Arterial Compliance Abnormalities in Isolated Systolic Hypertension

Alfredo Beltran, Gary McVeigh, Dennis Morgan, Stephen P. Glasser, Joel M. Neutel, Michael Weber, Stanley M. Finkelstein, and Jay N. Cohn

Arterial compliance measurements using intraarterial pulse contour analysis and a modified Windkessel model were carried out in 19 patients with isolated systolic hypertension (≥160/≤90 mm Hg) and compared to measurements in 29 patients with essential hypertension (diastolic blood pressure [BP] ≥95 mm Hg) and 47 normotensive control subjects. Arterial capacitive compliance was significantly lower in isolated systolic hypertension than in essential hypertension (P < .0002) and significantly lower in essential hypertension than in normotensive control subjects (P < .0001). Although the isolated systolic hypertension group was older than the essential hypertension group, the reduction of capacitive compliance in isolated systolic hypertension persisted even when comparison was made with a more nearly age-matched group of essential hypertension. In contrast, oscillatory compliance was reduced similarly in isolated systolic hypertension and essential hypertension compared to normotensive control subjects (P < .0001). Although pulse pressure was greater in isolated systolic hypertension than in essential hypertension, only a weak correlation (r = −0.34) existed between pulse pressure and capacitive compliance. These data indicate that both essential hypertension and isolated systolic hypertension patients exhibit comparably abnormal structure or tone of the small vessels that are the site of oscillations or reflections in the arterial vasculature. In isolated systolic hypertension there is a profound reduction in large artery or capacitive compliance that accounts for the increase in systolic BP and decrease in diastolic BP. This abnormality cannot be accurately assessed by pulse pressure alone. Am J Hypertens 2001;14:1007–1011 © 2001 American Journal of Hypertension, Ltd.

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The rise in systolic blood pressure (BP) with age usually is attributed to an age-dependent decrease in compliance of the aorta and large capacitance arteries.1–3 Isolated systolic hypertension (ISH) in the elderly has been viewed as an accentuation of this process4 and until recent years was not believed to require treatment. The Systolic Hypertension in the Elderly Program (SHEP) demonstrated, however, that antihypertensive therapy in this population could reduce morbidity and mortality.5

Several techniques have been used to assess arterial compliance. The simplest has been to relate the pulse pressure to the left ventricular stroke volume, a measurement that will intuitively demonstrate an increased arterial stiffness in patients with ISH, who, by definition, have a widened pulse pressure.6 Diastolic pulse wave contour analysis using a modified Windkessel model of the circulation allows the calculation of compliance both in proximal large capacitance arteries and in the more distal small arteries that serve as the site for reflected waves or oscillations within the arterial bed.7 Because this measurement is confined to an analysis of pressures after the diastolic notch, the calculation is not directly influenced by the arterial systolic or pulse pressures. In previous studies from this laboratory we have demonstrated a striking reduction in the distal, small artery compliance as a manifestation of the vascular abnormality in essential hypertension.8

The purpose of the present study was to assess the capacitive (large artery) and oscillatory (small artery) compliance in a group of patients with ISH to determine if the abnormality is confined to the large arteries or also affects the smaller arteries involved in the hypertensive process. Abnormalities in this population were compared to those in a cohort with essential hypertension and in a large normotensive population. Studies were performed in...
Table 1. Patient population

<table>
<thead>
<tr>
<th></th>
<th>ISH</th>
<th>EH</th>
<th>NT</th>
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</thead>
<tbody>
<tr>
<td>n</td>
<td>19</td>
<td>29</td>
<td>47</td>
</tr>
<tr>
<td>Age (y)</td>
<td>69 ± 8</td>
<td>54 ± 8</td>
<td>46 ± 15</td>
</tr>
<tr>
<td>Sex (M/F)</td>
<td>13/6</td>
<td>16/13</td>
<td>38/9</td>
</tr>
<tr>
<td>SBP (mm Hg)</td>
<td>191 ± 18</td>
<td>144 ± 12</td>
<td>130 ± 10</td>
</tr>
<tr>
<td>DBP (mm Hg)</td>
<td>78 ± 9</td>
<td>100 ± 4</td>
<td>68 ± 10</td>
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<tr>
<td>MAP (mm Hg)</td>
<td>120 ± 10</td>
<td>115 ± 6</td>
<td>91 ± 12</td>
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<tr>
<td>HR (beats/min)</td>
<td>69 ± 9</td>
<td>72 ± 10</td>
<td>60 ± 9</td>
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<td>CO (L/min)</td>
<td>5.0 ± 0.9</td>
<td>5.9 ± 0.7</td>
<td>5.3 ± 0.9</td>
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<tr>
<td>SVR (dynes · sec · cm⁻²)</td>
<td>1946 ± 357</td>
<td>1571 ± 179</td>
<td>1375 ± 357</td>
</tr>
</tbody>
</table>

ISH = isolated systolic hypertension; EH = essential hypertension; NT = normotensive control subjects; SBP = systolic blood pressure; DBP = diastolic blood pressure; MAP = mean arterial pressure; HR = heart rate; CO = cardiac output; SVR = systemic vascular resistance.

to two separate sites to augment the patient population with ISH.

Methods

Studies were performed at the University of Minnesota, Minneapolis, and the Veterans Affairs Medical Center, Long Beach, California. All computer analyses of wave forms and data analysis were carried out at the University of Minnesota.

Intra-arterial pulse wave recordings were obtained by cannulating the brachial artery of the nondominant arm by methods described previously from our laboratory.8 Cardiac outputs were measured differently at the two sites. In Minnesota, an indocyanine green dye dilution technique was used. In California, cardiac output was estimated by a Doppler technique examining the root of the aorta or by a pulse contour technique validated in the Minnesota laboratory.9 Heart rate and systolic and diastolic BP were recorded using Statham transducers and recording systems. Mean arterial pressure and systemic vascular resistance were calculated from these measurements. Written informed consent was obtained from all subjects. The study was approved by the Institutional Review Board at each center.

Arterial compliance was determined by relating the parameters derived from computer curve fitting of the arterial diastolic decay to a modified Windkessel model of the circulation.8–10 The model generates two compliances: a capacitive component (Cᵢ) and an oscillatory component (Cₒ). The capacitive component assesses the arterial storage capacity, which is a function predominantly of the larger conduit arteries. The oscillatory or reflective component is related to the cushioning effect of compliance, at the arterial reflective sites that are thought to reside primarily in small arteries and arterioles, and at branching sites of small arteries.

Patient Population

Patients for this study were recruited at the end of a 2- to 4-week single-blind, placebo washout phase. Three patient populations were compared. For the purposes of this study, ISH was defined as adult male and female patients between the ages of 50 and 85 years without evidence of any major organ system disease and who had a seated systolic BP ≥160 mm Hg with a diastolic BP ≤90 mm Hg. Nineteen patients met the inclusion criteria. Essential hypertension (EH) patients were aged between 18 and 70 years with seated diastolic BP ≥95 mm Hg and <114 mm Hg with no major organ system disease. Twenty-nine patients were included in this analysis. Patients with diabetes (elevated fasting blood sugar) were excluded, but rigorous evaluation of glucose intolerance was not carried out. Forty-seven successively studied normotensive subjects were used as a control group. These subjects had normal BP (<140/85 mm Hg) and were free of cardiovascular disease based on history and physical examination. The demographic and clinical characteristics of these groups are shown in Table 1. This was a cross-sectional retrospective comparison of three patient groups. The normal and EH subjects were studied in Minneapolis. The ISH group subjects were recruited and studied at the two sites, but all data analysis was performed in Minneapolis. The patients were studied over a similar time period so that technique differences are not likely to have influenced the results.

Statistical Methods

Analysis of variance was used to compare the hemodynamic parameters between the three groups with t-tests using a Bonferroni correction for between group analysis. Correlation coefficients were calculated to relate capacitive and oscillatory compliance to pulse pressure.

Results

Hemodynamic Results

Baseline systolic, diastolic and mean arterial BP in the three groups are shown in Table 1. The ISH group was significantly older and their systolic BP considerably higher. There was no difference in cardiac output between the groups, but systemic vascular resistance was statis-
Compliance Comparisons Between Groups

Capacitive compliance ($C_1$) was significantly lower in the ISH group compared to the EH and normotensive control group ($P < .0002$) (Fig. 1). $C_1$ was also significantly lower in the EH than in the control subjects ($P < .0001$). In contrast oscillatory compliance ($C_2$) was similarly reduced in the ISH and EH groups compared to the normal controls ($P < .0001$) (Fig. 2). Thus, ISH and EH demonstrated reduced large and small vessel compliance compared to normotensives, but ISH demonstrated a greater reduction in large vessel (capacitive) compliance and a similar reduction of small vessel ($C_2$) compliance compared to EH.

Because compliance decreases with age, we compared a group of age-matched EH ($n = 14$) to the patients with ISH and again found a greater reduction in large vessel compliance in the ISH group, suggesting that the differences between ISH and EH were not due to age alone (Fig. 3). $C_2$ in the EH group and ISH group were similar and lower than in the normotensive controls.

Pulse Pressure Comparisons

In the ISH group, pulse pressure in mm Hg was only weakly correlated with capacitive compliance ($r = -0.34$) (Fig. 4).

Discussion

A reduction of capacitive function of the arterial circulation would be expected to augment systolic BP during left ventricular ejection as the stroke volume cannot be as well accommodated by systolic distention of the arterial vasculature. The present study has confirmed that ISH is associated with a striking reduction of the capacitive compliance measured by computer-based contour analysis of the diastolic arterial waveform. Furthermore, the studies suggest that arterial pulse is only weakly correlated with compliance and, therefore, cannot serve by itself as an adequate guide to the reduction of capacitive compliance.

If the vascular abnormality in ISH were confined to the capacitance arteries, diastolic arterial pressure would be expected to be low. Maintenance of diastolic arterial pressure is dependent on the volume of blood in the arteries during diastole and is a function of systolic runoff from the
arteries and the release of blood in diastole from its storage site in the capacitance arteries. Substitution of a stiff “artery” for a compliant “artery” results in a marked drop of diastolic BP in a model system. 11

The ISH is commonly defined by the presence of an elevated systolic BP with a diastolic BP <90 mm Hg. In the present series the diastolic pressures averaged 78 mm Hg, a value slightly higher than in our normotensive controls. Thus, rather than a lower diastolic BP, which would be expected if the vascular abnormality were confined to the capacitance arteries, the diastolic BP was higher than normal in ISH. Indeed, systemic vascular resistance was slightly higher in the ISH group than in our essential hypertensive population, thus indicating that the vascular abnormality in ISH is not confined to the large arteries.

The oscillatory compliance, which probably resides primarily in small arteries, at branch points and at the terminal arterioles, was similarly reduced in the ISH and EH groups. Because abnormal reduction of compliance in this vascular segment has been demonstrated in EH, 8 diabetes, 12 and atherosclerosis, 9 these data suggest that the vascular abnormality in ISH is more extensive than in the large capacitance arteries. Thus, the diastolic BP <90 mm Hg in this group is not indicative of the absence of small artery involvement but probably is the result of a combination of functional and structural changes in both the large and small arteries.

It must be recognized that arterial compliance is influenced by arterial pressure because of the nonlinear vascular pressure:volume relationship. Therefore, some of the reduction of C1 and C2 observed in the hypertensive subjects in this study could be the passive result of the higher BP rather than due to a structural or functional abnormality of the arterial wall. This effect may influence the magnitude of compliance difference between the normo-

![FIG. 3. C1 in ISH compared to age-matched EH. Abbreviations as in Figs. 1 and 2.](image)

![FIG. 4. Correlation between C1 and pulse pressure in patients with ISH. Abbreviations as in Figs. 1–3.](image)
tensive and hypertensive subjects, but not the differences between the ISH and EH groups who exhibited similar mean arterial pressure.

These data help to understand the benefit of antihypertensive therapy in ISH. These patients have the hemodynamic characteristics of essential hypertension but with a component of stiffening of the large arteries that tends to normalize diastolic BP. In middle-aged and elderly individuals, therefore, systolic BP should be a better guide to the presence of the hypertensive disease state than diastolic BP. Because the compliance measurements described can now be performed simply by a noninvasive technique, clinical assessment of the capacitive and oscillatory compliance in such individuals could assist in diagnosis and management.

References