To investigate the relation between the small artery structure and different blood pressure parameters, spontaneously hypertensive rats were treated from 4 to 24 weeks of age (20 weeks in total) with five different antihypertensive therapies: two angiotensin converting enzyme inhibitors (perindopril and captopril), a calcium antagonist (isradipine), a β-blocker (metoprolol), and a vasodilator (hydralazine). At 24 weeks of age, 24-hour blood pressure was measured, and two mesenteric resistance vessels were taken from each animal. Blood pressure was 227/135 mm Hg (systolic/diastolic) and 161/106 mm Hg in untreated hypertensive and normotensive control rats, respectively. Heart rates were 376 min⁻¹ and 295 min⁻¹ for the two strains. All treatments reduced all blood pressure parameters except for metoprolol, which did not reduce pulse pressure. In the small arteries, the media cross-sectional area was unaffected by the treatments. When a simple correlation analysis was made, pulse pressure was found to correlate more closely (r=0.64, p<0.001) to the resistance vessel media/lumen ratio than any of the other pressure parameters studied: systolic (r=0.51, p=0.011), mean (r=0.41, p=0.05), or diastolic (r=0.28, p=0.19). When an analysis of covariance was performed that included pulse pressure, mean blood pressure, and heart rate, which also correlated significantly to the media/lumen ratio, 81% of the variation in the media/lumen ratio could be accounted for by the variation in the three covariates (p<10⁻⁵), pulse pressure being the major factor. In conclusion, it is indicated that a reduction in pulse pressure and heart rate during antihypertensive treatment may be important in preventing the development of abnormal small artery structure in hypertension. (Hypertension 1991;18:722-727)
branch off the superior mesenteric artery. The vessels were the second or third location that was at a constant distance from the intestinal wall. The vessels were constantly perfused with saline at a rate of 0.6 ml/hr, which raised the transducer pressure by 1 mm Hg. This was not corrected for. Twenty-four-hour SBP and DBP were calculated from the measurements of MBP and PP (DBP=MBP-0.46 PP; SBP=DBP+PP). By doing this, it was possible to avoid the variations in blood pressure with respiration and thus to have an exact measure not just of PP but also of SBP and DBP on a 24-hour basis.

Vascular Structure

As described previously,5 a vessel segment biopsy was taken from each side of the mesentery when the 24-hour measurements of MBP were terminated. By choosing the most distal vessels in each side of the biopsy, it was possible to obtain vessels from a specific anatomic location that was at a constant distance from the intestinal wall. The vessels were the second or third branch off the superior mesenteric artery. The vessels were held fully relaxed (i.e., unable to dilate further even in a Ca²⁺-free environment) in a physiological saline solution (PSS) consisting of (mmol/l): NaCl 119, KCl 4.7, NaHCO₃ 25, CaCl₂ 2.5, KH₂PO₄ 1.18, MgSO₄ 1.17, ethylenediaminetetraacetic acid 0.026, and glucose 5.5. The PSS was bubbled with 95% O₂ and 5% CO₂ to give a pH of 7.4 and was kept at 37°C. Two small arteries were taken, one from each side of the biopsy as distal as possible. The operator was unaware of the type of rat being investigated. Each vessel was mounted as a ring preparation on an isometric myograph,7 and structural parameters were determined.7,8

Media area was determined, and the vessel was set to 90% of the internal circumference expected from a transmural pressure of 100 mm Hg (Lᵢ). Lumen diameter was taken as Lᵢ/3.14, and the corresponding media thickness was calculated on the basis that the media area remained constant. From these data, media/lumen ratio was calculated. The vessels had lumen diameters ranging from 0.180 to 0.330 mm (mean 0.225 mm).

Statistics

Regression analysis between pressure and structural parameters was performed. One 24-hour average value for the pressure parameter and the average media/lumen ratio, media thickness, lumen diameter, or media area of the two small arteries from the same rat were taken as a single value for that rat. From the number of points and the coefficient of correlation (r), a probability value was calculated. All SHRs (treated and untreated) were included in the regression; WKY rats were excluded. Furthermore, using the same data, an analysis of covariance9 was performed with media/lumen ratio as base parameter and PP, HR, and MBP as covariates representing the level of blood pressure and the cyclic pressure loading (PP, amplitude and HR, frequency). From this analysis, it was possible to determine to which degree the variation in the covariates could account for the simultaneous variation in the base parameter. The effect of the drugs on the small artery structure and function has been described in detail in an earlier article including larger groups of rats.5

Results

At 24 weeks of age, when treatments had lasted 20 weeks, DBP for WKY rats ranged from 98 to 114 mm Hg compared with 122–145 mm Hg for untreated SHRs. For the treated SHRs, DBP ranged from 82 to 122 mm Hg. No single 24-hour measurement of SBP, DBP, MBP, or PP in an SHR control overlapped the WKY rat range and vice versa. In all five treated groups, all four pressure parameters were significantly reduced except for PP in the metoprolol group, which was unchanged. Three treatments reduced the average DBP to the same value as that of the WKY rats (namely, hydralazine, captopril, and metoprolol), although it was notable that metoprolol had little effect on PP (Table 1). The largest effects on PP were seen in the perindopril- and captopril-
TABLE 1. Twenty-Four-Hour Blood Pressure Parameters and 24-Hour Heart Rate

<table>
<thead>
<tr>
<th>Strain or treatment</th>
<th>MBP (mm Hg)</th>
<th>HR (min⁻¹)</th>
<th>SBP (mm Hg)</th>
<th>DBP (mm Hg)</th>
<th>PP (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHR</td>
<td>177±6</td>
<td>376±18</td>
<td>227±6</td>
<td>135±5</td>
<td>92±2</td>
</tr>
<tr>
<td>WKY</td>
<td>132±4</td>
<td>295±15</td>
<td>161±3</td>
<td>106±4</td>
<td>55±1</td>
</tr>
<tr>
<td>PER</td>
<td>121±7*</td>
<td>358±10</td>
<td>153±8*</td>
<td>94±6*</td>
<td>60±3*</td>
</tr>
<tr>
<td>CAP</td>
<td>137±2*</td>
<td>376±16</td>
<td>172±2*</td>
<td>107±2*</td>
<td>65±1*</td>
</tr>
<tr>
<td>HYD</td>
<td>140±5*</td>
<td>332±6</td>
<td>178±3*</td>
<td>107±5*</td>
<td>71±2*</td>
</tr>
<tr>
<td>ISR</td>
<td>149±3*</td>
<td>333±13</td>
<td>190±3*</td>
<td>115±4*</td>
<td>75±1*</td>
</tr>
<tr>
<td>MET</td>
<td>146±8*</td>
<td>392±26</td>
<td>193±7*</td>
<td>105±8*</td>
<td>88±2</td>
</tr>
</tbody>
</table>

Values show group mean±SEM for four rats per treated group. MBP, SBP, DBP, and PP, mean, systolic, diastolic, and pulse pressures, respectively; HR, heart rate; SHR, spontaneously hypertensive rat control group; WKY, Wistar-Kyoto rat control group; PER, CAP, HYD, ISR, and MET, perindopril-, captopril-, hydralazine-, isradipine-, and metoprolol-treated SHRs, respectively.

*Significantly reduced by the treatment (p<0.05).

treated groups. HR was not influenced significantly by the treatments. These differences were tested by one-way analysis of variance followed by Student's t test between treated and untreated SHRs. Figure 1 shows diagrams of small artery media/lumen ratio and the blood pressure parameters. PP was the best correlate, followed by (in order) SBP, MBP, and HR. DBP was not significantly correlated to media/lumen ratio. By analysis of covariance, using PP, HR, and MBP as covariates, the variation in media/lumen ratio was divided into two groups: residual (19.3%) and accounted for (80.7%; F=7.816; f1=8; f2=15; p<10⁻³). PP came out as the major factor (F=15.5; f1=1; f2=15; p=0.001), HR as a minor factor (F=4.3; f1=1; f2=15; p=0.056), whereas MBP could not account for any of the variation in media/lumen ratio (F=0.27; f1=1; f2=15; p=0.612). This somewhat surprising finding is discussed below. In the present subgroup as well as in the large study, the media areas did not differ either between SHR and WKY rats or between untreated and

FIGURE 1. Scatterplots show resistance vessel media/lumen ratio (m: l) plotted against 24-hour blood pressure parameters (panels A–D) and 24-hour heart rate (panel E). •, Hydralazine-treated rats; ●, metoprolol-treated rats; ▲, isradipine-treated rats; Δ, perindopril-treated rats; □, captopril-treated rats; ○, group mean±SEM for untreated control rats. r, Coefficient of correlation; P, corresponding probability value; DBP, diastolic blood pressure; MBP, mean blood pressure; SBP, systolic blood pressure; PP, pulse pressure; HR, heart rate.
treated SHRs (Table 2). The treatments did not change media thickness significantly, and only perindopril increased the lumen diameter. Details on the effects of the treatments on vascular structure are given in Reference 5. In Table 3, a correlation analysis of the pressure parameters and media thickness, lumen diameter, or media area is shown. For lumen diameter, the correlation of media/lumen ratio to PP was not closer as it was to MBP, whereas PP was the only significant correlate to media thickness. The media area was not correlated to any of the pressure parameters.

Discussion

The present study is the first long-term antihypertensive treatment study presenting 24-hour measurements of MBP, PP, and HR together with morphometric measurements of the small artery structure. Although the number of animals was relatively small and five different antihypertensive drugs were used, it seems clear that reduction in the cyclic pressure loading (especially the amplitude but also the frequency) on the small arteries may be considered an important factor for the level of media/lumen ratio during antihypertensive treatment. The correlation \( p < 0.001 \) between media/lumen ratio and PP was close even though only two resistance vessels were examined per animal.

The mechanism for the increased MBP in rat genetic and human essential hypertension is unknown but may be related to or mediated through structural changes in the resistance vessels. It has been shown that raised blood pressure level is associated with increases in the thickness of the smooth muscle layer and with decreases in lumen diameter of resistance vessels, resulting in an increase of media/lumen ratio and thus increased minimal vascular resistance. However, treatment studies do not entirely support the hypothesis that MBP and media/lumen ratio are closely related. When the blood pressure is decreased by antihypertensive treatment, although corresponding reductions in media/lumen ratio do sometimes occur, these are not always as pronounced as could be expected from the values measured in untreated hypertensive and normotensive subjects and the degree of blood pressure reduction. All these studies have, however, only examined the relation between vascular structure and a single pressure parameter representing the blood pressure level. The present data may help to explain why, although MBP is reduced, vascular structure is not always reduced by long-term antihypertensive treatment; the cyclic pressure loading represented by PP and HR may still have been elevated. It has been shown in humans that the pulsatile pressure persists as far as the capillary level; around 40% of both intravascular MBP and PP are transmitted down to the capillary level and thus increased minimal vascular resistance.

<table>
<thead>
<tr>
<th>Strain or treatment</th>
<th>Media ((\mu m))</th>
<th>Lumen ((\mu m))</th>
<th>m:l</th>
<th>Media area ((\mu m^2\times10^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHR</td>
<td>15.3±1.2</td>
<td>212±9</td>
<td>7.2±0.5</td>
<td>11.2±1.1</td>
</tr>
<tr>
<td>WKY</td>
<td>12.1±1.4*</td>
<td>233±14</td>
<td>5.2±0.4*</td>
<td>9.5±1.6</td>
</tr>
<tr>
<td>PER</td>
<td>13.1±1.0</td>
<td>297±14*</td>
<td>4.4±0.2*</td>
<td>12.8±1.8</td>
</tr>
<tr>
<td>CAP</td>
<td>15.0±0.8</td>
<td>236±25</td>
<td>6.4±0.4</td>
<td>11.9±1.8</td>
</tr>
<tr>
<td>HYD</td>
<td>15.4±1.0</td>
<td>240±17</td>
<td>6.4±0.4</td>
<td>12.5±1.7</td>
</tr>
<tr>
<td>ISR</td>
<td>14.0±0.5</td>
<td>150±17</td>
<td>5.6±0.2*</td>
<td>11.8±1.0</td>
</tr>
<tr>
<td>MET</td>
<td>16.2±0.7</td>
<td>203±11</td>
<td>8.0±0.2</td>
<td>11.2±0.9</td>
</tr>
</tbody>
</table>

Values show group mean±SEM for four rats per treated group. m:l, Media/lumen ratio; SHR, spontaneously hypertensive rat control group; WKY, Wistar-Kyot rat normotensive control group; PER, CAP, HYD, ISR, and MET, perindopril-, captopril-, hydralazine-, isradipine-, and metoprolol-treated SHRs, respectively.

*Significantly changed by the treatment \( p < 0.05 \).

**Table 2. Small Artery Structural Parameters**

**Table 3. Correlation Between 24-Hour Blood Pressure Parameters and Small Artery Structure Parameters**

<table>
<thead>
<tr>
<th>Blood pressure parameter</th>
<th>Media</th>
<th>Lumen</th>
<th>m:l</th>
<th>Media area</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>0.41*</td>
<td>-0.48*</td>
<td>0.64*</td>
<td>-0.10</td>
</tr>
<tr>
<td>SBP</td>
<td>0.31</td>
<td>-0.50*</td>
<td>0.51*</td>
<td>-0.15</td>
</tr>
<tr>
<td>MBP</td>
<td>0.29</td>
<td>-0.45*</td>
<td>0.41*</td>
<td>-0.12</td>
</tr>
<tr>
<td>DBP</td>
<td>0.19</td>
<td>-0.37</td>
<td>0.28</td>
<td>-0.11</td>
</tr>
<tr>
<td>HR</td>
<td>-0.07</td>
<td>-0.34</td>
<td>0.41*</td>
<td>-0.30</td>
</tr>
</tbody>
</table>

Values show coefficients of correlation calculated by linear regression analysis. Minus indicates inverse correlation. m:l, Media/lumen ratio; PP, pulse pressure; SBP, MBP, and DBP, systolic, mean, and diastolic blood pressures, respectively; HR, heart rate.

*Significantly correlated \( p < 0.05 \).
assuming that all else is equal. That PP should be
decreased through an effect of the treatments on
MBP in the present study appears unlikely, for one
would then expect a closer correlation between MBP
and media/lumen ratio rather than between PP and
media/lumen ratio. Other factors are important for
the level of PP including the duration of diastole and
the rate of the pressure decline in diastole. In
the present study, there was no change in HR due to the
treatments. Also, the decreased media/lumen ratio
found in some of the treated groups would tend to
increase the speed of the pressure drop in diastole
because of a reduction in peripheral resistance and
thus would tend to increase the PP. It therefore
seems likely that PP determines the level of media/
lumen ratio rather than the reverse, although no final
conclusion can be drawn from the abovementioned
arguments.

Graft studies, in which veins have been implanted
into the arterial system, appear to provide some of
the most convincing evidence that the blood pres-
sure level can change vascular structure. However,
the possibility cannot be excluded that it may be the
increase in pulsatile pressure loading rather than the
increased blood pressure level that gives rise to the
change in vascular structure. After all, in those
experiments, the vessel grafts were subjected to the
largest possible relative change in pulsatile pressure:
from almost zero in the veins to arterial PP. Mecha-
nisms for the morphological changes in grafted veins
have recently been investigated in dogs. Femoral
veins were implanted end-to-end or end-to-side into
the arterial system. Small cuffs were used for re-
stricting graft dilatation locally or for creating a
proximal stenosis to reduce the pressure load. In
3-month-old grafts, histological studies showed a
marked increase in media area that appeared to be
delayed by using cuffs to prevent distension of the
grafts. It was concluded that distension stimulates
the medial hyperplasia. Conversely, altering the flow
rate through the grafts did not lead to differences in
medial hyperplasia. Finally, the medial hyperplasia
was not delayed by lowering MBP (by 21%) and PP
(by 38%) simultaneously. This is in agreement with
our findings of no change in media area despite a
substantial pressure reduction. Further comparison
with our data is not possible since data on lumen
diameters were not shown.

At the cellular level, it is known that cells in vitro
respond to cyclic stretching with an increased mitotic
activity, perhaps explaining the mechanism by
which the cyclic pressure loading could influence
the structure of the resistance vessel wall. Furthermore,
during antihypertensive treatment of human essen-
tial hypertension it has been observed that it may be
dangerous to reduce DBP too much since this in-
creases the mortality from ischemic heart disease. It
was suggested that this could be ascribed to the
perfusion pressure in diastole becoming too low and
leading to infarction of the heart muscles; an alter-
native explanation may be that the PP was increased
too much by the treatment, maintaining an important
stimulus for preservation or aggravation of the ab-
normal vascular structure and thus for this reason
inducing ischemia. I believe this possibility deserves
further investigation.

Recent observations in a special kind of vascula-
ture, aortic aneurysms, indicate that their growth rate
is strongly related to PP. Aneurysm expansion rate
was positively correlated to SBP and negatively cor-
related to DBP.

In conclusion, the reduction in small artery media/
lumen ratio due to antihypertensive treatment was
accomplished by combined effects on media and
lumen with no significant change in media area
(muscle mass). It is indicated that changes in intralu-
minal mechanical factors may account for most of the
variation in the resistance vessel media/lumen ratio,
even in a mixed treatment study using five different
antihypertensive drugs, when parameters represent-
ating both the blood pressure level and the cyclic
pressure loading are included. This furthermore
speaks against the importance of drug-specific effects
on resistance vessel structure independent of intra-
vascular pressure. Based on this, one might point to
the potential importance of not just aiming antihy-
pertensive treatment efforts at DBP, but also of
trying to reduce PP and HR to reduce the cyclic
pressure load on the resistance vessels if normaliza-
tion of their structure (media/lumen ratio) is desired.
Already, it has been shown that reducing PP in
hypertension is beneficial concerning cardiac hyper-
trophy and the incidence of cardiovascular death in
hypertension. Clearly, much further work is neces-
sary to clarify the issue.

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**KEY WORDS** • chronic hypertension • pulse pressure • heart rate • vascular resistance • blood pressure monitoring • antihypertensive therapy • spontaneously hypertensive rats • Wistar-Kyto rats
Reducing pulse pressure in hypertension may normalize small artery structure.

K L Christensen

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