Prostaglandin-Like Substances Appearing In Canine Renal Venous Blood During Renal Ischemia

THEIR PARTIAL CHARACTERIZATION BY PHARMACOLOGIC AND CHROMATOGRAPHIC PROCEDURES

By John C. McGiff, M.D., Keith Crowshaw, Ph.D., Norberto A. Terragno, M.D., Andrew J. Lonigro, M.D., James C. Strand, B.A., Mary Anne Williamson, M.D., James B. Lee, M.D., and Kevin K. F. Ng, M.D., Ph.D.

ABSTRACT

Renal prostaglandins (PGs) might mediate an antihypertensive function of the kidney. The blood-superfused organ technique possesses the sensitivity (threshold < 0.4 ng/ml blood) and specificity required for identification of PGs in blood. Induction of unilateral renal ischemia in 14 chloralose-anesthetized dogs reduced renal blood flows from a mean value of 257 to 109 ml/min on the ischemic side and from 250 to 209 ml/min on the contralateral side. Concomitantly, PG-like substances were detected by assay organs in the venous blood of ischemic (13 experiments) and contralateral (11 experiments) kidneys. In one experiment, in a spontaneously hypertensive dog, PGs were not detected during renal ischemia.

Renal venous blood and renal medullary tissue were extracted for acidic lipids and assayed for PG-like substances. Extracts of venous blood collected during renal ischemia and extracts of renal medulla yielded substances with biological activity indistinguishable from PG-like substances or PG standards. Chromatographic characterization of PG-like substances suggests that they are predominantly a mixture of PGE₂ and PGF₂α.

ADDITIONAL KEY WORDS
antihypertensive function of kidney angiotensin II blood-superfused organ technique renal medulla acidic lipids renal prostaglandins renal blood flows renal vascular hypertension

From the Department of Internal Medicine, St. Louis University School of Medicine, St. Louis, Missouri 63104.

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only the PGs have been characterized chemically (10). Prostaglandins E₂ (PGE₂) and A₂ (PGA₂), which are found in renal medulla (11), are potent vasodepressor unsaturated hydroxy-acids having many of the properties of ideal antihypertensive hormones (12). Their relationship to the proposed renal antihypertensive hormone(s) is unknown, primarily because their identification in blood is limited by the sensitivity of available chemical methods (13, 14). An enzymatic analysis which was recently developed to assay PGs (15) is not now applicable to their measurement in blood.

Ferreira and Vane (16) have adapted a bioassay method, the hood-superfused organ technique developed by Gaddum (17), to identify PGs released from an organ into its effluent. We used this method to assay continuously the hormonal content of blood. The streaming of fluid over assay organs is called superfusion. Because this method bypasses conventional procedures for characterization and identification of hormones, selectivity must be achieved by including several different organs in the assay system, i.e., using the technique of parallel pharmacologic assay (18). Each group of assay organs, superfused by blood from a single site, is a bank of organs. By the use of three banks of organs, simultaneous assay of blood from each renal vein and from the aorta permits determination of the generation or disappearance, or both, of blood-borne substances of renal origin having activity on the assay organs. For example, during renal ischemia, the presence of PG-like substances in renal venous blood and their absence in aortic blood suggests their disappearance on passage through the heart or lungs.

To verify the tentative identification by the bioassay system of substances having the properties of PGs and to obtain biochemical characterization of PG-like substances, renal venous blood was removed at the time these substances were detected by the assay organs. At each stage of extraction and biochemical purification, samples were compared to PGE₂ and prostaglandin F₂α (PGF₂α) standards for their effects on assay tissues. Thus, a reference assay of high specificity was used during characterization of PG-like substances to check the reliability of our biochemical procedures for recovery of substances from the blood tentatively identified as PGs by the bioassay system. Finally, we recovered from the renal medulla substances having the same properties as PG-like substances extracted from renal venous blood.

Methods

Fourteen male mongrel dogs weighing 23 to 32 kg were anesthetized with morphine sulfate (2 mg/kg, sc) and chloralose (100 mg/kg, iv). Anesthesia was maintained with chloralose (50 mg/kg, iv). The trachea was cannulated and the lungs were ventilated mechanically. The renal arteries were isolated through a transabdominal incision, Two eight-channel direct writers (Hewlett-Packard, models 7720, 7718) recorded; (1) mean aortic blood pressure measured by a Statham transducer (model P23Db) via a catheter inserted in a retrograde direction into a femoral artery; (2) renal blood flows measured by electromagnetic flowmeters (Statham, model M-4001); and (3) changes in length of assay organs detected by isotonic transducers (Harvard Apparatus, model 356). We have verified the method for recording blood flow and obtaining zero flow (19). The renal artery was constricted by a screw clamp placed distal to the flowmeter sensor. The clamp was tightened without displacing the hood vessel from its bed or placing traction upon it. Plasma renin activity of thoracic caval blood was measured by the method of Pickens et al. (20) and is reported in nanograms (ng) of angiotensin II per 100 ml of plasma, generated during a 4-hour incubation (ng/100 ml plasma).

Blood-Superfused Organ Technique

Three banks of assay organs were arranged in parallel (Fig. 1). Each branch of organs consisted of three tissues each: rat stomach strip, rat colon, and chick rectum which were continuously superfused in series by renal venous blood (21-23). This combination of assay organs was shown to possess the specificity and sensitivity required for detection of PGs (16) (Fig. 2). PGE₂ and PGF₂α when injected into the extracorporeal circuit (18B of Fig. 1) produced contractions of all three tissues. For the blood-borne substances which are likely to be present in renal venous effluent, only PGs would elicit the responses...
Schematic diagram of blood-bathed organ system (one bank). The blood-superseded organ system schematized for one bank of organs (three banks of organs were used). Blood was withdrawn at the rate of 10 to 15 ml/min by a pump. After traversing a constant-temperature circuit, the blood cascaded over three assay organs arranged in series. Changes in the length of the assay organs were transduced and recorded on a multichannel recorder. The blood was collected in a reservoir and returned at a constant rate to the animal. Selective blockade of assay organs is possible by direct intraluminal application of a blocking agent. A major use of this method is shown by the schematized kidney on the right. Thus, a substance may be given into the renal artery (IRA) and its effects on assay organs compared to its direct effects on administration into the extracorporeal circuit (IBB = into the bathing blood) indicated by "injection site" in the diagram of the assay system. Indirect effects of hormones may thereby be determined, e.g., release of intrarenal substances by angiotensin II.

Vasopressin in very high concentrations was reported to produce patterns of response of the assay organs similar to PGs (18). However, vasopressin, 150 to 200 μU/ml blood, was without effect on our assay organs.
Differential patterns of responses of assay organs to vasoactive substances. Patterns of responses of assay organs to substances which may be found in renal venous blood. The activities of three assay organs, rat stomach strip, rat colon, and chick rectum, selected for their sensitivity and specificity to PGs were recorded simultaneously. Infusions of substances were made directly into Krebs solution which superfused the assay organs. PGE, and PGF were the only substances which produced contraction of all three assay organs.

Assay organs, loaded with 1 to 3 g, were suspended in polypropylene chambers from autotonic levers (25) and their contractions transduced and recorded. A polyethylene catheter (o.d., 2.0 mm) was inserted into each renal vein and into the aorta through which blood was withdrawn continuously by a peristaltic pump (Harvard Apparatus, model 1203) at the rate of 10 to 15 ml/min per bank of organs. After superfusing the banks of organs, the blood was returned to the external jugular vein of the dog. The superfusate was maintained at 38°C. No glass or polyvinyl chloride connections were used in the system (26, 27). Dextran was given (10 ml/kg, iv) on establishing the extracorporeal circuit to offset any effects its dead space (150 ml) might have. The assay organs were initially superfused with Krebs solution gassed with 95% oxygen and 5% carbon dioxide. Heparin (1500 IU/kg, iv) was given before superfusing the assay organs with blood. Blood-borne substances, which affected the activity of assay organs, were tentatively identified by infusing standards into the extracorporeal circuit (18A of Fig. 1) to reproduce the activity. Most of the observations were made after 1 to 2 hours of superfusion with blood when the sensitivities of the assay organs to PG standards, initially reduced when blood replaced Krebs solution, had returned to their former state. Estimates of the concentration of PG-like substances in extracts (Fig. 3) were made on the same day on assay organs having stable sensitivities as indicated by their responses to successive injections of PG standards. When assay organs were used for comparison on different days (Fig. 4), their sensitivities differed by less than 20% as determined by their response to PGE, and angiotensin II standards.

RAT BLOOD PRESSURE ASSAY

Sprague-Dawley strain male rats (250 to 300 g) were anesthetized with pentobarbital (50 mg/kg, ip). After tracheotomy and bilateral vagotony, atropine (1 mg/kg) and pentolinium (20 mg/kg) were given intraperitoneally. Arterial blood pressure was measured by a transducer (Statham, model P23Db) and recorded on a direct writer (Hewlett-Packard, model 7712). Catheters were placed in the vena cava and aorta for injections. The activity of samples obtained from PGE, PGF, and PGA zones of thin-layer chromatography plates was estimated by bracket assay against the changes in rat blood pressure produced by corresponding standards of PGE, PGF, and PGA. Blood pressure, made highly stable by vagotony and pentolinium, was recorded on an expanded scale; changes greater than 5 mm Hg were considered significant. There was a
Lipid extracts of canine renal medulla were purified by chromatographic procedures. The initial extract and the eluates at each step of purification were tested for activity on the assay organs superfused by Krebs solution. The responses of assay organs to these samples were then compared to those produced by standard solutions of PGF\(_2\alpha\) and PGE\(_2\). The amount of recovered PG-like substance(s) at each stage of purification is determined by the amount of the standard solution required to reproduce the response of the sample (either PGF\(_2\alpha\) or PGE\(_2\) equivalents) after correction for dilution of the sample. Thus, the PGE eluate from the first column contained activity equivalent to 33.0 ng PGE\(_2\). The PGF\(_2\alpha\) eluate, however, was found to contain both PGE- and PGF-like activity, which were separated by a second column chromatography. This yielded a pure PGF\(_2\alpha\) eluate, estimated to contain 28.0 ng PGF\(_2\alpha\). A minor eluate was estimated to contain an additional 7.5 ng PGE\(_2\) (total PGE\(_2\) content, 40.5 ng). In addition, a third compound without activity on the assay organs present in PGA eluates from the column was tested for vasodepressor activity in the pentolinium-treated rat (see Fig. 7). This material contained vasodepressor activity equivalent to 21.0 ng PGA\(_2\). TLC = thin-layer chromatography; Eqv. = equivalents; RSS = rat stomach strip; RC = rat colon; CR = chick rectum.

FIGURE 3

PREPARATION OF RENAL MEDULLARY EXTRACT

Renal medullas were obtained from 30 dogs, which were blood donors for experimental surgery. The kidneys were removed immediately postmortem. Either the medullas were excised at once or the kidneys were fresh frozen and the...
Top: Infusion of vasoactive agents over assay organs superfused by Krebs solution reproduced the responses of assay organs superfused by blood from an ischemic kidney. Bottom: Unilateral renal arterial constriction (RAC) was induced at the first arrow and released at the second arrow. Changes in activity of rat colon and rat stomach strip (superfused by renal effluent) which occurred immediately after induction of RAC and the subsequent increasing contractions of rat stomach strip and chick rectum were matched by angiotensin I and PGE₂ standards infused simultaneously over assay organs (superfused by Krebs solution) at the same time. The peak activity of assay organs elicited by removal of RAC was reproduced by a single injection of PGE₂ standard. The assay organ monitoring arterial blood showed increased activity within 8 minutes after induction of renal ischemia which was related to the generation of an angiotensin-like substance. Renal blood flows: L = left, contralateral; R = right, ischemic; aortic BP is mean aortic blood pressure. Vertical scales: 2 cm for assay organ activity; renal blood flows in min/ml; aortic BP in mm Hg. Other abbreviations as in Figure 3.

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medullas were dissected out within 24 hours. Each kidney was sectioned in a coronal plane and the medulla separated from the cortex by dissection through the corticomedullary junction (approximately 8 to 15 g of medulla was obtained per kidney). Medullary tissue was stored at —10° C until extracted by a method we have reported (11). This method in brief required homogenization of medullary tissue in ethanol, vacuum filtration of the homogenate for 24 hours, and evaporation of the filtrate which was diluted with water and extracted with ethyl acetate. A concentrate of the latter was extracted with phosphate buffer, from which we subsequently obtained acidic lipids by extraction with chloroform. The chloroform extract was evaporated to dryness, and the residue reconstituted in 10 ml ethanol.

Silicic acid chromatography was performed by the methods previously reported (10, 11) using the same solvent systems as those described by Samuelsson for the purification of PGs in human seminal fluid (28). To minimize losses of PGs during the procedure, the extract was separated on a 20-g silicic acid column and small volumes of solvents were used in the elution sequence (Table 1). The time during which PGs were adsorbed on the silicic acid was relatively short and the eluates were quickly evaporated. These precautions were necessary to minimize formation of artifacts, e.g., PGA2 from endogenous PGE2 (10). By these shortened procedures, fractions containing PGs were eluted with more polar solvent mixtures than previously observed (10, 28). However, by following standard procedures, we consistently obtained the reproducible sequence of column separations shown in Table 1.

The column was developed with increasing concentrations of ethyl acetate in benzene as shown in Table 1. Five eluates were collected at a flow rate of 1.0 to 2.0 ml/min. The fractions were evaporated to dryness and dissolved in 1.0 ml ethanol for assay on the isolated, superfused tissues and on rat blood pressure. All fractions were assayed and those with biological activity were stored in 4°C for further assay and thin-layer chromatographic characterization.

**EXTRACTION AND CHARACTERIZATION OF BIOLOGICALLY ACTIVE SUBSTANCES PRODUCED BY RENAL ISCHEMIA**

In three experiments (dogs 1, 2, and 3), during renal ischemia, venous blood was removed from both kidneys at 20 to 30 ml/min per kidney by a roller pump (Watson-Marlow, model MHRE) coincident with the appearance of PG-like substances in renal venous blood as detected by the assay organs. Removal of blood was accompanied by intravenous infusion of a corresponding amount of dextran (dogs 1 and 2) and blood from a donor (dog 3). Control samples (100 to 200 ml) of venous blood were collected for estimation of content of the PG-like substances.

After induction of unilateral renal ischemia, 100 ml (dog 1) or 500 ml (dog 2) of venous blood were collected from each kidney. In dog 3, venous blood, removed from the ischemic kidney, was collected in two parts consecutively; one extending for 8 minutes up to and including the release of constriction, the other extending 12 minutes into the period of recovery. Blood samples were immediately centrifuged (International Equipment Co., model HT) for 15 minutes at 8,000 g at 4°C and the plasma was collected and diluted with four parts of ethanol. The precipitated protein and peptides were separated by centrifuging at 2,000 g at room temperature. The combined supernatant fluids were then evaporated in vacuo. This procedure was modified for dog 3 as follows. The blood samples were mixed immediately into absolute ethanol such that the final solution was 80% ethanol. The precipitated protein and peptides were separated by centrifuging at 2,000 g at room temperature. The combined supernatant fluids were then evaporated in vacuo. This procedure was modified for dog 3 as follows. The blood samples were mixed immediately into absolute ethanol such that the final solution was 80% ethanol.
water and then evaporated to dryness. The residue was dissolved in a known volume of ethanol for biological testing and chromatographic purification.

Aliquots of the final ethanolic extract were emulsified in saline using ultrasound (Heat Systems Co., model W Branson Sonifier). The maximum permitted concentration of ethanol was 20%, but in most cases the final concentration was less than 10%. Sonification yielded an emulsion which was suitable for injection into the banks of assay organs and into rats for blood pressure assay. Similar extraction procedures have been reported to recover from 5 to 75% of PGs (29) and to eliminate all other substances known to contract the assay organs leaving only acidic and neutral lipids (30). PGs recovered by the extraction procedure were detected if their concentrations in the final dilution of the extract were greater than 10 ng/μl. Responses of the assay organs bathed in Krebs solution to the unknown solutions and to the PG standards were compared at two or more dosages. A dose-response curve for the most sensitive assay organ was obtained in each experiment. For PGF\(_2\alpha\), this was rat colon; for PGE\(_2\), rat stomach. The concentration of PG-like substances in the sample was verified by bracket assay as well as by relating its effect on the recorded lengths of assay organs to the dose-response curve obtained from PGE\(_2\) or PGF\(_2\alpha\) standards. Control solutions of identical composition (ethanol in 0.9% saline) and volume were without effect on the assay organs.

The active extracts were dissolved in 30 ml of benzene-ethyl acetate (9:1, v/v) and purified by silicic acid column chromatography by the method described previously (14). The extracts were applied to the top of the column and fractions (50 ml) were collected by stepwise elution with increasing concentrations of ethyl acetate in benzene (Table 1) at an elution rate of approximately 1.0 ml/min. Each fraction was evaporated, dissolved in ethanol, and aliquots assayed for effect on rat blood pressure and for activity on the assay organs bathed in Krebs solution. Column chromatography of extracts from dog 3 was omitted and purification was achieved by thin-layer chromatography as described below.

THIN-LAYER CHROMATOGRAPHY

Thin-layer chromatography was performed by the methods described in detail by Green and Samuelson (31), modified as described previously (32). AgNO\(_3\) was incorporated into the adsorbent (AgNO\(_3\)/adsorbent ratio 1:30, w/w) for further separation of individual PGs. Flashing

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**TABLE 1**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Value Mean ± SEM</th>
<th>Blood Pressure</th>
<th>Blood Flow</th>
<th>Contracted Kidney</th>
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</thead>
<tbody>
<tr>
<td>Control</td>
<td>100 ± 7</td>
<td>100 ± 14</td>
<td>100 ± 12</td>
<td></td>
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<td>245 ± 24</td>
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Values are means ± SE. *p < 0.05 vs. control. Differences were determined by the method of matched pair analysis (t-test for paired data).
Detection by continuous bioassay of substance(s) appearing in renal venous blood following induction of renal ischemia in a chloralose-anesthetized dog. Constriction of the right renal artery (RAC) was induced at the first arrow and released at the second arrow. The response of the assay organs superfused by venous blood of the ischemic kidney was reproduced by PGE2 standard given into the extracorporeal circuit (IBB) 20 minutes after release of RAC. Vertical scales: 2 cm for assay organ activity; renal blood flows in ml/min; aortic BP in mm Hg. Abbreviations as in Figures 3 and 4.

Statistical analyses, using the method of matched pairs, of changes in renal blood flow and mean aortic blood pressure during and following renal ischemia were performed as described by Steel and Torrie (33). A P value of 0.05 or less was considered statistically significant.

Drugs used were: angiotensin I (iso-leucine*), Schwartz/Mann, Orangeburg, N. Y.) and angiotensin II amide (CIBA, Summit, N. J.); prostaglandins E2 (PGE2), F2a (PGF2a), and A2 (PGA2) and propranolol (Ayerst Laboratories Inc., New York, N. Y.). Prostaglandins E2, F2a, and A2 were crystalline samples and were prepared as 1 mg/ml stock solutions in 95% ethanol and diluted before use with 0.9% saline so that volumes added to the extracorporeal circuit of the banks of organs did not exceed 0.1 ml.

Table 2 shows the mean values for renal blood flow and mean aortic blood pressure obtained during control periods, immediately after induction of renal artery constriction (28 minutes mean duration), immediately before removal of constriction, and during recovery. The control renal blood flow was 4.5 ml/min/g of kidney.

Response of the assay organs to renal ischemia

During unilateral renal ischemia, in 13 of 14 experiments, PG-like substances appeared in
Left: Detection by continuous bioassay of substance(s) appearing in the venous blood of the contralateral kidney of a chloralose-anesthetized dog in response to unilateral renal arterial constriction (RAC) induced at the first arrow. Assay organs, superfused by the effluent of the contralateral kidney, demonstrated increased activity several minutes after induction of RAC. After release of RAC, infusion of angiotensin II into the artery (IRA) of the same kidney resulted in activity of the assay organs similar to that observed during renal ischemia. Right: In contrast, angiotensin II, infused directly over assay organs, produced significant activity on only one assay organ, rat colon (RC). PGE₂ infusion, however, produced effects on all assay organs similar to that seen during renal ischemia or during infusion of angiotensin II, IRA. These assay organs were superfused by Krebs solution. Abbreviations as in Figure 3.

the venous blood of the ischemic kidney as detected by the superfusion technique (Figs. 4 and 5). In 11 of these 13 experiments, these substances also appeared in the venous blood of the contralateral kidney during renal ischemia (Fig. 6). In seven experiments, removal of renal artery constriction resulted in the appearance of a peak of PG-like activity in the effluent of the ischemic kidney (Figs. 4 and 5). The assay organs superfused by arterial blood demonstrated angiotensin-like activity during renal artery constriction in all experiments in which this bank of organs was used (13 of 14 experiments). In one experiment, in a spontaneously hypertensive dog, PG-like substances did not appear in venous blood in response to renal ischemia. The control mean aortic blood pressure of 165 mm Hg in this dog was the highest recorded in these experiments.

**APPEARANCE AND FATE OF SUBSTANCES FORMED IN RESPONSE TO RENAL ISCHEMIA**

PG-like substances were demonstrated only in renal venous blood, whereas angiotensin-like substance(s) were demonstrated invariably in aortic blood as indicated by increased contraction of rat colon, superfused by aortic blood, several minutes after induction of renal ischemia (Fig. 4). Rat colon was reported to be the most sensitive tissue to angiotensin II (22) (Fig. 2). The release of renal PG-like substances by angiotensin II was suggested by comparing its effects on the assay organs when given directly into the extracorporeal circuit (IBB of Fig. 1) to those effects on the same assay tissues produced by its infusion into the renal artery. Thus, in Figure 6 the effects of angiotensin II on the assay organs, when administered intra-arterially, could only be accounted for by the release of PG-like substances into renal venous blood.

The earliest change in activity of the assay organs resulting from renal artery constriction was demonstrated by the bank of organs superfused by venous blood of the ischemic kidney (Fig. 4). In seven experiments, relaxation of one or more assay organs occurred as an initial response to renal artery constriction (Fig. 5). In six experiments, selective application of a beta-receptor blocking agent to assay organs by intrahuminal infusion of propranolol (100 μg/min) prevented their relaxation.
Renal Prostaglandin-Like Substances

Changes in length of the assay organs could not be related to alterations in tensions of gases or pH of the blood resulting from renal ischemia, since induction of renal ischemia comparable to that found in Table 2 did not alter PCO₂, Po₂ or pH of renal venous blood.

In Figure 4, plasma renin activity increased from a control value of 333 to 4,033 ng angiotensin I/100 ml coincident with peak contraction of rat colon. In two additional experiments, plasma renin activity of blood obtained within 10 minutes after induction of renal artery constriction was increased by more than tenfold; viz., from control values of 270 and 293 to 2,797 and 3,180 ng angiotensin I/100 ml respectively, coincident with the appearance of an angiotensin-like substance in aortic blood and in effluent of the ischemic kidney as detected by changes in activity of the assay organs.

Extraction and Purification of Canine Renal Medulla

Portions of the initial acidic lipid extract were dissolved in saline and tested for prostaglandin-like activity on the assay organs. The extract appeared to contain a mixture of prostaglandins E and F (Fig. 3). This was confirmed by separating a portion of the acidic lipid extract directly by thin-layer chromatography on silica gel "G" layers. Two zones from the plate contained smooth muscle stimulating activity. The more polar material had the same chromatographic mobility and biological activity as PGF₂α. The less polar material was found to be indistinguishable from PGE₂. Purification of the lipid extract by column chromatography on silicone gel plates and the distribution of PG-like material was determined by bioassay (Fig. 3). This procedure permitted the tentative identification of PGE₂, PGF₂α, and PGA₂ as the major, if not exclusive, PGs of the E, F, and A series found in canine renal medulla.

Additional biological characterization of the PG fractions was obtained by rat blood pressure assay. The property of PGAs to pass freely across the pulmonary circulation (35), in contrast to PGEs and PGFs (16), was used for its tentative identification. Thus, PGA₂ had equal effects on rat blood pressure on either intravenous or intra-arterial injection, whereas PGE₂ and PGF₂α were without activity on rat blood pressure at these doses on intravenous administration. In contrast, intra-arterial injection of PGE₂ and PGF₂α which bypassed the lungs allowed demonstration of the vasodepressor action of PGE₂ and the pressor action of PGF₂α (Fig. 7). We have adapted this property of the rat lung, differential removal of PGs, to obtain additional verification of the presence of a particular PG in purified samples of dog renal medulla. The column eluate which contained PGA-like material was estimated to contain vasodepressor activity equivalent to 21 μg PGA₂. Similarly, samples from the PGE column eluates when injected into the rat demonstrated vasodepressor activity which was identical to that of PGE₂ standards. This activity was equivalent to 40 μg PGE₂. Finally, when the purified PGF eluate was characterized by its presor effect on rat blood pressure, the activity which was identical to that produced by injections of PGF₂α standards (Fig. 7) was equivalent to 18 μg PGF₂α. These estimates compare...
Characterization of PG-like Substances in Blood

Renal venous blood removed from ischemic and contralateral kidneys of dogs was extracted to yield crude lipid extracts. Aliquots of these extracts, reconstituted in saline, had biological activity similar to a mixture of PGE$_2$ and PGF$_2$ as detected by the response of the assay organs (Table 3). Because of the reported variability of recoveries of PGs from blood (28), we have not corrected the estimated concentrations of PG-like substances for losses incurred during the extraction procedure (Tables 3 and 4).

In an attempt to obtain larger quantities of PG-like substances for further characterization, a total of 1760 ml of renal venous blood was removed terminally from both kidneys in dog 1 during a second period of unilateral renal ischemia with simultaneous dextran replacement. After acidic lipid extraction and silicic acid chromatography using the procedures indicated in Table 1, samples removed favorably with those estimates obtained by smooth-muscle bioassay; viz., 40.5 µg PGE$_2$ and 25 µg PGF$_2$ (Fig. 3).

TABLE 3

<table>
<thead>
<tr>
<th>Blood sample</th>
<th>Dog 1</th>
<th>Dog 2</th>
<th>Dog 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>ND*</td>
<td>ND*</td>
<td>ND*</td>
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<tr>
<td>Kidney</td>
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<tr>
<td>Ischemic</td>
<td>1.0</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>1st period 3.3*</td>
<td>2nd period 0.8*</td>
<td></td>
</tr>
<tr>
<td>Contralateral</td>
<td>1.0</td>
<td>0.6</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Indicated concentrations are not corrected for losses incurred by extraction and chromatography. *PGs were not detected (ND) if their concentrations in the final dilution were less than 10 ng/ml of the extract. Volume of blood collected and the method of extraction is described in Methods. In the case of dog 3, the first period refers to blood collected during ischemia and immediately after release (300 ml); collection of blood (550 ml), continued during recovery, is designated 2nd period.

TABLE 4

| Thin-layer Chromatographic Purification and Estimation of Prostaglandin-like Substances (Assayed as PGE$_2$ or PGF$_2$) in Extracts from Blood of Dog 3 |
|---|---|---|---|
| PGE$_2$ with same mobility as standard source | Total PG-like substances estimated in blood extracts (µg) |
|    | 1st period | 2nd period | Contralateral kidney |
| Initial extract* | 0.995 PGE$_2$ | 0.43 PGE$_2$ | 0.74 PGE$_2$ |
| 1st TLC | 0.35 PGE$_2$ | 0.34 PGE$_2$ | 0.52 PGE$_2$ |
| 2nd TLC | 0.57 PGE$_2$ | 0.58 PGE$_2$ | 0.44 PGE$_2$ |
| PGE$_2$ | PGE$_2$ | PGF$_2$ activity present | |
| AgNO$_3$ silica gel TLC | 0.53 PGE$_2$ | ND | 0.53 PGE$_2$ |
| PGE$_2$ | ND | ND | ND |
| PGE$_2$ | 0.4 PGE$_2$ | 0.4 PGE$_2$ | 0.4 PGE$_2$ |
| AgNO$_3$ silica gel TLC | 0.4 PGE$_2$ | ND | 0.4 PGE$_2$ |

TLC = thin-layer chromatography. ND = not detected.

*Control blood (200 ml) contained no detectable PG-like activity. See Table 3 for explanation of collection of blood from ischemic and contralateral kidneys. Extracts were separated on silic gel C plates in solvent system A (see Methods). Extracts of ischemic kidney blood from the 1st period were separated in solvent system A1; due to insufficient separation between PGF$_2$ and PGF$_2$, the PGF material could not be fully characterized. Extracts from the blood of contralateral kidney were separated in system C (see Methods).
RENAL PROSTAGLANDIN-LIKE SUBSTANCES

from the column eluates demonstrated weak but unambiguous PGE- and PGF-like activity. However, this procedure resulted in considerable loss of biological activity and when acidic lipid extracts obtained from smaller quantities of renal venous blood in dog 2 were separated by silicic acid chromatography, the procedure resulted in complete loss of PG-like activity.

Because of demonstrated low concentrations of PG-like substances in the renal venous blood of dogs 1 and 2 and their poor recovery after column chromatography, the latter procedure was bypassed and lipid extracts of renal venous blood obtained just before release of renal artery constriction in Figure 5 were purified directly by thin-layer chromatography (dog 3). Table 4 shows the results obtained from the successive stages of purification of the extracted renal venous blood obtained during renal ischemia when bioassayed as equivalents of PGE₂ or PGF₂α. Each thin-layer chromatography was performed using one quarter or less of the total extract available. Thus, under the best conditions, we were separating less than 0.25 μg PGE₂-like material present in large quantities of other...
PG-like substances isolated from venous blood of the ischemic and contralateral kidneys of dog 3 were purified by argentous thin-layer chromatography (AgNO₃-TLC). The smooth muscle stimulating activity of typical samples of isolated PGE₂-like and PGF₂α-like material are compared with standard solutions of PGE₂ and PGF₂α, respectively. The chromatographic and biological properties of the extracted and purified PG-like substances are indistinguishable from PGE₂ and PGF₂α standards. Abbreviations as in Figure 3.

Discussion

Substances having properties of PGs were released into venous blood of ischemic and contralateral kidneys in response to unilateral renal ischemia. The only exception occurred in a spontaneously hypertensive dog. The proposal that canine kidney releases PGs into venous blood in response to renal ischemia was strengthened by the demonstration that substances having the biological and chromatographic properties of PGs were present in renal medullary extracts. The release of PG-like substances from either kidney may be partially mediated by angiotensin II since its infusion into the renal artery resulted in the appearance of these substances in renal venous blood (Fig. 6).⁴ We have reported:

Since complete conversion of angiotensin I to angiotensin II is assumed to occur in the lungs (36), angiotensin I, if it participates in release of PG-like substance, presumably does so only in the ischemic kidney. This suggestion requires experimental confirmation.

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that arterial blood concentrations of angioten-
sin II of less than 0.1 ng/ml blood released PG-
like substances into renal venous blood (32).
The proposal that angiotensin II might release
renal PG-like substances was also supported by
the observation that their release into the venous
effluent of the contralateral kidney was always
associated with the appearance of angiotensin-
like activity in aortic blood. Furthermore,
increases in plasma renin activity (greater
than tenfold of control) occurred at the time
these substances appeared in the venous blood
of the contralateral kidney.

The blood-bathed organ method used in
this study has the following limitations. (1)
The appearance of several hormones simul-
taneously in response to a stimulus may
obscure the response of the assay organs to
PCs which might be present in renal effluent.
In the experiments reported, activity of the
assay organs, not entirely related to the release
of PC-like substances, was accounted for by
the simultaneous appearance of angioten-
sin(s) or catecholamines, or both, with PG-
like substances in renal venous blood. The
most important demonstration that these
responses were due to a mixture of PCs and
angiotensin(s) was provided by infusing
angiotensin I and PGE2 standards (Fig. 4)
directly over the assay organs superfused by
Krebs solution at infusion rates which repro-
duced the original responses. Under these
conditions, other hormones could be excluded
from affecting the responses. Thus, the re-
sponse during renal ischemia could be ac-
counted for entirely by summation of the
effect of angiotensin(s) and PC-like sub-
stances, and occasionally norepinephrine. In
most experiments, the effects of these sub-
stances on the assay organs were reproduced
by PGE2 standards alone (Figs. 5 and 6),
suggesting little modification of the responses
to the PC-like substances by other substances
present in renal venous effluent. (2) Changes
in concentrations of circulating hormones
were appreciated only above those present at
the start of the experiments, i.e., background
levels of hormones could not be detected
(18). Thus, the failure to observe release of
these substances in a hypertensive dog might
represent either deficiency of the substance or
preexisting high basal levels. (3) These assay
organs are insensitive to some substances such
as PCs of the A series (Fig. 2). (4) The
possibility cannot be excluded that unknown
substances could produce activity of assay
organs similar to PCs.

To counter some of the objections cited
above, we obtained additional evidence that
the changes in length of assay organs due to
PC-like substances produced during renal
ischemia behaved as a mixture of PCs as
determined by extraction and chromatograph-
ic characterization. In three experiments renal
venous blood, obtained during renal ischemia
(Fig. 5) coincident with the appearance of
PC-like substances as detected by the assay
organs, was extracted and purified to charac-
terize these substances (Fig. 8). Both extracts
and purified materials obtained by thin-layer
chromatographic methods elicited activity of
the assay organs similar, if not identical, to
that produced by standard solutions of PGE2
and PGE2 (Fig. 5). In addition, substances
having biological and chromatographic prop-
erties similar to the PG-like substances were
isolated from canine renal medulla and
characterized as a mixture of PGE2, PGF2α,
and PGA2.

Whether these observations made in acute
experiments relate to the proposed antihyper-
tensive function of the kidney cannot be
stated. Thus, the apparent release of a mixture
of PCs, which includes one with pressor
properties (PGE2α), as an immediate re-
sponse to acute renal ischemia appears to be
inconsistent with the proposal that a PG is the
renal antihypertensive principle. Although, a
vasodepressor PGE2-like compound was found
in larger quantities in renal venous blood than
a PGF2α-like substance and the latter had only
a slight pressor effects in the dog (37), we are
still faced with the problem of accounting for
their fate on passage across the lung. In a

Angiotensin (without roman numerical designa-
tions) shall denote angiotensin I and II since it is
impossible to distinguish their separate effects on
assay organs.

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recent clinical study, Edwards et al. identified a substance having the properties of PGE₂ in venous blood of ischemic kidneys (38). In the present study, we have tentatively identified PGE₂ as the major constituent of PG-like substances extracted from renal venous blood and the renal medulla.

PGA₂ would seem to be the more effective antihypertensive substance of renal origin since it has a vasodepressor potency similar to PGE₂ (39) and passes through the lungs without loss of activity. However, assigning an antihypertensive action to PGA₂ is not now possible since: (1) the presence of PGA₂ in renal medulla may at least in part result from dehydration of PGE₂ during purification of the renal medullary extract (30); (2) we cannot determine the presence of PGA₂ in renal effluent because of limitations of the bioassay procedures. In addition, there are factors, other than PGs, which might be of greater importance in modifying the evolution of renal vascular hypertension; viz., the antihypertensive neutral lipid identified by Muirhead (7) and the antirenin phospholipid which prevents the generation of angiotensin I (8).

An integrated construction of the release, fate, and effect of vasoactive substances, evoked by renal ischemia under the present experimental conditions, suggests the following sequence. PGs (predominantly PGE₂) and renin are released into the venous blood of the ischemic kidney as an early response to renal ischemia. Most of the PGs released from the ischemic kidney are removed on passage across the lung. If any PGA₂ is released, however, it will escape destruction, as well from 5 to 10% of the PGE₂ or PGA₂ (35). Increased release of renin from the ischemic kidney accelerates formation of angiotensin I, which on passage across the lung (and perhaps within the ischemic kidney as well) is converted to angiotensin II. The latter may mediate the release of PGs from the contralateral kidney (35) (Fig. 6). The development of hypertension then depends in part upon angiotensin-PG interactions, i.e., the amount of vaso depressor PG released from kidneys presumably is related to the increased arterial concentration of angiotensin II evoked by renal ischemia. Other factors, such as the state of sodium balance (40), rate of secretion and metabolism of aldosterone (41), level of activity of the adrenergic nervous system (42), and activation or inactivation of an antirenin phospholipid (8) may modify either the vascular response to, or the rate of formation of, the principle interactants (angiotensin-PGs). The above must be considered a provisional scheme which includes some of the suggested major humoral determinants of renal vascular hypertension.

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Prostaglandin-Like Substances Appearing in Canine Renal Venous Blood During Renal Ischemia: Their Partial Characterization By Pharmacologic And Chromatographic Procedures

JOHN C. McGIFF, KEITH CROWSHAW, NORBERTO A. TERRAGNO, ANDREW J. LONIGRO, JAMES C. STRAND, MARY ANNE WILLIAMSON, JAMES B. LEE and KEVIN K. F. NG

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