Hypertension in Experimental Diabetes Mellitus
Renin-Prostaglandin Interaction

SHIGEHIRO KATAYAMA AND JAMES B. LEE

SUMMARY To investigate mechanisms involved in the high incidence of hypertension in diabetes mellitus, the relationship between renin-angiotensin production and renal prostaglandin E\textsubscript{2} synthesis was studied in rats 1 week after diabetes mellitus had been induced by streptozotocin injection. The diabetic rats became hypertensive, although plasma renin activity did not increase despite the plasma volume contraction resulting from polyuria and natriuresis. Subcutaneous insulin injection resulted in a marked increase in plasma renin activity, while more rigid control of diabetes mellitus achieved by constant insulin infusion decreased blood pressure. Cortical renin content and renin release as well as papillary prostaglandin E\textsubscript{2} synthesis in vitro were significantly lower in diabetic rats than in nondiabetic controls. Isoproterenol and prostaglandin E\textsubscript{2} stimulated renin release in controls, while diabetic rats responded only to isoproterenol. Insulin infusion by pump reversed these abnormalities. An additive effect of a maximum dose of isoproterenol (10^{-7} \text{M}) and prostaglandin E\textsubscript{2} (10^{-4} \text{M}) on renin release was observed in nondiabetic controls and in diabetic rats treated with insulin pump, but not in untreated diabetic rats. The results suggest that 1) renal renin release and prostaglandin E\textsubscript{2} synthesis in diabetes mellitus are insulin dependent, 2) inappropriately lower plasma renin activity in diabetes mellitus may be attributed to a diminished renal renin pool and a lack of renin release in response to renal prostaglandin E\textsubscript{2}, the synthesis of which is also impaired in diabetes, 3) prostaglandin E\textsubscript{2}-induced renin release may operate independently from isoproterenol-induced renin release, and 4) impaired renal prostaglandin E\textsubscript{2} synthesis may contribute to the development of hypertension in the face of an unchanged prohypertensive renin-angiotensin II system.

(Hypertension 7: 554-561, 1985)

KEY WORDS • sodium excretion • insulin • streptozotocin • hyperglycemia • plasma volume

DIABETES mellitus (DM) is associated with characteristic morphological and functional changes in the kidney. In addition, cardiovascular complications, including hypertension, atherosclerosis, and thrombotic disease, are more prevalent among diabetics than nondiabetics. Increased sensitivity of diabetic platelets to aggregating agents as well as increased diabetic platelet production of thrombox-

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Received March 26, 1984; accepted February 12, 1985.
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streptozotocin-induced diabetes. However, the latter study demonstrated no difference in glomerular 6-keto-prostaglandin F\textsubscript{1a} and PGE\textsubscript{2}, synthesis between diabetic and nondiabetic rats.\textsuperscript{4} On the other hand, plasma renin activity (PRA) is well known to be low in DM, as indicated by hyporeninemic hypoaldosteronism. This suppressed PRA has been reported to be due to volume expansion following hyperglycemia,\textsuperscript{9, 10} impaired renin release,\textsuperscript{11} inadequate conversion of prorenin to renin,\textsuperscript{12} and diminished catecholamine secretion.\textsuperscript{13}

As reported previously, during high renin states such as low sodium diet and renovascular hypertension, increased renal PGE\textsubscript{2}, synthesis, stimulated by the associated rise in angiotensin II, has an important physiological role in offsetting renin-angiotensin induced renal vasoconstriction and antinatriuresis.\textsuperscript{14, 15} Conversely, PGE\textsubscript{2}, prostacyclin, and their precursor arachidonic acid stimulate renin release in humans and experimental animals in vivo and in vitro.\textsuperscript{16-18} Thus, the present study was designed to investigate the alterations in urinary PGE\textsubscript{2}, excretion and PRA in vivo and renal papillary PGE\textsubscript{2}, synthesis as well as renin release in vitro in experimental diabetic rats and to correlate the effects of insulin administration with any observed changes in the renin-prostaglandin systems, sodium homeostasis, and blood pressure regulation.

Materials and Methods

Wistar male rats weighing 200 to 250 g (Charles River Breeding Laboratories, Boston, MA, USA) were housed in metabolic cages with free access to tap water and Purina rat chow (normal sodium intake, Ralston Purina Co., St. Louis, MO, USA). To induce diabetes, 65 mg/kg of streptozotocin (Upjohn Co., Kalamazoo, MI, USA) was injected intraperitoneally. The control group received only the vehicle (2.0 ml/kg of 0.1 M sodium citrate buffer, pH 4.5). Body weight and urine volume were recorded daily. Glycosuria and ketonuria were monitored semiquantitatively with Keto-Diastix reagent strips (Ames Division, Miles Laboratories, Elkhart, IN, USA). Two days after the injection of streptozotocin, plasma glucose levels were determined by the glucose oxidase method using blood samples obtained from the tail vein. Diabetics with plasma glucose levels greater than 300 mg/dl were separated randomly into three groups: 1) untreated diabetics, 2) diabetics treated with 2 units of s.c. lente-regular insulin (1:1; Eli Lilly and Co., Indianapolis, IN, USA) daily for 5 days with one-third in the morning and the remainder in the evening, and 3) diabetics treated with constant infusion of insulin for 5 days by miniosmotic pump (Alza Corp., Palo Alto, CA, USA) implanted subcutaneously in the back during ether anesthesia. Regular insulin was diluted in saline containing 0.7% glutamic acid to block insulin aggregation, and the concentration of insulin in the pump was adjusted to infuse at a rate of 2 U/200 g body weight/24 hr. Infusion of vehicle alone did not show any effect on blood pressure, plasma glucose levels, or PRA.

In Vivo Studies

Five days after the injection of streptozotocin, 24-hour urine samples were collected during the ensuing 2 days to determine urinary sodium and potassium concentrations by flame photometry (Instrumentation Laboratory Inc, Boston, MA, USA) and urinary PGE\textsubscript{2}, excretion by the specific radioimmunoassay described in the following section. After the completion of urinary collection, blood pressure was determined by the tail cuff method. The first pulse appearing on the Grass polygraph recorder (Grass Instrument Co., Quincy, MA, USA) during cuff deflation was assigned as the systolic pressure. After the in vivo studies, the animals were decapitated and truncal blood was collected into a chilled tube containing 5 mg/ml of ethylenediaminetetraacetic acid for determination of PRA, plasma glucose levels, and hematocrit. The PRA was determined by a specific radioimmunoassay measuring angiotensin I generated at pH 6.0, with an interassay and intraassay variation of 13 and 8% respectively, and expressed as nanograms of angiotensin I per milliliter per hour.\textsuperscript{19}

In Vitro Studies

Four papillary slices (8-15 mg) were made with a Stadie-Riggs microtome (A. H. Thomas, Philadelphia, PA, USA), placed in 25-ml flasks containing 2 ml of Krebs-Ringer bicarbonate buffer (pH 7.4), and incubated in duplicate for 30 minutes at 37 °C with 95% O\textsubscript{2}, 5% CO\textsubscript{2}, in an Eberbach apparatus (A. H. Thomas) at 80 oscillations/min. Slices were homogenized before and after incubation in the medium, urine and slice homogenates were extracted, and PGE\textsubscript{2}, was assayed with a highly specific radioimmunoassay (Institute Pasteur, Paris, France) as previously reported.\textsuperscript{14} Results are expressed as nanograms per 24 hours and nanograms per milligram of tissue for urine and slices respectively. For estimation of de novo PGE\textsubscript{2}, synthesis, initial slice PGE\textsubscript{2}, content was subtracted from final slice plus medium value and expressed as nanograms per milligram of tissue per 30 minutes. The PGE\textsubscript{2}, production measured in this fashion reflects de novo synthesis since PGE\textsubscript{2}, levels after incubation in the absence of oxygen or the presence of indomethacin revealed no difference from initial values before incubation.\textsuperscript{14}

To determine cortical renin content and release in vitro, four to 14 cortical slices (20-40 mg) were prepared from another set of control, untreated diabetic, and insulin-infused diabetic animals as described above. Two cortical slices were immediately homogenized in 2 ml of 0.1 M phosphate buffer with 15 mM EDTA, pH 6.0, with the use of 20 stroke glass homogenizer and diluted with buffer 100 to 250 times for renin assay. Using the incubation technique already described, the remaining slices were incubated in duplicate with or without dl-isoproterenol (10\textsuperscript{-7}-10\textsuperscript{-3} M) or PGE\textsubscript{2}, (10\textsuperscript{-6}-10\textsuperscript{-4} M) or both. To achieve these concentrations, isoproterenol (Sigma, St. Louis, MO, USA) was dissolved in Krebs-Ringer bicarbonate buffer containing ascorbic acid to prevent oxidation (final
concentration, 0.1% wt/vol) and PGE₃, originally dissolved in methanol, was diluted in Krebs-Ringer bicarbonate buffer to yield a final methanol concentration of 0.1% v/v, which was determined not to affect renin release or PGE₃ production. All incubation media for initial renin content and basal renin release determination were adjusted to the same concentration of ascorbic acid and methanol. After incubation the medium was diluted 5 to 10 times in 0.1 M phosphate buffer with 15 mM EDTA, pH 6.0. To obtain rabbit renin substrate, rabbits were nephrectomized under general anesthesia (ketamine hydrochloride, 40 mg/kg, and xylazine hydrochloride, 5 mg/kg s.c.) and plasma was withdrawn 48 hours later under the same anesthetic conditions. Fifty microliters of the diluted samples was incubated with 300 μl of rabbit plasma as renin substrate for 1 hour at 37 °C in the presence of EDTA (2.6 mM), dimeracpol (1.6 mM), and 8-hydroxyquinoline (3.6 mM). The reaction was stopped at the end of incubation by the addition of equal amounts of ice-cold phosphate-buffered saline containing 0.1% bovine serum albumin, pH 7.0, and samples were kept frozen at −20 °C until the assay for angiotensin I was performed. Preliminary studies demonstrated that angiotensin I generation in this system was linear, with enzyme concentration ranging from 5 to 200 ng of angiotensin I per milliliter. The recovery of angiotensin I was 95% ± 3%. Cortical renin content was expressed as nanograms of angiotensin I per milligram of tissue, and renin release as nanograms of angiotensin I per milligram of tissue per 30 minutes. Renin release in response to isoproterenol or PGE₃ or both also was expressed as percentage of basal release without either drug.

**Plasma Volume Determination**

In the other set of control and diabetic animals prepared as described previously, plasma volume was measured by collecting blood samples (100 μl) every 10 minutes for 60 minutes after the injection of ¹²⁵I-labeled bovine serum albumin through a catheter implanted into the right atrium through the jugular vein while the animals were under pentobarbital anesthesia (35 mg/kg i.p.). Radioactivity in plasma was counted and extrapolated to time 0 by the least-squares method. Plasma volume was calculated by dividing total radioactivity injected by the counted radioactivity in 1 ml of plasma at time 0 and expressed as milliliters per 100 g of body weight.

**Statistical Analysis**

All data were expressed as the mean ± se. Statistical significance was determined by the Student’s t test for unpaired data.

**Results**

As can be seen in Table 1, the diabetic animals showed a marked rise in plasma glucose levels, urinary volume, sodium excretion, and potassium excretion (p < 0.01). Daily administration of 2 units of insulin significantly decreased plasma glucose concentration when compared with that of untreated diabetics (p < 0.01), which was still higher than that of nondiabetic controls. However, constant infusion of 2 units of insulin by pump resulted in euglycemia. In all the insulin-treated groups urine volume and sodium and potassium excretion, although higher than those of nondiabetic controls, were significantly lower than those in untreated diabetics (p < 0.01).

Blood pressure in diabetic animals was significantly higher than in controls (p < 0.01; Table 2); however, insulin infusion restored the elevated blood pressure to control values. The PRA in untreated diabetic animals (see Table 2) was not different from that in controls; however, there was a marked rise in PRA in insulin-injected diabetics compared with that observed in control and untreated diabetic animals. The statistically insignificant rise in PRA in insulin-infused diabetic animals reached values intermediate between those of controls and insulin-injected diabetics. The hematocrit was slightly elevated in the hyperglycemic animals (p

<table>
<thead>
<tr>
<th>TABLE 1. Plasma Glucose Level, Urine Volume, and Urinary Excretion of Sodium and Potassium in Nondiabetic Control and Streptozotocin Diabetic Animals with or Without Insulin Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diabetes</strong></td>
</tr>
<tr>
<td>Plasma glucose (mg/dl)</td>
</tr>
<tr>
<td>UV (ml/24 h)</td>
</tr>
<tr>
<td>U₉NaV (mEq/24 h)</td>
</tr>
<tr>
<td>U₉K V (mEq/24 h)</td>
</tr>
<tr>
<td>No. of rats</td>
</tr>
</tbody>
</table>

Each value represents mean ± se. See Methods for experimental details. UV = urinary volume; U₉NaV = urinary excretion of sodium; U₉K V = urinary excretion of potassium. *p < 0.01 (vs nondiabetics); †p < 0.01 (vs untreated diabetics)
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TABLE 2. Blood Pressure, Plasma Renin Activity, and Hematocrit in Nondiabetic Control and Diabetic Animals with or Without Insulin Treatment

<table>
<thead>
<tr>
<th></th>
<th>Nondiabetics</th>
<th>Untreated</th>
<th>Insulin (s.c.) (2 U/24 hr)</th>
<th>Insulin pump (2 U/200 g/24 hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Blood pressure (mm Hg)</strong></td>
<td>120 ± 3.5</td>
<td>135 ± 3.1*</td>
<td>115 ± 4.4†</td>
<td></td>
</tr>
<tr>
<td><strong>PRA (ng ANG I/ml/hr)</strong></td>
<td>8.6 ± 0.5</td>
<td>8.5 ± 1.5</td>
<td>19.2 ± 4.4*</td>
<td>11.3 ± 2.0</td>
</tr>
<tr>
<td><strong>Hematocrit (%)</strong></td>
<td>40.2 ± 0.8</td>
<td>41.7 ± 0.9</td>
<td>42.7 ± 0.6†</td>
<td>39.4 ± 1.5</td>
</tr>
<tr>
<td><strong>No. of rats</strong></td>
<td>8</td>
<td>7</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

Each value represents mean ± se.
See Methods for experimental details.
ANG I = angiotensin I; PRA = plasma renin activity.
* p < 0.01 (vs nondiabetics), †p < 0.05 (vs nondiabetics), ‡p < 0.01 (vs untreated diabetics).

< 0.05) and decreased to control values in the euglycemic animals treated by insulin infusion. Plasma volume determined in another set of control and untreated diabetics was significantly lower in untreated diabetics (3.73 ± 0.10 ml/100 g) as compared to controls (4.42 ± 0.16 ml/100 g; p < 0.01).

Urinary excretion of PGE₂ is shown in Figure 1. A significant decrease in urinary excretion of PGE₂ was observed in diabetics treated with 2 units of s.c. insulin (p < 0.05), and a significant increase was seen in those treated with 2 units by constant infusion (p < 0.01), as compared to controls and untreated diabetics, which were not significantly different from each other.

Figure 2 shows that papillary PGE₂ slice content in diabetics with and without treatment with subcutaneous injection of insulin was significantly lower than in nondiabetic controls (p < 0.01), although insulin injection partially restored the decreased PGE₂ content found in diabetics. Insulin by constant infusion restored the decreased PGE₂ content to normal values. Although de novo PGE₂, synthesis in untreated diabetic rats was significantly lower than in controls (p < 0.05), there was a marked decrease in the PGE₂ synthesis rate with injection of 2 units of insulin. In the pump-implanted rats with DM, de novo PGE₂ synthesis was markedly greater than values observed in nondiabetic controls, untreated diabetics, and insulin-injected diabetics. Although blood pressure did not show any significant relation to PRA, a significant negative correlation was obtained between blood pressure and papillary PGE₂ synthesis (p < 0.05; Figure 3).

Basal renin content decreased significantly in diabetic animals as compared to controls, as shown in Table 3 (p < 0.05). Insulin administration by pump partially restored the diminished renin content to control values. Basal renin release, which was also lower in diabetics, returned toward control values with insulin infusion. The percentage of renin released from the
Figure 3. Correlation between blood pressure and papillary prostaglandin E2 (PGE2) synthesis ($y = -0.30x + 132, r = 0.576, n = 22, p < 0.05$) in eight nondiabetic control rats, seven untreated rats with diabetes mellitus (DM), and seven rats with DM treated with constant pump infusion of insulin, 2 U/200 g body weight/24 hr (DM with pump).

Figure 4. Dose-response relation of cortical renin release with isoproterenol (iso) or prostaglandin E2 (PGE2) added into the incubation medium in vitro of cortical slices from six nondiabetic control rats, six untreated rats with diabetes mellitus (DM), and five rats with DM treated with constant pump infusion of insulin, 2 U/200 g body weight/24 hr (DM 2 U pump). Renin release was expressed as percent of basal release without either drug (mean ± se). Open star = $p < 0.05$ vs basal release; closed star = $p < 0.07$ vs basal release.

The present study demonstrates that diabetic rats are hypertensive as early as 1 week after the induction of DM by streptozotocin administration and that insulin infusion reduces the elevation in blood pressure. These findings confirm recent studies by Bunag et al.20 21 In these studies, diabetic rats in which hypertension was established 2 or more weeks after the onset of DM were characterized by narrowed pulse pressure, bradycardia with increased reflex responses to norepinephrine, and reduced pressor responses to hypothalamic stimulation and vasopressin. In addition to these abnormalities, the present studies demonstrate that PRA was not stimulated in untreated diabetic rats in spite of a marked sodium diuresis, which is consistent with

Table 3. Cortical Renin Content, Basal Renin Release, and Percent of Renin Release in Nondiabetic Control and Diabetic Animals with or Without Insulin Infusion

<table>
<thead>
<tr>
<th></th>
<th>Nondiabetics</th>
<th>Untreated</th>
<th>Insulin pump (2 U/200 g/24 hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma glucose (mg/dl)</td>
<td>137 ± 6</td>
<td>504 ± 28*</td>
<td>86 ± 11*</td>
</tr>
<tr>
<td>Renal renin content (ng ANG I/mg)</td>
<td>232 ± 14.9</td>
<td>187 ± 15.8*</td>
<td>202 ± 28.1</td>
</tr>
<tr>
<td>Basal renin release (ng ANG I/mg/30 min)</td>
<td>4.96 ± 0.33</td>
<td>3.01 ± 0.33*</td>
<td>3.88 ± 0.46</td>
</tr>
<tr>
<td>Renin release (%)</td>
<td>2.28 ± 0.20</td>
<td>1.71 ± 0.22*</td>
<td>2.06 ± 0.28</td>
</tr>
<tr>
<td>No. of rats</td>
<td>9</td>
<td>9</td>
<td>5</td>
</tr>
</tbody>
</table>

Each value represents mean ± se.
See Methods for experimental details.
ANG I = angiotensin I
*p < 0.01 (vs nondiabetics), †p < 0.05 (vs nondiabetics), ‡p < 0.01 (vs untreated diabetics).
been attributed to volume expansion following hyperglycemia, impaired renin release, inadequate conversion of prorenin to renin, and decreasing catecholamine secretion. Although other investigators reported no marked change in diabetic renocortical renin release in response to β-adrenergic stimulus was well preserved in diabetic animals, although the absolute increment was lower in diabetics than in controls. Iso- proterenol-stimulated renin release has been shown to be derived from a storage pool of previously synthesized, but not newly synthesized, renin, which again suggests that DM leads to a diminished renal renin synthesis resulting in a decreased size of renin pool that responds normally to β-adrenergic stimulation. Thus, the intermediate step(s) from β-adrenergic stimulation to the ultimate release of renin itself may not be impaired in DM based on its normally preserved response.

The β-adrenergic agonist isoproterenol is believed to directly stimulate juxtaglomerular β-adrenergic receptors, which results in renin release. The prostaglandin synthesis inhibitor indomethacin has been reported to inhibit not only renin release stimulated by upright posture, furosemide, and hemorrhage, but also isoproterenol-induced renin release. Recently, Campbell et al. reported that dibutyryl cyclic adenosine monophosphate-induced renin release was also blocked by indomethacin. Despite these observations suggesting a prostaglandin-β-adrenergic link in the mechanism of renin release, most recent data do not support such an interaction of prostaglandins with the β-adrenergic system. In the present studies, maximal concentrations of PGE and isoproterenol showed additive effects on renin release in normal and insulin-treated diabetic rat renal cortical slices, which again suggests an action of PGE independent of that of β-adrenergic mechanisms. This hypothesis was also supported by the finding that no such additive effect was observed in untreated diabetic rats, which displayed impaired renin release in response to PGE, but normal responses to isoproterenol. If, as some believe, PGE is involved in the final pathway by which isoproterenol releases renin at a step beyond cyclic adenosine monophosphate formation, the response of renin to both these compounds would more likely be impaired to the same extent in diabetics. Since this does not appear to be the case, the present studies indicate that PGE-mediated renin release has different mechanisms that are independent from β-adrenergic renin release, even if cyclic adenosine monophosphate is the final mediator in both of them (Figure 6). Thus, impaired renin release in untreated DM does not appear to be the result of β-adrenergic insensitivity but may be a reflection of a decreased basal renin content that is sensitive to an insulin-mediated action on renin release by PGE. The high PRA and low PGE synthesis and excretion in animals receiving s.c. insulin cannot be explained by this hypothesis, and a direct effect of insulin on renin...
release in these hyperglycemic animals cannot be excluded. Whether exogenous PGE₂ has a different action from endogenous PGE₂-mediated renin secretion in juxtaglomerular cells or whether exogenous PGE₂ modulates cyclic adenosine monophosphate, either by adenyl cyclase activation or cyclic adenosine monophosphate degradation, remains to be clarified.

In addition to the abnormalities already discussed, we found that papillary PGE₂ biosynthesis in vitro was lower in untreated diabetic animals and in the diabetic group treated with 2 units of s.c. insulin injection, although the untreated diabetic rats had a normal urinary PGE₂ excretion. This phenomenon might be explained, based on intrarenal washout effect, by a marked polyuria induced by DM. In fact, rats with DM showed a marked decrease in initial PGE₂ content that was partially restored as polyuria was decreased by s.c. insulin injection at 2 U/24 hr despite a continuously lower PGE₂ synthesis rate. Interestingly, a constant infusion of 2 units of insulin by pump in diabetic animals resulted in a marked increase in renal PGE₂ synthesis exceeding that of controls and untreated diabetics and led to complete normalization of PGE₂ levels in vitro and urinary PGE₂ excretion in vivo, which is in accord with the previously proposed hypothesis for an action of insulin on renin release mediated by PGE₂. It must be recognized, however, that streptozotocin has effects other than hypoglycemia (e.g., oxidant tone) that may have an effect on prostaglandin synthesis.

In summary, these results suggest that any dependency of renal PGE₂ on the renin-angiotensin axis as well as renin release on PGE₂ is conditioned by a permissive action of the normal presence of insulin, which modulates interactions between renin and PGE₂. The difference in efficiency of insulin to restore or increase PGE₂ levels or synthesis may be attributed to the method of administration, since subcutaneous injection results in peaks and valleys of insulin plasma levels in vitro and urinary PGE₂ excretion in vivo, which is in accord with the previously proposed hypothesis for an action of insulin on renin release mediated by PGE₂. It must be recognized, however, that streptozotocin has effects other than hypoglycemia (e.g., oxidant tone) that may have an effect on prostaglandin synthesis.

Finally, the marked natriuresis and polyuria observed in untreated diabetic humans and animals may be attributed not only to an osmotic effect of glycosuria but to a deficiency of an appropriate insulin-mediated rise in the renin-angiotensin-aldosterone axis, which bears a pathophysiological resemblance to renal events associated with adrenal insufficiency in the sense that in both conditions an inappropriately low aldosterone level may underlie the renal polyuria and sodium loss.

Acknowledgment

We thank Mrs. Darlene Campanella for expert technical assistance and Mrs. Audrey Lee for preparation of the manuscript.

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Hypertension in experimental diabetes mellitus. Renin-prostaglandin interaction.
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Hypertension. 1985;7:554-561
doi: 10.1161/01.HYP.7.4.554

Hypertension is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0194-911X. Online ISSN: 1524-4563

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