBP, which was obtained by auscultatory sphygmomanometry, is also marked in the figure. Similar curves were obtained for the other subjects, and the PPG pulses reappeared when the cuff pressure was in the vicinity of the SBP value, obtained by auscultatory sphygmomanometry. No abrupt change was found between PPG pulses below and above DBP.

For quantitative comparison SBP values were obtained both by visual detection of the PPG pulse reappearance and by start of Korotkoff sounds. In most cases the reappearance of the PPG pulses distal to the cuff was clearly visible despite the low signal-to-noise ratio, and in the other examinations the PPG pulse reappearance could be missed by no more than one pulse, equivalent to 2–3 mmHg. In Fig. 3 SBP values, obtained by visual detection of the PPG pulse reappearance, are displayed as a function of SBP, measured by auscultatory sphygmomanometry. The results show that start of the Korotkoff sounds and the reappearance of the PPG pulse are strongly correlated, though in some cases, especially for low SBP, Korotkoff sounds were heard before the reappearance of the PPG pulse and *vice versa.*

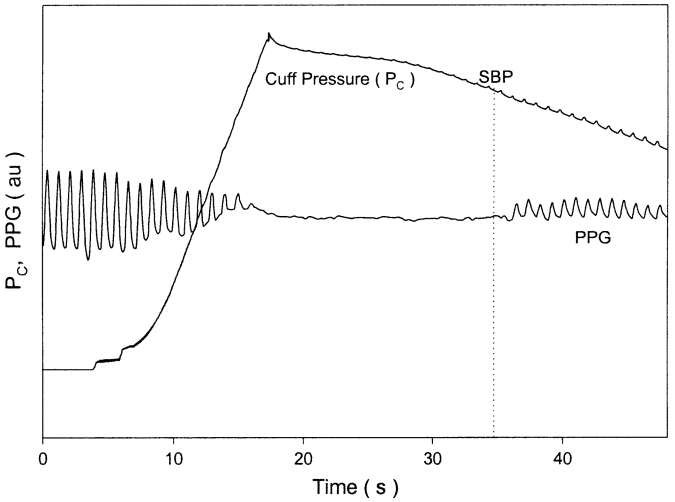

Fig. 2. The curves of the PPG and the cuff pressure as a function of time for one of the subjects. The PPG pulses reappear when the cuff pressure decreases to below systolic blood pressure. The systolic blood pressure as obtained by auscultatory sphygmomanometry is also marked.

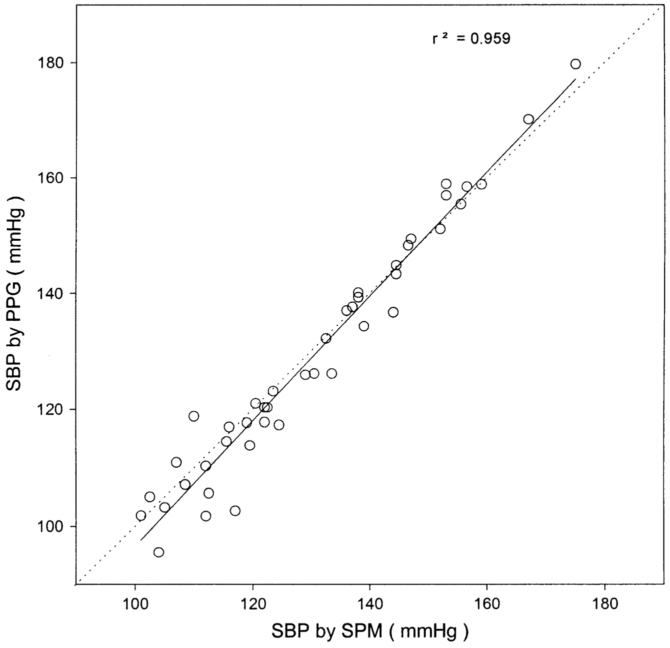

Fig. 3. The value of SBP measured by the detection of the reappearance of the PPG pulses as a function of SBP, measured by auscultatory sphygmomanometry.

Cuff pressures lower than SBP demonstrated significant changes in the start time of the distal PPG pulse and its amplitude, and these results follow.

B. Pulse Time-Delay Changes With Cuff Pressure

The time-delay ΔTD of the first PPG pulses after their reappearance (for cuff pressure in the neighborhood of the SBP value) generally lay between 100–200 ms. Table II presents the values of ΔTD for the second of these PPG pulses (the first pulse was generally small and the measurement of its ΔTD was less accurate than for the second). For lower values of cuff pressure ΔTD decreased. Table II presents the average value and the range of values of ΔTD for cuff pressures equal to SBP, DBP, and 50 mmHg.

TABLE II

Mean, SD, and Range of Values for the PPG Characteristics: ΔTD at SBP, DBP, and 50 mmHg. $(\mathrm{AM/BL_{MX}})/(\mathrm{AM/BL_0})$, $(\mathrm{AM/BL_{DBP}})/(\mathrm{AM/BL_0})$, and $(\mathrm{AM/BL_{50\,mmHg}})/(\mathrm{AM/BL_0})$ and the Value of $\mathrm{P_C}$ at $\mathrm{AM/BL_{MX}}$ Relative to SBP. p Indicates the Significance of the Mean, Which for Time-Delays Were Compared to 0 ms, and for Amplitude Ratios to 1, Representing No Change

	Mean	SD	p	Range
ΔTD_{SBP} (ms)	150	31	<0.001	97-221
ΔTD_{DBP} (ms)	41.7	19.4	<0.001	12.6-89.1
ΔTD_{50mmHg} (ms)	6.2	8.7	<0.001	-9.1-29.4
$(AM/BL_{MX})/(AM/BL_0)$	1.06	0.66	NS	0.29-4.25
$(AM/BL_{DBP})/(AM/BL_0)$	0.61	0.41	<0.001	0.20-2.51
$(AM/BL_{50mmHg})/(AM/BL_0)$	0.54	0.24	<0.001	0.21-1.51
$SBP\text{-}P_{CMX}$ (mmHg)	24.5	8.3	<0.001	8.2-41.4

Very significant positive values of ΔTD for cuff pressure equal to DBP were found for the 44 examinations (Table II), with a mean ±SD of 42 ± 19 ms ($p < 0.001$). This fact is important because the nonzero values of ΔTD cannot originate from the arterial closure effect for cuff pressure equal to or lower than DBP. The mean ±SD of ΔTD for cuff pressure equal to 50 mmHg (which was below DBP in all subjects) was 6.2 ± 8.7 ms, which was still significantly higher than zero ($p < 0.001$). For 32 subjects ΔTD for cuff pressure equal to 50 mmHg was positive.

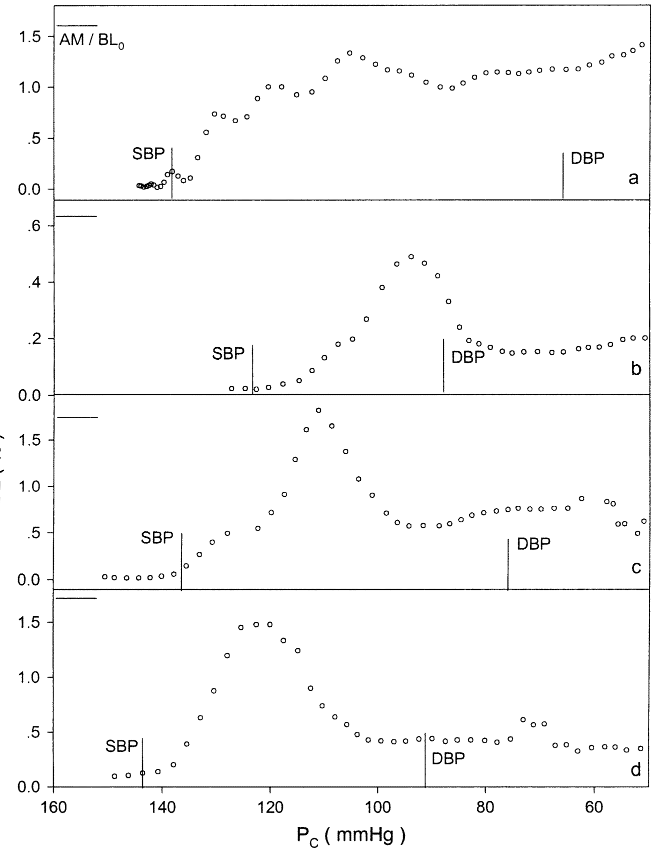

Fig. 4. The value of AM/BL of the PPG pulse distal to the pressure cuff as a function of the cuff pressure, for four subjects. The values of SBP, DBP and AM/BL with no external pressure $(\mathrm{AM/BL_0})$ are also shown. AM/BL for cuff pressure equal to DBP was generally lower than $(\mathrm{AM/BL_0})$.

C. *Pulse AM/BL Changes With Cuff Pressure*

The AM/BL versus cuff pressure curve also deviated from that predicted from the model of brachial artery closure, according to which the *pulse pressure* amplitude should increase from zero to the pulse pressure value when cuff pressure decreases from SBP to DBP, and then remain constant. Similar behavior would then be expected for AM/BL, which is proportional to the pulse pressure (see Appendix). In the current study, however, for most subjects AM/BL steeply increased in the neighborhood of SBP, reaching a maximum value $(\mathrm{AM/BL_{MX}})$ at cuff pressures higher than DBP, as shown in the curves of Fig. 4.

AM/BL versus cuff pressure curve with maximum value of AM/BL occurred in 41 out of the 44 subjects. In three examinations AM/BL increased monotonically with the cuff pressure and no significant maximum of AM/BL was found between SBP and DBP (subject age range 57–72 years). For the 41 subjects with the maximum value of $\mathrm{AM/BL}$, $\mathrm{AM/BL_{MX}}$ appeared at cuff pressure values 8.2–41.1 mmHg below SBP, as seen in Table II.

The average value of AM/BL for cuff pressure equal to DBP $(\mathrm{AM/BL_{DBP}})$ was only 0.61 of that before the pressure application, $\mathrm{AM/BL_0}$. For only five subjects, $\mathrm{AM/BL_{DBP}}$ was higher than $\mathrm{AM/BL_0}$ (subject age range 20–55 years). Table II presents the mean and the range of values for $(\mathrm{AM/BL_{MX}})/(\mathrm{AM/BL_0})$, $(\mathrm{AM/BL_{DBP}})/(\mathrm{AM/BL_0})$, and $(\mathrm{AM/BL_{50\,mmHg}})/(\mathrm{AM/BL_0})$.

D. *Correlations With Pulse Characteristics*

The coefficients of correlation between the PPG characteristics and the subject characteristics of age, DBP, SBP, and PP are shown in Table III. Since one of the subjects showed exceptional values of the three AM/BL characteristics [4.25, 2.52, and 1.51 for $(\mathrm{AM/BL_{MX}})(\mathrm{AM/BL_0})$, $(\mathrm{AM/BL_{DBP}})(\mathrm{AM/BL_0})$ and $(\mathrm{AM/BL_{50\,mmHg}})/(\mathrm{AM/BL_0})$, respectively] nonparametric Pearson correlation test was used for the three AM/BL characteristics.

$\Delta\mathrm{TD}$ for $\mathrm{P_C} = 50$ mmHg decreased with SBP and DBP, and $\Delta\mathrm{TD}$ for $\mathrm{P_C} = \mathrm{DBP}$ decreased with SBP and pulse pressure, with correlation coefficients of -0.62 to $-0.82 (p < 0.001)$. Figs. 5 and 6 show these dependencies. The value of $\mathrm{SBP} - \mathrm{P_{CMX}}$ decreased with age ($r = 0.47, p < 0.01$, see Fig. 7) and DBP ($r = 056, p < 0.001$). ΔTD at SBP significantly *increased* with age ($r = 0.48, p < 0.01$, see Fig. 7). The other characteristics showed smaller correlation with the subject characteristics, though some were statistically significant.

It can be noted that with multiregression analysis the coefficient of correlation between DBP and the two PPG parameters, $\Delta\mathrm{TD}$ for $\mathrm{P_C} = 50$ mmHg and $\mathrm{SBP} - \mathrm{P_{CMX}}$, increases to 0.75. With the addition of SBP measured from the reappearance of

TABLE III

COEFFICIENT OF CORRELATION r BETWEEN THE PPG CHARACTERISTICS AND THE SUBJECT CHARACTERISTICS: AGE, DBP, SBP, AND PP. THE CORRELATION COEFFICIENTS FOR THE AM/BL PARAMETERS WERE OBTAINED THROUGH NONPARAMETRIC TEST

	AGE		**DBP**		**SBP**		**PP**	
	r	**p**	**r**	**p**	**r**	**p**	**r**	**p**
ΔTD_{SBP}	+0.48	<0.01	0.09	NS	0.08	NS	0.04	NS
ΔTD_{DBP}	-0.04	NS	-0.16	NS	-0.62	<0.001	-0.82	<0.001
ΔTD_{50mmHg}	-0.34	<0.05	-0.63	<0.001	-0.72	<0.001	-0.49	<0.01
$(AM/BL_{MX})/(AM/BL_0)$	-0.13	NS	-0.38	<0.02	-0.31	NS	-0.14	NS
$(AM/BL_{DBP})/(AM/BL_0)$	-0.23	NS	-0.35	<0.02	-0.34	<0.05	-0.29	NS
$(AM/BL_{50mmHg})/(AM/BL_0)$	-0.07	NS	-0.33	<0.05	-0.21	NS	-0.08	NS
$SBP-P_{CMX}$(mmHg)	-0.47	<0.01	-0.56	<0.001	-0.31	<0.05	0.07	NS

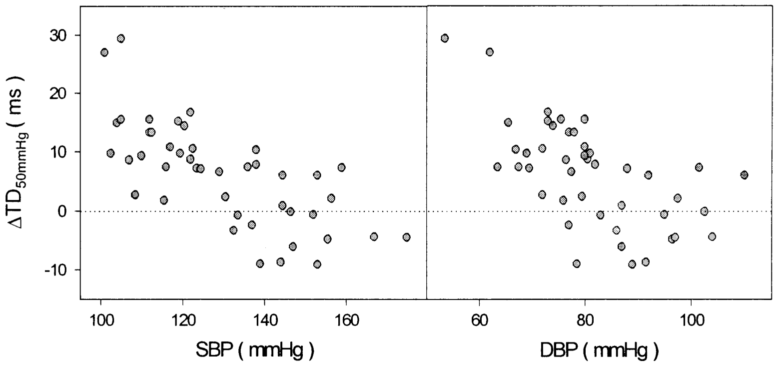

Fig. 5. The decrease of $\Delta\mathrm{TD}$ for cuff pressure equal to 50 mmHg with SBP and DBP (measured by sphygmomanometry).

the PPG pulses during the deflation period as a third independent variable, the correlation with DBP increases to 0.85.

IV. DISCUSSION AND CONCLUSION

In this study we examined the effect of cuff pressure on two characteristics of the PPG signal distal to the cuff: AM/BL and the time-delay $\Delta\mathrm{TD}$. $\Delta\mathrm{TD}$ was found to decrease with decreasing cuff pressure and was higher than zero for cuff pressure equal to DBP in all examinations and for cuff pressure equal to 50 mmHg in more than $2/3$ of the examinations. AM/BL increased from very low values when the cuff pressure was in the neighborhood of SBP to a mean of $0.61\mathrm{AM/BL}_0$ for cuff pressure equal to DBP, and in most examinations a peak of AM/BL was found between SBP and DBP.

For cuff pressure between SBP and DBP the brachial artery is closed by the external cuff pressure during the period of arterial blood pressure lower than cuff pressure, resulting in reduction of the pressure pulse amplitude and positive time-delay of the pressure pulse distal to the cuff. However, the effect of arterial closure by the cuff cannot explain the nonzero time-delay found for cuff pressures lower than DBP, as this model expects time-delay equal to zero. Furthermore, AM/BL did not increase monotonically from zero to $\mathrm{AM/BL}_0$ when the cuff pressure decreases from SBP to DBP, as is expected from the arterial closure model.

The deviations of the PPG signal from what is expected from the arterial closure model indicate that the PPG pulse is influenced by the external cuff pressure through an additional mechanism. An explanation of this is the change in the compliance of the arteries under or distal to the cuff, which can influence both AM/BL and $\Delta\mathrm{TD}$. AM/BL mainly depends on the compliance of the *small arteries* under the PPG sensor [Appendix (1), (2)], and $\Delta\mathrm{TD}$ mainly depends on the compliance of the *conduit arteries* from the cuff to the sensor site, since the pulse wave velocity in an artery is directly related to the arterial distensibility (the ratio between arterial compliance and the arterial blood volume) [10]–[12].

The positive values of $\Delta\mathrm{TD}$ for cuff pressure lower than DBP can be attributed to lower pulse wave velocities, which originate from higher distensibility of the arteries under (or distal) to the cuff. Two sources for this higher arterial distensibility can be designated the following.

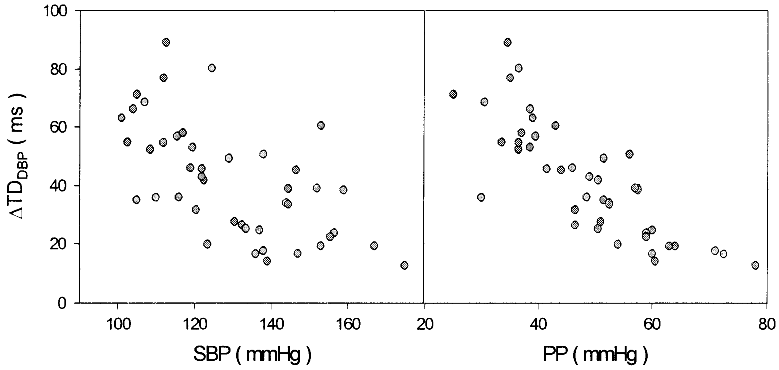

Fig. 6. The decrease of $\Delta \mathrm{TD}$ for cuff pressure equal to DBP with SBP and PP (measured by sphygmomanometry).

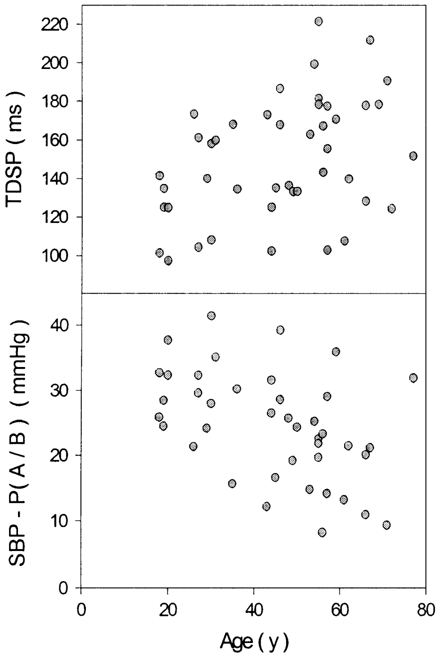

Fig. 7. $\mathrm{SBP}-\mathrm{P}_{\mathrm{CMX}}$ and $\Delta \mathrm{TD}$ at SBP as a function of subject's age.

— The external pressure exerted by the cuff on the tissue lowers the transmural pressure (the difference between the arterial blood pressure and the external pressure) in the brachial artery under the cuff and increases thereby its compliance [13], [14].

— The fast increase of the cuff pressure to above the SBP value closes the arteries in the limb shortly after the closure of the veins. When both arteries and veins are closed, arterial blood drains into the veins due to the pressure difference between them, until equalization of the blood pressure in the distal vascular system is achieved. (For high SBP the time of deflation until the cuff pressure reaches SBP value is relatively short and arterial-venous blood pressure equalization may not be achieved; even though the arterial blood pressure will significantly decrease). When the cuff pressure decreases to slightly below SBP and the PPG pulses reappear, the lower blood pressure in the arteries and the resultant higher arterial compliance are associated with positive time-delay in the PPG pulse distal to the cuff. During further cuff deflation blood flows into the arteries in the short periods when the artery under the cuff is open, resulting in gradual increase of the blood pressure in the distal arteries and consequent gradual decrease in arterial compliance and PPG pulse time-delay.

These effects cause positive time-delay in the PPG signal distal to the cuff, which decreases for lower cuff pressure. While these two effects might be expected to create a smooth decrease in the $\Delta \mathrm{TD}$ versus cuff pressure curve, fluctuations in many $\Delta \mathrm{TD}$ curves were also demonstrated. There are additional factors, including respiration, which also affect the arterial compliance and consequently pulse transit time [15], [16]. Another effect that is also related to arterial compliance is the relaxation of the smooth muscle, which can be developed due to the arterial occlusion by the cuff, when the cuff pressure is above SBP. Similar smooth muscle relaxation is known to appear in postocclusive reactive hyperemia, after arterial occlusion for 3–6 min, and to cause vasodilatation and increased blood flow to values several fold than normal [17]. Though the period of above-systolic pressure occlusion in our study is much shorter, less than 1 min, smooth muscle relaxation is still expected. The stimulation of the sympathetic nervous system by the cuff inflation may also change the compliance of the conduit arteries and the small arteries.

The gradual decrease in the distal arteries compliance during the deflation period from SBP to DBP can also explain the changes in AM/BL. The change in AM/BL during the deflation period is caused by two opposing effects: the increase in the pressure pulse amplitude and the decrease of the compliance of the small arteries under the PPG sensor. The pressure pulse amplitude increases when the cuff pressure decreases from SBP to DBP, then remains constant. The compliance of the small arteries can be high for cuff pressures slightly lower than SBP, as explained, but as the cuff pressure decreases the pressure in the small arteries will increase, thereby decreasing their compliance. The combination of these two effects can in part explain the great increase of AM/BL for cuff pressures close to SBP, and its subsequent decrease for lower cuff pressure.

Due to its relationship to atherosclerosis and hypertension, arterial compliance possesses great clinical significance and several noninvasive techniques have been developed for assessing the compliance of the different components of the arterial system [10], [18], [19]. Measurement by echo tracking of the changes in the localized blood volume induced by blood pressure changes enables direct determination of the ratio of localized blood volume changes to blood pressure changes and the local arterial compliance [18]–[21]. Indirect assessment of arterial distensibility can be obtained by measuring the pulse wave velocity (PWV) in a conduit artery, which is related to the arterial distensibility in that artery by the Bramwell-Hill formula [10]–[12], [18], [22]. The pressure pulse waveform provides information on the compliance of both conduit arteries and small arteries through measurement of the augmentation of the pressure pulse originated from pulse reflection or by analyzing diastolic pressure decay contour [10], [18], [19], [23], [24], and parameters derived from the second derivative curve of the photoplethysmographic waveform were found to be related to vasoactive agents use and aging, due to their dependence on the pressure pulse reflection [10], [25]. Because of the complexity of the systemic arterial system several techniques should be used in order to obtain comprehensive view on the compliance of the arterial system and its different components.

The PPG signal strongly depends on the arterial compliance: PPG amplitude depends on the compliance of the small arteries and arterioles under the PPG probe and the PPG arrival time depends on the compliance of the conduit arteries between the left ventricle and the PPG measurement site. In the current study we investigated the dependence of the PPG amplitude and arrival time on the external pressure and provided interpretation of the changes in the PPG signal through changes in arterial compliance. The measurement and analysis of the PPG signal during cuff deflation is a potential tool, which may offer complementary information on arterial compliance, of both physiological and clinical merit.

APPENDIX

The PPG signal originates from the arterial blood volume increase in the tissue under the PPG probe, which is induced by the blood pressure increase during systole. The PPG amplitude is related to the pulse pressure $\mathrm{PP} = (\mathrm{SBP} - \mathrm{DBP})$ through their relationship to the maximal arterial blood volume increase $(\Delta \mathrm{V_A})$ in the tissue. $\Delta \mathrm{V_A}$ depends on the compliance C of the small arteries and arterioles, defined by $\mathrm{C} = \mathrm{dV}/\mathrm{dP}$:

$$\Delta \mathrm{V_A} = (\mathrm{dV}/\mathrm{dP})\Delta \mathrm{P} = \mathrm{CPP} \tag{1}$$

where P is the arterial blood pressure and V is the blood volume in the arteries in the tissue under measurement. $\Delta \mathrm{V_A}$ is related [9] to the PPG parameters:

$$\mathrm{AM}/\mathrm{BL} \approx \alpha_{\mathrm{A}} \Delta \mathrm{V_A} = \alpha_{\mathrm{A}} \mathrm{CPP} \tag{2}$$

where α_{A} is the effective light absorption coefficient of the arterial blood. α_{A} can be considered constant for the time of measurement so that AM/BL is proportional to $\Delta \mathrm{V_A}$ and consequently to PP.

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