Role of Prostaglandins in Angiotensin-Induced Steroidogenesis

Absence of an Effect by Prostaglandin E₂

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SUMMARY Recently, we have found that the prostaglandin synthesis inhibitor, indomethacin, reduced basal and angiotensin-stimulated aldosterone release. To further test the possibility that prostaglandins (PGs) function as mediators of adrenal steroidogenesis, we examined the release of aldosterone, PGE₂, and PGF₆ in isolated adrenal capsular cells in vitro. Angiotensin II and III caused a dose-related increase in aldosterone release without significantly altering the release of PGE₂ or PGF₆. Indomethacin inhibited basal, angiotensin II, and angiotensin III-induced steroidogenesis by 40%, 15%, and 52% respectively. Additionally, it inhibited the release of PGE₂ by 60% in the control and angiotensin-treated cells. In indomethacin-treated cells, PGE₂ stimulated aldosterone release in supraphysiologic doses; however, its steroidogenic effect was not additive with angiotensin II. The prostaglandin precursor, arachidonic acid, increased the adrenal synthesis of PGE₂ and PGF₆ in a dose-related manner without altering the synthesis of aldosterone. Similarly, the prostaglandin endoperoxide PGH₂ increased the synthesis of PGE₂ by 250-fold, yet failed to alter aldosterone synthesis. These findings indicate that PGE₂ does not mediate or modulate basal or angiotensin-stimulated steroidogenesis. Furthermore, it would appear that indomethacin may inhibit adrenal steroidogenesis via a mechanism other than inhibition of prostaglandin synthesis.

(Hypertension 2: 471-476, 1980)

KEY WORDS • indomethacin • arachidonic acid • prostaglandin H₂ • prostaglandin F₆ • angiotensin II • angiotensin III

RECENTLY, we have found that the prostaglandin synthesis inhibitor indomethacin inhibited the release of aldosterone by angiotensin II and III in normal and sodium-depleted conscious rats and in rat adrenal cell suspensions.1 Another prostaglandin synthesis inhibitor, meclofenamate, inhibited angiotensin III but not angiotensin II-induced steroidogenesis. Since both drugs simultaneously inhibited the urinary excretion of prostaglandin E₂ (PGE₂), and prostaglandin F₆ is (PGF₆) reduced the adrenal prostaglandin content and reduced the adrenal conversion of ¹⁴C-arachidonic acid to ¹⁴C-PGE₂ and ¹⁴C-PGF₆, it was suggested that adrenal prostaglandins mediate a portion of the steroidogenic effects of the angiotensins. This contention was also suggested by the observations of Saruta and Kaplan4 that PGE₂ stimulated the release of aldosterone from adrenal cortical slices, an effect that was additive with angiotensin II. Subsequent studies confirmed the steroidogenic effects of PGE₂ and PGE₂ in vitro5-8 but not in vivo;4 however, it should be mentioned that in each of the in vitro studies supraphysiological doses of the prostaglandins were required for the release of aldosterone.

Our present studies were designed to further test the possibility that angiotensin stimulates the adrenal production of PGE₂ and that this PGE₂ augments the steroidogenic activity of the peptide. To accomplish this, we examined the effects of angiotensin II and III on the release of aldosterone, PGE₂, and PGF₆ in adrenal cell suspensions. Also, the effects of the precursors of these prostaglandins, arachidonic acid and prostaglandin cyclic endoperoxide (PGH₂), on the release of aldosterone were determined.

Methods

Male Sprague-Dawley rats (225-300 g; Simonsen Laboratories) were used in these studies. The rats were maintained on a standard Wayne Rat Chow diet containing 142 mEq/kg of sodium and 290 mEq/kg of potassium and tap water ad libitum.
Adrenal cell suspensions were prepared by the method of Sarstedt et al.\textsuperscript{1} with several modifications.\textsuperscript{1} Rats were killed by decapitation, and their adrenal glands were removed and placed in potassium-free medium 199. The adrenals were separated from the adhering fat, and the capsules removed. The capsular tissue was minced and incubated in potassium-free medium 199 containing 0.5 mg/ml of trypsin (Sigma) for 15 minutes in a Dubnoff metabolic shaker at 37°C under an atmosphere of 95% O\textsubscript{2} and 5% CO\textsubscript{2} with 60 rpm agitation. After 30 and 60 minutes of incubation, the cells were dispersed by repeated (30 times) pipetting. The suspension was then washed twice with potassium-free medium 199 containing 1 mg/ml of lima-bean trypsin inhibitor and 60 rpm agitation. After 30 and 60 minutes of incubation, the cells were dispersed by repeated (30 times) pipetting. The suspension was then washed twice with potassium-free medium 199 containing 1 mg/ml of lima-bean trypsin inhibitor and 2 mg/ml of bovine serum albumin, and resuspended in medium 199 containing 4.5 mEq/liter of potassium (Sigma), 0.05 mg/ml of ribonuclease (Sigma), and 2 mg/ml of bovine serum albumin. In the studies we then placed 0.5 ml containing 500,000 to 700,000 viable cells per adrenal capsule, and the viability of the cells was determined by exclusion staining of trypan blue. Using this method, we obtained approximately 300,000 viable cells per adrenal capsule, and the viability of the cells was approximately 94%.

We then placed 0.5 ml containing 500,000 to 700,000 cells in a Dubnoff metabolic shaker at 37°C under an atmosphere of 95% O\textsubscript{2} and 5% CO\textsubscript{2}. All compounds were added in a constant volume of 10\mu{l}, and an equal volume of their vehicle was added to the control tubes. Following these additions, the cells were incubated for 1 hour. At the end of the incubation period, the cell suspensions were centrifuged and the supernatant assayed for aldosterone by direct radioimmunoassay. The results were expressed as nanograms (ng) of aldosterone/10\textsuperscript{6}cells/hr. The remainder of the supernatants were combined from two incubation tubes and assayed for PGE\textsubscript{2} and PGF\textsubscript{2\alpha} by radioimmunoassay.

Prostaglandin E\textsubscript{2} and F\textsubscript{2\alpha} were measured by the method of Dray et al.\textsuperscript{4} with several modifications. The PGE\textsubscript{2} and PGF\textsubscript{2\alpha} antisera were produced in our laboratory in rabbits immunized against a prostaglandin-thyroglobulin conjugate. The conjugate was prepared by the method of Jaffe and Behrman.\textsuperscript{10} mixed with Freund’s complete adjuvant (Grand Island Biologicals), and injected monthly in multiple subcutaneous sites in rabbits. The cross reactivities of the antibodies with known prostaglandins are listed in table 1.

The assay consisted of extracting 1 ml of incubation media (containing 1000 cpm of \textsuperscript{3}H-PGE\textsubscript{2} and \textsuperscript{3}H-PGF\textsubscript{2\alpha}, New England Nuclear) with 10 ml of ethyl acetate:cyclohexane (50:50) after acidification to pH 3.0 with glacial acetic acid. The organic phase was then removed and evaporated to dryness at 30°C under nitrogen. The extract was reconstituted in a benzene:ethyl acetate:methanol mixture (60:40:10) and placed on an 0.8 X 10 cm silicic acid column (Sigma, S1L-B200). The prostaglandins were then eluted with solvents of increasing polarity with PGA, PGB\textsubscript{2}, and PGD\textsubscript{2} in the first fraction, PGE\textsubscript{2} in the second, and PGE\textsubscript{2} and PGF\textsubscript{2\alpha} in the third (fig. 1). These column eluates were dried at 30°C under nitrogen and reconstituted in 1.0 ml of phosphate-buffered saline containing 0.1% polyvinylpyrrolidone. Radioimmunoassay was performed by adding 0.1 ml of the unknown to 3000 cpm of \textsuperscript{3}H-PGE\textsubscript{2} or \textsuperscript{3}H-PGF\textsubscript{2\alpha} and 0.1 ml of the prostaglandin antisera (titer 1:8000 for PGE\textsubscript{2} and 1:30,000 for PGF\textsubscript{2\alpha}). After incubating overnight at 4\textdegree C, the bound and free prostaglandins were separated by the addition of dextran-coated charcoal. The bound counts were

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Prostaglandin & Anti-PGE\textsubscript{2} & Anti-PGF\textsubscript{2\alpha} \\
\hline
PGE\textsubscript{2} & (1:8,000) & (1:30,000) \\
\hline
PGF\textsubscript{2\alpha} & 0.30 & 0.01 \\
\hline
PGF\textsubscript{2\alpha} & 0.60 & 0.01 \\
\hline
PGD\textsubscript{2} & 0.10 & 1.00 \\
\hline
PGF\textsubscript{2\alpha} & 100.00 & 0.27 \\
\hline
PGE\textsubscript{2} & 14.00 & 0.30 \\
\hline
15-keto-PGE\textsubscript{2} & 0.01 & \\
\hline
PGF\textsubscript{2\alpha} & 0.70 & 100.00 \\
\hline
PGF\textsubscript{2\alpha} & 0.01 & 100.00 \\
\hline
15-keto-PGF\textsubscript{2\alpha} & 0.20 & \\
\hline
6-keto-PGF\textsubscript{2\alpha} & 0.20 & 0.80 \\
\hline
\end{tabular}
\caption{Cross-Reactivity of Prostaglandin E\textsubscript{2} and F\textsubscript{2\alpha} Antisera with Known Prostaglandins}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.jpg}
\caption{Separation of \textsuperscript{3}H-prostaglandin A\textsubscript{2}, E\textsubscript{2} and F\textsubscript{2\alpha} by silicic acid (Sigma, S1L-B200) column chromatography.}
\end{figure}
determined by liquid scintillation spectrometry (Beckman Instruments), corrected for recoveries, and the results expressed as pg/10⁶ cells/hr. The sensitivity of the assay was < 5 pg/tube and the recoveries averaged 85%. Also, the interassay and intraassay variability was 9% and 6% respectively.

Since incubation of the cells with [³H]-PGE₂ or [³H]-PGF₆α for periods of 1 and 2 hours failed to demonstrate metabolism or degradation of the prostaglandins, the levels of PGE₂ and PGF₆α measured in the incubation media must reflect adrenal cell synthesis and release only.

Prostaglandin H₂ was biosynthesized by the method of Green et al.¹ using ram seminal vesicle microsomes. The product was identified as PGH₂ by the following criteria: 1) treatment with stannous chloride converted it to a compound that behaved as PGF₆α by chromatographic and immunoassay methods; 2) treatment with bovine serum albumin converted it to a compound with the chromatographic properties of PGD₂, and 3) when added to human platelets, it was converted to immunoreactive thromboxane B₂. The PGH₂ was stored at -20°C in dry diethyl ether. This ethereal solution was added to the adrenal cells during incubation at 37°C, and the diethyl ether vehicle was added to the control cells.

Statistical analyses were performed by analysis of variance and student's t test when comparing groups and by analysis of covariance when comparing dose-response curves.

**Results**

The effects of angiotensin II and III on the release of aldosterone and prostaglandins from adrenal cells is illustrated in figures 2 and 3. Both peptides caused a dose-related increase in aldosterone release without significantly altering the release of PGE₂ or PGF₆α. At the 10 pmole dose of angiotensin II, the PGE₂ concentration in the medium was significantly elevated; however, with a higher dose, the PGE₂ concentration returned to control levels.

Indomethacin was found to inhibit basal and angiotensin-II-induced aldosterone release by 40% (p < 0.001) and 15% (p < 0.05) respectively (fig. 4). While angiotensin II failed to alter PGE₂ release in the dose tested, indomethacin reduced the release of PGE₂ into the medium by 60% in both control and angiotensin II treated cells. Similar results were obtained with angiotensin III with indomethacin inhibiting angiotensin III-stimulated steroidogenesis by 52% (p < 0.01) and PGE₂ release by 60% (p < 0.05) (fig. 5). When figures 4 and 5 are compared, it is clear that indomethacin was more effective in inhibiting angiotensin II-induced steroidogenesis when compared with angiotensin II despite similar reductions in PGE₂ release.

While angiotensin II did not release PGE₂, it was possible that basal amounts of PGE₂ might "prime" or sensitize the adrenal cortex to angiotensin II and that such an action could explain the inhibitory effects of indomethacin. However, when the effect of angiotensin II on aldosterone release was examined in the presence and absence of PGE₂ in indomethacin-treated cells, similar dose responses were observed in both groups indicating a lack of sensitization by PGE₂ (fig. 6). Furthermore, the effects of angiotensin II and PGE₂ were additive only at the lowest dose of angiotensin II tested.

**Figure 2.** Effect of angiotensin II on the release of aldosterone (left) and PGE₂ and PGF₆α (right) in rat adrenal cell suspensions. (Each point represents the mean ± SEM.) *p < 0.05; **p < 0.01, ***p < 0.001 compared with control.
**Figure 3.** Effect of angiotensin III on the release of aldosterone (left) and PGE$_2$ and PGF$_2$ (right) in rat adrenal cell suspensions. *p < 0.05; **p < 0.01; ***p < 0.001 compared with control.

**Figure 4.** Effect of indomethacin on angiotensin II-induced aldosterone release and prostaglandin release in rat adrenal cell suspensions. Each value represents the mean ± SEM. Statistical significance is indicated in the brackets connecting the compared bars.

**Figure 5.** Effect of indomethacin on angiotensin III-induced aldosterone release and prostaglandin release in rat adrenal cell suspensions. Each value represents the mean ± SEM. Statistical significance is indicated in the brackets connecting the compared bars.
To further examine the role of prostaglandins in steroidogenesis, the effects of the fatty acid precursor of PGE, arachidonic acid, was tested (fig. 7). While arachidonic acid caused a dose-related increase in PGE, and PGF release, the fatty acid failed to alter the release of aldosterone. Similarly, the cyclic endoperoxide intermediate, PGH, increased the adrenal PGE, production by 230-fold, yet did not alter steroidogenesis (fig. 8).

Discussion

Our present experiments indicate that prostaglandin E does not function as a mediator of adrenal steroidogenesis in physiologically relevant doses. While adrenal cortical cells are capable of synthesizing PGE from both arachidonic acid and PGH, aldosterone release is not stimulated by these prostaglandin E, precursors. Other investigators have reported a dose-related increase in aldosterone release in vitro with prostaglandin E, and E; however, doses in the microgram range were required for steroidogenic activity. Thus, it appears that prostaglandin E is unable to stimulate aldosterone

**Figure 6.** Effect of exogenous prostaglandin E on angiotensin II-induced aldosterone release in indomethacin-treated rat adrenal cell suspensions.

**Figure 7.** Effect of exogenous arachidonic acid on the release of aldosterone, PGE, and PGF in rat adrenal cell suspensions. Each point represents the mean ± SEM. **p < 0.001 compared with control.

**Figure 8.** Effect of exogenous PGH on the release of aldosterone and PGE in rat adrenal cell suspensions. Each point represents the mean ± SEM. Statistical significance is indicated in the brackets connecting the compared bars.
secretion in concentrations that the adrenal is capable of synthesizing.

Angiotensin II and III release PGE₃ from the kidney and mesenteric vasculature; however, we could detect no change in the release of PGE₂ and PGF₂α from adrenal cortical cells by steroidogenic doses of these peptides. Since adrenal cells contain the cyclooxygenase and isomerase necessary for the synthesis of PGE₂, the failure of angiotensin to release the prostaglandin must be due to a failure of the peptides to release arachidonic acid from its phospholipid or cholesterol ester stores. This lack of stimulation of the angiotensin-sensitive phospholipase could be due to the presence of glucocorticoids in the incubation media since these steroids are known to inhibit phospholipase A₂. However, when steroid synthesis is blocked by aminogluthethimide, angiotensin II still fails to stimulate the release of PGE₂ from adrenal cells (M. J. Dunn, personal communication). Thus, the mechanism of adrenal insensitivity to angiotensin is unknown.

As in our previous studies, indomethacin inhibited basal, angiotensin II, and angiotensin III-stimulated aldosterone release as well as inhibiting the adrenal synthesis of PGE₂ by 60%. Interestingly, indomethacin was more effective in inhibiting angiotensin III-induced steroidogenesis than that stimulated by angiotensin II; however, the reason for this difference is unknown. Indomethacin has also been found to inhibit angiotensin-induced steroidogenesis in normal subjects but not in patients with post-malignant hypertension. This 60% decrease in basal prostaglandin synthesis with indomethacin may be interpreted to explain the observed decreases in basal and angiotensin-stimulated aldosterone release. However, since a dose of PGE₂ (100 ng) that was 250 times greater than the basal adrenal cell production was required to stimulate aldosterone production twofold in indomethacin-treated adrenal cells, this would not appear to be the case. Furthermore, we could not demonstrate that this dose of PGE₂ was additive with angiotensin II on steroidogenesis or that it sensitized the adrenal to the actions of angiotensin II.

These findings suggest that indomethacin inhibits aldosterone release by an action independent of prostaglandin synthesis inhibition. Alternatively, indomethacin may inhibit angiotensin-steroidogenesis by blocking the synthesis of an arachidonic acid metabolite other than prostaglandin E₂. The most probable prostaglandin candidate would appear to be prostacyclin, PG₁₂. In this regard, Ellis et al. found that PGI₂ was 100–1000 times more potent than PGE₂ in stimulating the release of corticosterone from adrenal cortical cells. However, this latter possibility would appear unlikely in view of our findings that steroidogenesis is not stimulated by either arachidonic acid or PGI₂.

In summary, prostaglandin E₂ does not appear to mediate or modulate basal or angiotensin-stimulated steroidogenesis. This is based on the observations that angiotensin II and III do not stimulate prostaglandin synthesis in steroidogenic doses, that supraphysiologic doses of PGE₂ are required for steroidogenesis, and that arachidonic acid and PGI₂ fail to stimulate steroidogenesis even though prostaglandin synthesis is increased.

Acknowledgments

The authors express their appreciation to Ellen Rudisill for her secretarial assistance. We also appreciate the gift of the anti-aldosterone serum provided by the National Institute of Arthritis, Metabolism, and Digestive Diseases, and the prostaglandins provided by Dr. J. E. Pike of the Upjohn Company.

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Role of prostaglandins in angiotensin-induced steroidogenesis absence of an effect by prostaglandin E2.

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Hypertension. 1980;2:471-476
doi: 10.1161/01.HYP.2.4.471

Hypertension is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1980 American Heart Association, Inc. All rights reserved.
Print ISSN: 0194-911X. Online ISSN: 1524-4563

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