Contribution of Stroke Volume to the Change in Pulse Pressure Pattern With Age

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Abstract—This study investigated the effect of age on pulse pressure and its underlying mechanisms in unmedicated hypertensive men with the same level of mean arterial pressure. We included 77 men 17 to 76 years old with daytime mean arterial pressure between 95 and 114 mm Hg. In the supine position, pulse pressure showed a significant widening in young (<30 years) and older (≥60 years) patients. Pulse pressure decreased in parallel with stroke index from age ≥30 to 40 to 49 years. Upright posture, however, eliminated this difference through a larger orthostatic fall in stroke index and pulse pressure in the youngest patients. After age 50 years, pulse pressure exhibited a progressive widening despite the further age-related decrease in stroke index. Supine, upright, and 24-hour pulse pressure fitted a curvilinear correlation with age (r = 0.55, 0.56, and 0.68, respectively, P < 0.001), with a transition at age 50 years. Before age 50 years, 24-hour pulse pressure correlated positively with stroke volume (r = 0.5, P < 0.001) and negatively with arterial compliance (SV/PP ratio, r = −0.37, P < 0.01). In contrast, in men ≥50 years old, 24-hour pulse pressure correlated negatively with the SV/PP ratio (r = −0.5; P < 0.01), without significant influence of stroke volume. Thus, in hypertensive men, the age-related change in stroke volume significantly accounted for the change in clinic and ambulatory pulse pressure during young adulthood, but its contribution decreased after the fifth decade. (Hypertension. 1999;34[part 2]:808–812.)

Key words: age ■ pulse pressure ■ stroke volume ■ hypertension, arterial ■ blood pressure monitoring

Increased pulse pressure represents a hemodynamic stimulus for cardiac and vascular hypertrophy and may reflect arterial stiffness and atherosclerotic disease. Stiffness of large conduit arteries impairs the capacity to buffer the change in pulse pressure for a given stroke volume and explains the increased pulse pressure in the elderly. Increased pulse pressure, however, may be also explained by a hyperkinetic circulatory state in young patients with systolic hypertension.

High cardiac output characterizes the early phase of arterial hypertension. As patients get older, however, cardiac output gradually decreases at the expense of stroke volume. The age-related decrease in stroke volume, by reducing pulse pressure, could explain the low proportion of systolic hypertension among middle-aged hypertensive individuals. A reduction in arterial compliance after the middle adult years, however, could overcome the negative effect of the decreasing stroke volume on pulse pressure in older patients.

In addition to ventricular ejection and structural characteristics of the arterial wall, the amplitude of pulse pressure is passively related to the level of mean arterial pressure (MAP). Therefore, unless MAP is controlled at the same level, it would not be possible to analyze the effect of age on pulse pressure. Accordingly, in the present study we investigated the effect of age on conventional and ambulatory pulse pressure and its underlying mechanisms in unmedicated hypertensive men with the same level of MAP. Increasing age is associated with a greater increase in clinic than ambulatory blood pressure. Therefore, in this study patients were matched by the level of ambulatory MAP.

Methods

We screened 99 hypertensive men (clinic blood pressures ≥140 mm Hg systolic or ≥90 mm Hg diastolic, or both, on 2 occasions) with body mass index (BMI) ≤35 kg/m² who had no evidence of secondary cause of hypertension or major diseases and were free of antihypertensive medication for ≥2 weeks (1 month in the case of diuretics). Patients were carefully matched according to daytime MAP. Finally, 77 patients with daytime MAP between 95 and 114 mm Hg were selected.

Anthropometric measurements (height and weight) were made after patients had removed their shoes and upper garments. BMI was calculated as weight (in kilograms) divided by height (in meters squared).

Ambulatory blood pressure was recorded in the nondominant arm every 10 minutes between 7 AM and 11 PM and every 20 minutes between 11 PM and 7 AM with a Spacelabs 90207 monitor. Nighttime was defined according to the period of nighttime sleep based on the patient’s diary. Readings of systolic blood pressure (SBP) >260 or <70 mm Hg, diastolic blood pressure (DBP) >150 or <40 mm Hg, and pulse pressure >150 or <20 mm Hg were automatically discarded. Only studies with ≥90% of valid readings were included.

Patients were instructed to avoid smoking and avoid drinking tea or coffee the morning of the hemodynamic study. Hemodynamic...
evaluations were performed immediately before or after the 24-hour ambulatory blood pressure monitoring in most cases, or at least within the same week. Blood pressure was determined with a mercury sphygmomanometer on the right arm with cuffs of adequate size. Stroke volume was estimated noninvasively by impedance cardiography (Minnesota model 304B, Surcom Inc) by use of a technique and formula described elsewhere. Blood pressure and tracings of the first derivative of thoracic impedance were obtained in duplicate after 10 minutes of supine rest and during the first 3 minutes of upright position by observers blinded to the ambulatory blood pressure findings. Heart rate and stroke volume were calculated from tracings of consecutive cardiac cycles recorded at a paper speed of 50 mm/s. Several reports have shown the accuracy of impedance cardiography for estimating stroke volume and cardiac output. In our hands, the correlation coefficient between simultaneous impedance cardiography and thermodilution determinations of cardiac output was 0.94, and the mean paired difference was 0.08 L/min (95% CI, 0.12 to 0.27 L/min).  

\[ y = 20.76 + 1.17x \]

where \( y \) = cardiac output by impedance cardiography and \( x \) = cardiac output by thermodilution.  

Stroke index was obtained by dividing stroke volume by meters squared. Pulse pressure was calculated as the difference between SBP and DBP (using the Korotkoff phase V for defining DBP). The ratio of stroke volume to brachial pulse pressure (SV/PP) was used as a crude measure of systemic arterial compliance.

### Statistical Analysis

Results are expressed as mean±SD. Subjects were grouped into 5 age strata (<30, 30 to 39, 40 to 49, 50 to 59, and ≥60 years). Differences among age groups were assessed by ANOVA with Bonferroni’s test when the ANOVA was significant. The relationships of pulse pressure and age were also evaluated by use of linear and quadratic models. The transition in the curve of pulse pressure and age was estimated by multiple regression analysis including a dummy variable. Within-group differences were evaluated by paired t test. Associations between 24-hour pulse pressure and hemodynamic variables were assessed by simple correlation coefficients.

### Results

The clinical characteristics of the study subjects are shown in the Table. Patients in the fourth and fifth age groups had a shorter stature than those in the younger groups but comparable BMI.

### Supine Pulse Pressure

As shown in Figure 1, supine stroke index decreased significantly (\( P<0.05 \) by ANOVA) between the first (<30 years) and the fifth (≥60 years) age groups, with a parallel narrowing of pulse pressure up to age 40 to 49 years (\( P<0.05 \) by ANOVA). After age 50 years, pulse pressure showed a progressive widening despite the further decrease in stroke index (Figure 1). In contrast to stroke index, there were no significant age-related differences in heart rate. The SV/PP ratio remained constant up to the third age group, reflecting the parallel change of stroke index and pulse pressure during young adulthood. It fell significantly, however, after age 50.

### Figure 1

Top, Influence of age on supine and upright pulse pressure (PP, ◦) and stroke index (SI, ◦). Bottom, Influence of age on supine and upright SV/PP ratio. Values are mean±SD.  

+\( P<0.05 \) vs first age group and *\( P<0.05 \) vs fifth age group.

### Figure 2

Relation of supine and 24-hour pulse pressure and age (left) and upright and 24-hour pulse pressure and age (right).
years, indicating the progressive dissociation between pulse pressure and stroke index in the older decades (Figure 2).

**Upright Pulse Pressure**

When patients assumed an upright position (Figure 1), stroke index and pulse pressure showed a parallel fall, but the changes were significantly attenuated by age (1-way ANOVA, \( P < 0.05 \) and \( P < 0.001 \), respectively). Therefore, in the upright position, pulse pressure became "normal" in the youngest group but remained significantly increased in the oldest group (Figure 1). The SV/PP ratio decreased in the vertical position (\( P < 0.001 \)), indicating a greater postural fall in stroke index than the corresponding change in pulse pressure (Figure 1).

**Ambulatory Pulse Pressure**

Supine, upright, and 24-hour pulse pressure fitted a curvilinear correlation with age (\( r = 0.58, 0.56, \) and 0.80, respectively, \( P < 0.001 \)), with a transition at age 50 years for the 3 correlations. Supine pulse pressure overestimated (8\( \pm \)10 mm Hg, \( P < 0.001 \)) and upright pulse pressure underestimated (\(-4\pm11 \) mm Hg, \( P < 0.003 \)) the corresponding 24-hour measurement. Interindividual variation was much greater for supine and upright pulse pressure than for 24-hour pulse pressure (Figure 2).

The paired difference between daytime and nighttime pulse pressure reached statistical significance but showed a considerable overlap (50\( \pm \)8 versus 48\( \pm \)7 mm Hg, respectively, \( P < 0.01 \)). As shown in Figure 3, MAP exhibited a much larger decrease from day to night (105\( \pm \)5 versus 87\( \pm \)8 mm Hg, \( P < 0.001 \)), with a progressive attenuation in the older decades. The night-day ratio of pulse pressure showed a better correlation with the night-day ratio for SBP (\( r = 0.59, P < 0.001 \)) than with the corresponding night-day ratio for MAP, DBP, or heart rate (\( r = 0.37, P < 0.002; r = 0.23, P < 0.05 \); and \( r = 0.23, P < 0.05 \), respectively).

The hemodynamic correlates for ambulatory pulse pressure were assessed separately in the <50- and \( \geq \)50-year-old groups (\( n = 51 \) and 26, respectively). In younger men, 24-hour pulse pressure showed positive and significant correlations with both supine and upright stroke volume (\( r = 0.47, P < 0.002 \) and \( r = 0.44, P < 0.002 \), respectively) and a negative correlation with supine SV/PP ratio (\( r = -0.37, P < 0.01 \)). In contrast, in men \( \geq 50 \) years old, 24-hour pulse pressure showed negative and significant correlations with both supine and upright SV/PP ratio (\( r = -0.5, P < 0.01 \) and \( r = -0.6, P < 0.002 \), respectively), without significant correlation with stroke volume (Figure 4).

**Discussion**

The present study investigates the change in conventional and ambulatory pulse pressure as a continuum across the adult age range in untreated hypertensive men with the same level of MAP. Both supine and ambulatory pulse pressure exhibited a U-shaped relation with age. Widening of pulse pressure was associated with increased stroke volume in the young and reduced arterial compliance in the older patients. The age-related decrease in stroke volume resulted in a parallel narrowing of pulse pressure up to age 50 years. A significantly larger postural fall in stroke volume in the youngest patients, however, "normalized" the increased supine pulse pressure observed before age 30 years.

The postural decrease in pulse pressure was smaller than the corresponding change in stroke volume. The orthostatic decrease in the SV/PP ratio suggests an adaptive response of
conduit arteries to attenuate the effect of the postural decrease in blood flow on pulse pressure.

Widening of pulse pressure after age 50 years was independent of the level of stroke volume. Moreover, a progressive dissociation between pulse pressure and stroke volume was noted after that age. The reduction in arterial compliance (indicated by the progressive decrease in the SV/PP ratio) overcame the effect of the decreasing stroke volume on pulse pressure, explaining the lack of correlation between stroke volume and pulse pressure after age 50 years.

Narrowing of pulse pressure during young adulthood could favor the change from a systolic to a diastolic pattern of hypertension in middle-aged patients. The reciprocal change in the proportion of systolic and diastolic forms of hypertension between 25 and 65 years observed in population studies resembles the curvilinear change in pulse pressure reported here. In a national survey from Argentina, systolic hypertension (SBP ≥140 and DBP <90 mm Hg) was found in 42% of the hypertensive population before age 25 years and fell to <20% between age 35 and 54 years, returning to the initial proportion after age 65 years. A transient narrowing of pulse pressure produced by the age-related decrease in stroke volume could favor these changes in the pattern of blood pressure elevation. A decrease in arterial compliance after the middle adult years could overcome the effect of the decreasing stroke volume.

The age-related change in SV/PP ratio in our study resembles the findings reported by de Simone and colleagues in normotensive individuals. In agreement with their results, SV/PP ratio remained relatively constant between 17 and 50 years, after which it decreased steeply.

In the present study, brachial instead of aortic pulse pressure was used for the calculation of the SV/PP ratio. An increase in pulse-wave velocity with aging causes a proximal summation of the forward and backward waves, attenuating the difference between central and peripheral pulse pressure. Therefore, the use of brachial instead of aortic pulse pressure could underestimate arterial compliance in young patients.

Previous studies have found better correlations between pulse pressure and target organ damage and cardiovascular risk in hypertension when ambulatory rather than conventional measurements were used. The present data show that postural differences in pulse pressure represent a source of discrepancy between conventional and ambulatory measurements. Supine pulse pressure overestimated, and upright pulse pressure underestimated, the corresponding ambulatory readings. The pulse pressure value in the upright position would be expected to be similar to that during daytime (when patients spend most of the time in the vertical position). Sitting or walking pulse pressure, however, could attenuate the mere effect of upright posture on daytime pulse pressure value.

It has been well established that increasing age attenuates the nocturnal fall in SBP and DBP and heart rate; however, the corresponding change in pulse pressure has been less explored. The present study shows that in contrast to the diurnal change in MAP, there was a considerable overlap between daytime and nighttime pulse pressure through the adult age range. Correlation analyses indicate that the magnitude of the nocturnal fall in pulse pressure is more closely related to the nocturnal change in SBP than to the change in DBP. Hemodynamic changes evoked during sleep could explain the smaller nocturnal decrease in pulse pressure compared with the MAP. The increase in venous return and stroke volume during recumbency or the nocturnal bradycardia could maintain a wide pulse pressure despite the passive improvement of arterial compliance due to a lower MAP.

Calculation of daytime and nighttime pulse pressure from SBP and DBP reported in larger studies shows comparable findings. For example, in 1052 hypertensive men from the PIUMA study, daytime and nighttime pulse pressure averaged 53 and 53 mm Hg, 49 and 46 mm Hg, 48 and 44 mm Hg, 50 and 48 mm Hg, 57 and 56 mm Hg, and 61 and 61 mm Hg from the third to the eighth decade, respectively. Similarly, in 517 normotensive men from the Belgian Population Study, daytime and nighttime pulse pressure averaged 50 and 49 mm Hg between 20 and 39 years, 46 and 44 mm Hg between 40 and 59 years, and 52 and 49 mm Hg in those ≥60 years old.

In conclusion, the study shows a curvilinear change of pulse pressure with age in men with similar levels of MAP. Before the age of 50 years, the amplitude of pulse pressure was proportional to the changes in stroke volume. In contrast, a progressive dissociation between stroke volume and pulse pressure was noted after age 50 years, indicating a reduction in arterial compliance. Ambulatory pulse pressure reproduced the U-shaped relation with age observed with supine measurements, with a considerable overlap between daytime and nighttime readings.

References


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