

# Regulation of Endothelial Cell Cyclic Nucleotide Metabolism by Prostacyclin

NANCY K. HOPKINS and ROBERT R. GORMAN, *Experimental Biology, The Upjohn Company, Kalamazoo, Michigan 49001*

**ABSTRACT** An analysis of prostaglandin-stimulated adenosine 3',5'-cyclic monophosphate (cyclic AMP) accumulation in cultured human umbilical vein endothelial cells showed prostacyclin (PGI<sub>2</sub>) to be the most potent agonist followed by prostaglandin (PG)H<sub>2</sub>, which was more potent than PGE<sub>2</sub>, while PGD<sub>2</sub> was essentially inactive.

The endothelial cells studied apparently have a high rate of cyclic AMP phosphodiesterase activity because significant PGI<sub>2</sub>-mediated increases in cyclic AMP could only be shown in the presence of the phosphodiesterase inhibitor isobutylmethylxanthine (MIX).

Endoperoxide PGH<sub>2</sub>-stimulation of cyclic AMP accumulation was inhibited 75–80% by the prostacyclin synthetase inhibitors 12-hydroperoxyeicosatetraenoic acid or 9,11-azoprosta-5,13-dienoic acid. These data indicate that the PGH<sub>2</sub>-stimulation is due primarily to conversion to PGI<sub>2</sub>.

The beta-adrenergic agonist L-isoproterenol stimulated cyclic AMP accumulation in the endothelial cells. This accumulation was completely blocked by propranolol. However, stimulation of cyclic AMP accumulation by the beta-adrenergic agent did not equal that induced by PGI<sub>2</sub>. Furthermore, the PGI<sub>2</sub> response could not be blocked by propranolol.

Thrombin-stimulated PGI<sub>2</sub> biosynthesis was attenuated by PGE<sub>1</sub> or isoproterenol in the presence of MIX. MIX alone was less effective than a combination of PGE<sub>1</sub> or isoproterenol plus MIX.

These data suggest two potential effects of PGI<sub>2</sub> biosynthesis by endothelial cells: first, the PGI<sub>2</sub> can elevate cyclic AMP in platelets, and second, endothelial cell cyclic AMP can be elevated as well, so that subsequent PGI<sub>2</sub> synthesis will be attenuated.

## INTRODUCTION

Prostacyclin [(5Z)-9-deoxy-6,9- $\alpha$ -epoxy- $\Delta^5$ -prostaglandin F<sub>1 $\alpha$</sub> ] (PGI<sub>2</sub>)<sup>1</sup> is a labile prostaglandin that is a

potent vasodilator and the most powerful inhibitor of human platelet aggregation yet described (1–4). Vascular tissue and especially vascular endothelium are rich sources of PGI<sub>2</sub> synthetase activity (5–7), and the relationship(s) between the synthesis of the antiaggregatory PGI<sub>2</sub> by vascular elements and the synthesis of the proaggregatory molecule thromboxane A<sub>2</sub> by platelets have been widely discussed (3, 4, 8, 9).

PGI<sub>2</sub> is a potent stimulator of platelet adenylate cyclase (3, 4), and elevates cyclic AMP levels in cultured human foreskin fibroblasts (10), human fat cell ghosts (11), and several clonal cell lines of central nervous system origin (12). PGI<sub>2</sub> also elevates cyclic AMP levels in arterial rings (13), but no experiments on the effect of PGI<sub>2</sub> on cyclic AMP levels in endothelial cells have been reported to date.

In the present study we show that PGI<sub>2</sub> is a potent stimulator of cultured human umbilical vein endothelial cell cyclic AMP levels, and suggest that endogenously produced PGI<sub>2</sub> may regulate subsequent PGI<sub>2</sub> biosynthesis by stimulating adenylate cyclase.

## METHODS

**Materials.** Prostaglandins (PG) I<sub>2</sub>, E<sub>1</sub>, E<sub>2</sub>, D<sub>2</sub>, and the prostaglandin analog 9,11 azoprosta-5,13-dienoic acid (azo analog I) were obtained from The Upjohn Company, Kalamazoo, Mich. PGH<sub>2</sub> and 12-hydroperoxyeicosatetraenoic acid (12-HPETE) were biosynthesized according to Gorman et al. (14) and Nugteren et al. (15). [ $\alpha$ -<sup>32</sup>P] ATP (10–30 Ci/mmol) was purchased from ICN Pharmaceuticals, Irvine, Calif., and [<sup>3</sup>H]cyclic AMP was obtained from Schwarz/Mann Div., Becton, Dickinson & Co., Orangeburg, N. Y. [<sup>3</sup>H] 6-Keto-PGF<sub>1 $\alpha$</sub>  was purchased from New England Nuclear, Boston, Mass. Dowex AG 50W-4X was purchased from Bio-Rad Laboratories, Richmond, Calif. Type I collagenase was purchased from Worthington Biochemical Corp., Freehold, N. J. [<sup>125</sup>I]-2'-O-Succinyl cyclic AMP tyrosine methyl ester and cyclic AMP antiserum were purchased from Collaborative Research Inc., Waltham, Mass. Isobutylmethylxanthine (MIX) was purchased from Aldrich Chemical Co., Milwaukee, Wis.

Received for publication 13 June 1980 and in revised form 16 October 1980.

<sup>1</sup>Abbreviations used in this paper: azo analog I, 9,11-azoprosta-5, 13-dienoic acid; 12-HPETE, 12-hydroperoxyeicos-

atetraenoic acid; MEM, minimal essential medium; MIX, isobutylmethylxanthine; PG, prostaglandin; PGI<sub>2</sub>, prostacyclin.

L-Isoproterenol hydrochloride, D,L-propranolol hydrochloride, thrombin (3,000 U/ml) and ristocetin were purchased from Sigma Chemical Co., St. Louis, Mo. Human Factor VIII antiserum was purchased from Calbiochem-Behring Corp., American Hoechst Corp., San Diego, Calif., and the fluorescein conjugated goat anti-rabbit antiserum was obtained from N. L. Cappel Laboratories Inc., Cochranville, Pa. Plastic tissue culture flasks and plates were from Falcon Plastics, Labware, Div. of Becton, Dickinson & Co., Oxnard, Calif. and Costar, Data Packaging, Cambridge, Mass.

Medium 199 with Earle's salts and L-glutamine as well as Hepes buffer were purchased from Microbiological Associates, Walkersville, Md.

The medium 199 was supplemented with sterile filtered human serum to a volume of 20% serum, Hepes buffer (15 mM, pH 7.5), L-glutamine (2 mM), sodium penicillin G (100 U/ml, The Upjohn Co.) and streptomycin sulfate (100 µg/ml, Eli Lilly Co., Indianapolis, Ind.). Sterile saline and distilled water were purchased from Abbott Diagnostics, Chicago, Ill.

**Radioimmunoassay of cyclic AMP.** Cyclic AMP was measured in confluent endothelial cell monolayers  $\sim 0.8 \times 10^6$  cells/35-mm well. Each well was washed once with 2.0 ml of warmed minimal essential medium (MEM) containing 25 mM Hepes buffer (no serum or phenol indicator). The cells were allowed to equilibrate with 1.0 ml of MEM-Hepes containing 1.0 mM MIX for 10 min before the addition of agonists. The reactions were terminated by the addition of 0.5 ml of 10% trichloroacetic acid, and the aqueous samples extracted three times with 10 vol of diethylether. Cyclic AMP was measured by radioimmunoassay according to Steiner et al. (16) with the incorporation of the acetylation modification of Harper and Brooker (17). All samples were tested at two dilutions. Data are presented as the mean  $\pm$  SEM of triplicate determinations.

**Radioimmunoassay of 6-keto PGF<sub>1 $\alpha$</sub> .** Thrombin-stimulated PGI<sub>2</sub> biosynthesis was studied by measuring 6-keto-PGF<sub>1 $\alpha$</sub>  by radioimmunoassay according to Dray et al. (18). The antiserum was a gift from Dr. Fernando Dray, The Pasteur Institute, Paris, France. All samples were assayed at two dilutions. Data are presented as mean  $\pm$  SEM of triplicate determinations.

Endothelial cell monolayers were washed once with 2.0 ml of MEM-Hepes buffer and allowed to equilibrate with an additional 1.0 ml of MEM-Hepes for 10 min at 37°C. After the equilibration period, the cells were challenged with 2.0 U of thrombin, and allowed to incubate for an additional 10 min at 37°C. The media was then immediately withdrawn and frozen in liquid N<sub>2</sub>, and aliquots of the samples were analyzed for 6-keto-PGF<sub>1 $\alpha$</sub> .

In experiments where PGE<sub>1</sub> was used to stimulate cyclic AMP levels, all of the samples and standards were assayed before and after alkali treatment. This was done to dehydrate PGE<sub>1</sub> to PGA<sub>1</sub> and eliminate PGE<sub>1</sub> crossreaction with the 6-keto-PGF<sub>1 $\alpha$</sub>  antiserum. Base treatment was done by adjusting the samples to pH 10.0 with NaHCO<sub>3</sub>, followed by boiling to dryness. The dried samples were reconstituted with H<sub>2</sub>O and the pH readjusted to 7.4 for subsequent radioimmunoassay. Authentic 6-keto-PGF<sub>1 $\alpha$</sub>  was degraded <5% by this procedure, whereas PGE<sub>1</sub> was essentially completely dehydrated to PGA<sub>1</sub>.

**Preparation of particulate fraction for adenylate cyclase assay.** To eliminate PGI<sub>2</sub> biosynthesis during processing, particulate fractions were prepared from endothelial cells pretreated for 1 h with 1 mM acetylsalicylic acid. Previous experience has shown that this treatment inhibits at least 95% of the thrombin-stimulated PGI<sub>2</sub> biosynthesis. Cells were harvested with a rubber spatula, and the pooled cells centrifuged at 4°C for 15 min at 2,000  $\times$  g. The cell pellet was resuspended in cold 50 mM Tris-HCl, 0.15M NaCl buffer, pH

7.50, and frozen and thawed three times in liquid N<sub>2</sub>, followed by 10 strokes of a Dounce homogenizer (Kontes Co., Vineland, N. J.) (glass/glass). The homogenate was then centrifuged at 10,000  $\times$  g for 15 min at 4°C. The resulting pellet was then resuspended in 1 mM KHCO<sub>3</sub> and used directly in the adenylate cyclase assay.

Adenylate cyclase activity was measured according to Rodbell (19) with modifications as reported by Salomon et al. (20), from the rate of formation of cyclic AMP from [ $\alpha$ -<sup>32</sup>P]ATP. All incubations contained 10 mM theophylline. Data are presented as picomoles cyclic AMP per 10 min per milligram protein determined according to Lowry et al. (21).

**Culture and characterization of endothelial cells.** Endothelial cells were derived from human umbilical cord veins as described by Jaffe et al. (22). Cords were stored in sterile containers with 20 ml of cord buffer (137 mM NaCl, 4 mM KCl, 10 mM Hepes, pH 7.5, and 11 mM glucose). A disposable syringe was attached to a blunt needle and the vein was flushed with 50 ml of cord buffer to remove any blood. The vein was then perfused with 10 ml of 0.1% collagenase in cord buffer, and incubated at 37°C in a bath of cord buffer for 10 min. The collagenase-cell mixture was flushed from the vein with 30 ml of buffer into a plastic centrifuge tube that contained 10 ml of medium 199 and centrifuged at 200 g for 5 min. The cell pellet was resuspended in 10 ml of fresh medium 199 and added to a T-75 flask. Cells were exposed to an atmosphere of 95% air - 5% CO<sub>2</sub> and were fed twice a week until subculturing. Confluency was usually reached in 4-5 d.

For subculturing the medium was removed and the cells rinsed once with cord buffer. A 5-min incubation with a 1:1 mixture of 0.02% EDTA: 0.2% collagenase followed by centrifugation was used to harvest the cells. Cells were grown in either T-150 culture flasks or distributed into 35-mm wells.

Endothelial cells were characterized by (a) the presence of Weibel-Palade bodies as observed by electron microscopy (23), (b) the ability of the medium from cultured cells to support ristocetin-induced agglutination of washed human platelets (24), and (c) by immunofluorescence studies of Factor VIII antigen using a rabbit antibody to human Factor VIII, and a fluorescein-conjugated goat anti-rabbit gamma globulin (25).

## RESULTS

Incubation of intact endothelial cell monolayers with 2.8 µM PGI<sub>2</sub> resulted in a marked increase in cyclic AMP within 1 min. The response was maximal at 10 min, and then gradually declined over the next 50 min (Fig. 1). Most of the cyclic AMP remained intracellular for at least 60 min (Fig. 1). We included 1 mM MIX, the cyclic AMP phosphodiesterase inhibitor, in all of our experiments because without MIX there was only a small increase in cyclic AMP in response to PGI<sub>2</sub> (Fig. 1).

Dose-response analysis indicated that PGI<sub>2</sub> was a more potent stimulator of endothelial cell cyclic AMP levels than either PGH<sub>2</sub> or PGE<sub>2</sub>, whereas PGD<sub>2</sub> was essentially inactive (Fig. 2). As little as 28 nM PGI<sub>2</sub> significantly elevated cyclic AMP levels above basal levels, and 2.8 µM PGI<sub>2</sub> gave maximal stimulation (Fig. 2). This dose-response profile was similar to data previously reported in cultured human foreskin fibroblasts (10).

Most of the stimulation of cyclic AMP levels in response to PGH<sub>2</sub> was shown to be due to conversion of PGH<sub>2</sub> to PGI<sub>2</sub> by the endothelial cell monolayers. Incu-

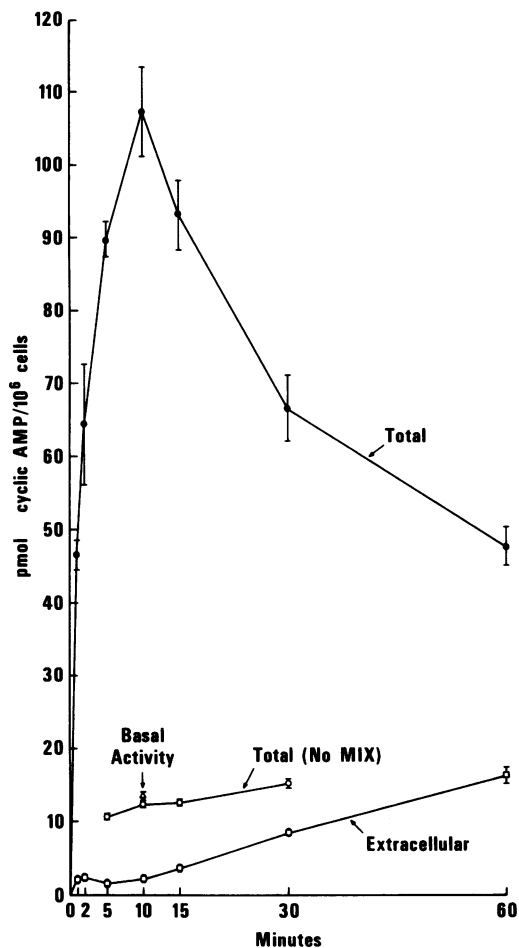


FIGURE 1 Time-course of total and extracellular cyclic AMP levels in human endothelial cells. Cells were stimulated with  $2.8 \mu\text{M}$   $\text{PGI}_2$  from 1 to 60 min and both total (●) and extracellular (□) cyclic AMP levels measured in the presence of 1 mM MIX. Other wells of endothelial cells were challenged with the same concentration of  $\text{PGI}_2$  but without MIX (○) present. Data are presented as mean  $\pm$  SEM pmol cyclic AMP/ $10^6$  cells of triplicate samples.

bation of endothelial cell monolayers with the  $\text{PGI}_2$  synthetase inhibitors 12-HPETE ( $28 \mu\text{M}$ ), or azo analog I ( $2.8 \mu\text{M}$ ) inhibited  $\text{PGH}_2$ -stimulated cyclic AMP levels 75 and 80%, respectively when base-line activity was subtracted (Fig. 3). Neither inhibitor significantly changed the basal level of cyclic AMP (Fig. 3).

As shown previously (26), endothelial cells also have a  $\beta$ -adrenergic receptor that is coupled to the adenylate cyclase. Our data shows that the maximal  $\beta$ -adrenergic stimulation of cyclic AMP accumulation by L-isoproterenol is considerably less than the stimulation observed with  $2.8 \mu\text{M}$   $\text{PGI}_2$  (Fig. 4). The isoproterenol-stimulation was completely blocked by  $10 \mu\text{M}$  propranolol, but propranolol did not inhibit the  $\text{PGI}_2$ -stimulation of cyclic AMP levels (Fig. 4).

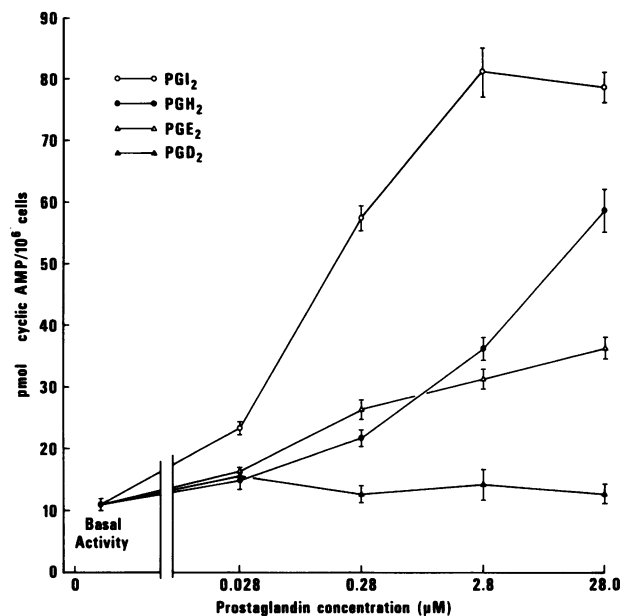


FIGURE 2 Dose-response relationship for prostaglandin stimulation of cyclic AMP. Endothelial cells were incubated for 10 min with 1 mM MIX before challenging with from 28 nM to  $28.0 \mu\text{M}$   $\text{PGI}_2$ ,  $\text{PGH}_2$ ,  $\text{PGE}_2$ , or  $\text{PGD}_2$ . All prostaglandins were incubated with the cells for 10 min at  $37^\circ\text{C}$ . Data are presented as mean  $\pm$  SEM pmol cyclic AMP/ $10^6$  cells of triplicate samples.

In contrast, the  $\alpha$ -adrenergic agonist phenylephrine did not stimulate or inhibit endothelial cell adenylate cyclase (unpublished experiments).

In addition to measuring cyclic AMP in intact endo-

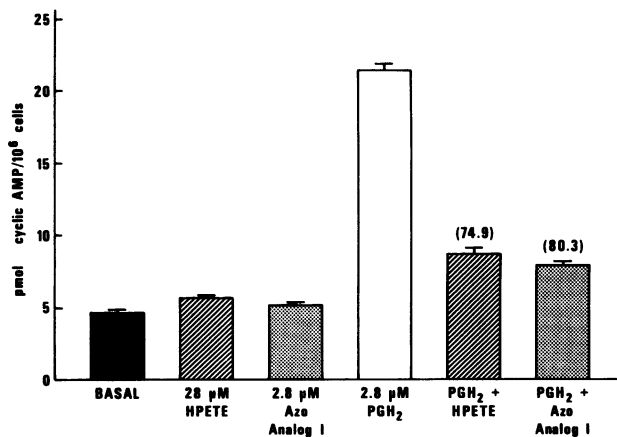


FIGURE 3 Inhibition of  $\text{PGH}_2$  stimulation of cyclic AMP accumulation by 12-HPETE or azo analog I. Confluent human endothelial cells were preincubated for 10 min at  $37^\circ\text{C}$  with 1 mM MIX and with either  $28 \mu\text{M}$  12-HPETE or  $2.8 \mu\text{M}$  azo analog I before exposure to  $2.8 \mu\text{M}$   $\text{PGH}_2$ . Numbers in brackets above bar graphs represent percent inhibition of  $\text{PGH}_2$ -stimulated cyclic AMP accumulation when basal levels of cyclic AMP are subtracted. Data reported as mean  $\pm$  SEM pmol cyclic AMP/ $10^6$  cells of triplicate samples.

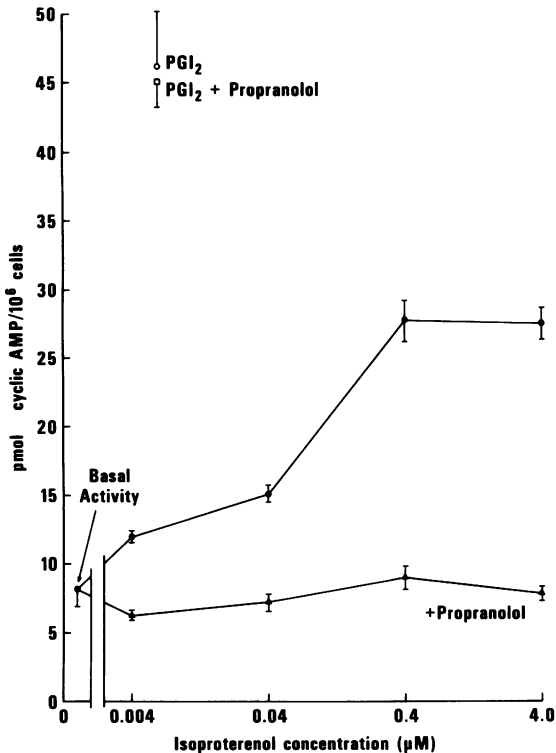


FIGURE 4 Isoproterenol dose-response curve. Endothelial cells were incubated for 10 min at 37°C with from 4 nM to 4 μM isoproterenol in the presence of 1 mM MIX. Another group of cells were preincubated for 10 min with MIX plus 33.8 μM propranolol before challenging with several concentrations of isoproterenol. Stimulation of cyclic AMP levels by 2.8 μM PGI<sub>2</sub> was also done with and without propranolol. Data are presented as mean ± SEM pmol cyclic AMP/10<sup>6</sup> cells of triplicate samples.

thelial cell monolayers, we also measured adenylate cyclase activity in homogenates prepared from endothelial cells. PGI<sub>2</sub> and PGE<sub>1</sub> gave modest increases in enzyme activity and isoproterenol an even smaller stimulation (Table I). Both PGD<sub>2</sub> and adenosine were inactive as stimulators of adenylate cyclase (Table I).

Weksler et al. (27) have shown that thrombin stimulates endothelial cell PGI<sub>2</sub> biosynthesis. We have found that thrombin-stimulated PGI<sub>2</sub> biosynthesis (as measured by 6-keto-PGF<sub>1α</sub> levels) was attenuated by both PGE<sub>1</sub> and L-isoproterenol when the phosphodiesterase was inhibited (Table II). Neither PGE<sub>1</sub> nor L-isoproterenol inhibited PGI<sub>2</sub> biosynthesis in the absence of phosphodiesterase inhibition (Table II). The data presented were obtained before and after base treatment (Methods), because PGE<sub>1</sub> was used to elevate cyclic AMP levels, and PGE<sub>1</sub> cross-reacts with the 6-keto-PGF<sub>1α</sub> antibody. Authentic PGI<sub>2</sub> could not be used because this would have generated too much exogenous 6-keto-PGF<sub>1α</sub>, and hampered the subsequent measurement of endogenously synthesized PGI<sub>2</sub>. Base

TABLE I  
Endothelial Cell Adenylate Cyclase Activity

Additions	Adenylate cyclase activity pmol cyclic AMP/mg protein
None-Basal	633.6 ± 44
28 μM PGI <sub>2</sub>	976.5 ± 74
28 μM PGE <sub>1</sub>	957.9 ± 66
28 μM PGD <sub>2</sub>	624.6 ± 32
10 μM Isoproterenol	721.1 ± 38
10 μM Adenosine	605.4 ± 42

A particulate preparation of homogenized endothelial cells (82 μg protein) was incubated for 10 min at 30°C with either 28 μM PGI<sub>2</sub>, PGE<sub>1</sub>, or PGD<sub>2</sub>, or with 10 μM isoproterenol or adenosine. Assay conditions and purification of cyclic AMP are described in the Methods. Data are representative of three confirmatory experiments and are presented as the mean ± SEM of triplicate samples. Membranes prepared in this manner converted 15.4% of exogenously added [1-<sup>14</sup>C]PGH<sub>2</sub> to 6-keto-PGF<sub>1α</sub> and the synthesis of 6-keto-PGF<sub>1α</sub> was blocked by 2.8 μM azo analog I. This rate of conversion is analogous to previously published data in endothelial cells (7).

treatment of samples hydrolyzes PGE<sub>1</sub> to PGA<sub>1</sub>, and PGA<sub>1</sub> does not interfere with the measurement of 6-keto-PGF<sub>1α</sub> (18). Authentic 6-keto-PGF<sub>1α</sub> is not degraded by base treatment (Table II). Of particular interest was the observation that 1.0 mM MIX alone could also reduce thrombin-stimulated PGI<sub>2</sub> biosynthesis (Table II). A combination of PGE<sub>1</sub> and 1.0 mM MIX inhibited PGI<sub>2</sub> biosynthesis 70.0% whereas 1.0 mM MIX inhibited synthesis 38% (Table II).

TABLE II  
Inhibition of PGI<sub>2</sub> Biosynthesis by PGE<sub>1</sub> and L-Isoproterenol

Treatment	Before base treatment	After base treatment
ng 6-Keto-PGF <sub>1α</sub> /10 <sup>6</sup> Cells		
None-basal	1.8 ± 0.3	1.7 ± 0.2
2 U Thrombin	18.2 ± 0.7	18.8 ± 1.0
0.28 μM PGE <sub>1</sub>	22.4 ± 2.0	1.1 ± 0.1
Thrombin + PGE <sub>1</sub>	51.4 ± 2.7	21.2 ± 0.5
Thrombin + PGE <sub>1</sub> + 1.0 mM MIX	31.2 ± 0.7	5.6 ± 0.3
4.0 μM Isoproterenol	1.5 ± 0.3	1.4 ± 0.1
Thrombin + isoproterenol	18.9 ± 1.5	18.1 ± 1.3
Thrombin + iso + 1.0 mM MIX	6.1 ± 0.2	6.2 ± 0.4
Thrombin + 1.0 mM MIX	12.4 ± 0.4	11.6 ± 0.6

Confluent monolayers of endothelial cells in 35-mm wells were washed once with 2.0 ml of warm MEM containing 25 mM Hepes buffer. The cells were allowed to equilibrate with 1.0 ml of MEM-Hepes with or without PGE<sub>1</sub>, isoproterenol or 1.0 mM MIX for 10 min at 37°C. Thrombin was added at the end of the 10-min equilibration period and allowed to incubate for an additional 10 min with the cells. Data are reported as mean ± SEM of triplicate samples.

TABLE III  
Elevation of Endothelial Cell Cyclic AMP  
Levels by PGI<sub>2</sub> and Thrombin

Additions	Cyclic AMP <i>pmol/10<sup>6</sup> cells</i>
None-basal	1.9±0.2
0.1 mM MIX	4.6±0.1
1.0 mM MIX	8.7±0.6
0.28 μM PGI <sub>2</sub>	3.4±0.1
2 U Thrombin	2.6±0.2
0.1 mM MIX + PGI <sub>2</sub>	15.2±0.4
1.0 mM MIX + PGI <sub>2</sub>	64.4±2.5
0.1 mM MIX + thrombin	8.4±1.2
1.0 mM MIX + thrombin	22.8±0.6

Confluent monolayers of endothelial cells in 35-mm wells were washed once with 2.0 ml of warm MEM containing 25 mM Hepes buffer. The cells were then allowed to equilibrate with 1.0 ml of MEM-Hepes buffer with or without 0.1 or 1.0 mM MIX for 10 min at 37°C. After the 10-min equilibration period the cells were exposed to either 0.28 μM PGI<sub>2</sub> or 2 U of thrombin for an additional 10 min at 37°C. Data are presented as mean±SEM of triplicate samples.

It should be emphasized that marked elevations in cyclic AMP and inhibition of thrombin-stimulated PGI<sub>2</sub> biosynthesis were observed only when the phosphodiesterase was inhibited.

To assess the possible correlation between cyclic AMP elevation and the inhibition of PGI<sub>2</sub> biosynthesis, we measured cyclic AMP levels in endothelial cells exposed to either PGI<sub>2</sub> or thrombin with or without 0.1 or 1.0 mM MIX (Table III). Treatment of the monolayers with 0.1 mM or 1.0 mM MIX increased cyclic AMP levels two- and four-fold, respectively (Table III). PGI<sub>2</sub> or thrombin gave small increases in cyclic AMP without MIX, but 0.1 mM MIX potentiated the PGI<sub>2</sub> response to an eight-fold increase, and the thrombin response to a fourfold increase. In the presence of 1.0 mM MIX PGI<sub>2</sub> increased cyclic AMP levels 33-fold, and thrombin 12-fold (Table III).

## DISCUSSION

The observation that endothelial cells can synthesize PGI<sub>2</sub> from either endogenous or exogenous endoperoxide PGH<sub>2</sub> or arachidonic acid (6, 7) has generated a great deal of research concerning endothelial cell-platelet interactions. The thrust of the work has been to assess the influence of PGI<sub>2</sub> produced by the endothelium on platelet aggregation and/or adhesion (5–10), but the possible effects of endogenously produced PGI<sub>2</sub> on endothelial cell physiology per se have not as yet been explored.

Since PGI<sub>2</sub> is a potent stimulator of adenylate cyclase in a variety of cell types (10–12) we felt it was important to assess the influence of PGI<sub>2</sub> on endothelial cell adenylate cyclase as well. PGI<sub>2</sub> proved to be a potent stimulator of endothelial cell cyclic AMP accumulation when the cyclic AMP phosphodiesterase was inhibited. This dependence on phosphodiesterase inhibition contrasts sharply with the observed potency in other cultured cell lines (10, 12), but we have previously observed an analogous high level of cyclic AMP phosphodiesterase activity in isolated arterial rings (13). The control of endothelial cell sensitivity to PGI<sub>2</sub> may be indirectly regulated through the phosphodiesterase, and any agent that suppresses phosphodiesterase activity would enhance the PGI<sub>2</sub> response.

In addition to PGI<sub>2</sub>, exogenously added PGH<sub>2</sub> was also readily converted to PGI<sub>2</sub> by the endothelial cells resulting in an increase in endothelial cyclic AMP levels. The PGI<sub>2</sub> dependence of the PGH<sub>2</sub> response was evident by the ability of the prostacyclin synthetase inhibitors 12-HPETE or azo analog I to inhibit most of the PGH<sub>2</sub> response. Complete inhibition of the PGH<sub>2</sub> response is probably not attainable because considerable amounts of PGE<sub>2</sub> are synthesized from PGH<sub>2</sub> when the PGI<sub>2</sub> synthetase is blocked, and PGE<sub>2</sub> itself is a weak stimulator of cyclic AMP accumulation. The inhibition of the PGI<sub>2</sub> synthetase by 12-HPETE is potentially of in vivo significance. Since 12-HPETE is produced by the platelet (28, 29), it is possible that platelets interacting with the endothelium could inhibit PGI<sub>2</sub> biosynthesis by producing 12-HPETE. Interestingly, aspirin treatment of platelets could exacerbate any 12-HPETE inhibition by shunting arachidonic acid toward the platelet lipoxygenase.

Besides prostaglandins, endothelial cell cyclic AMP levels can also be elevated by isoproterenol, but the β-adrenergic stimulation does not approach the magnitude of the PGI<sub>2</sub> response.

The direct assay of adenylate cyclase activity in endothelial cell homogenates was not as successful as measurement of cyclic AMP levels in monolayers. The stimulations by both prostaglandins and isoproterenol were quite small, but correlate qualitatively with the data obtained in intact cells. The problem of loss of hormone responsive adenylate cyclase during cell processing is not a new one, but appears to be particularly troublesome in endothelial cells.

Our direct measurements of 6-keto-PGF<sub>1α</sub> levels in thrombin-stimulated endothelial cells supports the work of Weksler et al. (27) that showed thrombin stimulation of PGI<sub>2</sub> biosynthesis. In addition, we observed that when the phosphodiesterase was inhibited, agents that elevated cyclic AMP levels also attenuated thrombin-stimulated PGI<sub>2</sub> biosynthesis. Our data showed that the phosphodiesterase inhibitor MIX at 1.0

mM can also inhibit thrombin-stimulated PGI<sub>2</sub> biosynthesis. These data at first were somewhat confusing because 1.0 mM MIX alone did not markedly elevate cyclic AMP levels. However, these data are quite consistent with the other data because a combination of 1.0 mM MIX and thrombin elevated cyclic AMP levels 12-fold due to the PGI<sub>2</sub> biosynthesized in response to thrombin (Tables II and III). Subsequent experiments have shown that either 1 mM aspirin or 10 μM indomethacin completely inhibit thrombin-stimulated cyclic AMP accumulation.

The finding that PGI<sub>2</sub> was a potent stimulator of cyclic AMP accumulation in endothelial cells suggests that once PGI<sub>2</sub> is produced it can have at least two actions. Newly synthesized PGI<sub>2</sub> can interact with platelets, elevate cyclic AMP, and inhibit aggregation. Concurrently, it would be capable of elevating endothelial cell cyclic AMP levels and attenuating further PGI<sub>2</sub> biosynthesis. This type of feedback inhibition would have to be highly sensitive to small increases in cyclic AMP, because without phosphodiesterase inhibition, there was little increase in cyclic AMP. In the human platelet, PGI<sub>2</sub> inhibits platelet aggregation in the nanomolar range by elevating cyclic AMP 10–15 pmol/10<sup>9</sup> platelets above basal levels, but the platelet is capable of making 6,000–7,000 pmol of cyclic AMP in response to 2.8 μM PGI<sub>2</sub> (30). Clearly most of the potential responsiveness to PGI<sub>2</sub> in the platelet is not expressed. An analogous situation may exist in the endothelial cell.

The precise physiological significance of the PGI<sub>2</sub> elevation of endothelial cell cyclic AMP levels and subsequent inhibition of PGI<sub>2</sub> biosynthesis cannot be established by this paper. Previous work has shown that by elevating cyclic AMP, PGI<sub>2</sub> can inhibit arachidonic acid transformation in the human platelet (31). The inhibition by cyclic AMP was at the level of the phospholipase. Our data are consistent with a phospholipase inhibition, but do not rule out inhibition at the level of the cyclooxygenase or the PGI<sub>2</sub> synthetase.

We are presently studying PGI<sub>2</sub> biosynthesis in endothelial cells to establish exactly at what level(s) biosynthesis is interrupted. Regardless of the exact point of control, it is clear that endothelial biosynthesis of PGI<sub>2</sub> is not a passive phenomenon. The cells are responsive to this compound as well.

## REFERENCES

1. Moncada, S., R. J. Gryglewski, B. Bunting, and J. R. Vane. 1976. An enzyme isolated from arteries transforms prostaglandin endoperoxides to an unstable substance that inhibits platelet aggregation. *Nature (Lond.)* **263**: 663–665.
2. Johnson, R. A., D. R. Morton, J. H. Kinner, R. R. Gorman, J. C. McGuire, F. F. Sun, N. Whittaker, S. Bunting, J. Salomon, S. Moncada, and J. R. Vane. 1976. The chemical structure of prostaglandin X (prostacyclin). *Prostaglandins*. **12**: 915–928.
3. Gorman, R. R., S. Bunting, and O. V. Miller. 1977. Modulation of human platelet adenylate cyclase by prostacyclin (PGX). *Prostaglandins*. **13**: 377–388.
4. Tateson, J., S. Moncada, and J. R. Vane. 1977. Effects of prostacyclin (PGX) on cyclic AMP concentrations in human platelets. *Prostaglandins*. **13**: 389–399.
5. Moncada, S., E. A. Higgs, and J. R. Vane. 1977. Human arterial and venous tissues generate prostacyclin (prostaglandin X), a potent inhibitor of platelet aggregation. *Lancet*. **I**: 18–21.
6. Weksler, B. B., A. J. Marcus, and E. A. Jaffe. 1977. Synthesis of prostaglandin I<sub>2</sub> (prostacyclin) by cultured human and bovine endothelial cells. *Proc. Natl. Acad. Sci. U. S. A.* **74**: 3922–3926.
7. Marcus, A. J., B. B. Weksler, and E. A. Jaffe. 1978. Enzymatic conversion of prostaglandin endoperoxide H<sub>2</sub> and arachidonic acid to prostacyclin by cultured human endothelial cells. *J. Biol. Chem.* **253**: 7138–7141.
8. Gorman, R. R. 1979. Modulation of human platelet function by prostacyclin and thromboxane A<sub>2</sub>. *Fed. Proc.* **38**: 79–85.
9. Moncada, S., and J. R. Vane. 1979. Prostacyclin in perspective. In *Prostacyclin*. J. R. Vane and S. Bergstrom, editors. Raven Press, New York. 5–16.
10. Gorman, R. R., R. D. Hamilton, and N. K. Hopkins. 1979. Stimulation of human foreskin fibroblast adenosine 3',5'-cyclic monophosphate levels by prostacyclin (PGI<sub>2</sub>). *J. Biol. Chem.* **254**: 1671–1676.
11. Kather, H., and B. Simon. 1979. Effects of some naturally occurring prostaglandins of the D, E, and I-type and synthetic analogues on adenylate cyclase of human fat cell ghosts. *Res. Exp. Med.* **176**: 25–29.
12. Ortmann, R. 1978. Effect of PGI<sub>2</sub> and stable endoperoxide analogues on cyclic nucleotide levels in clonal cell lines of CNS origin. *FEBS (Fed. Eur. Biochem. Soc.) Lett.* **90**: 348–352.
13. Miller, O. V., J. W. Aiken, D. P. Hemker, R. J. Shebuski, and R. R. Gorman. 1979. Prostacyclin stimulation of dog arterial cyclic AMP levels. *Prostaglandins*. **18**: 915–925.
14. Gorman, R. R., F. F. Sun, O. V. Miller, and R. A. Johnson. 1977. Prostaglandins H<sub>1</sub> and H<sub>2</sub>. Convenient biochemical synthesis and isolation. Further biological and spectroscopic characterization. *Prostaglandins*. **13**: 1043–1053.
15. Nugteren, D. H. 1975. Arachidonate lipoxygenase in blood platelets. *Biochim. Biophys. Acta.* **380**: 299–307.
16. Steiner, A. L., C. W. Parker, and D. M. Kipnis. 1972. Radioimmunoassay for cyclic nucleotides. I. Preparation of antibodies and iodinated cyclic nucleotides. *J. Biol. Chem.* **247**: 1106–1113.
17. Harper, J. F., and G. Brooker. 1975. Femtomole sensitive radioimmunoassay for cyclic AMP and cyclic GMP after 2'0 acetylation by acetic anhydride in aqueous solution. *J. Cyclic Nucleotide Res.* **1**: 207–218.
18. Dray, F., K. Gerozissis, B. Kouznetzova, and S. Mamas, P. Pradelles, and G. Trugnan. 1980. New Approaches to the RIA of Prostaglandins and Related Compounds Using Iodinated Tracers. *Adv. Prostaglandin Thromboxane Res.* **6**: 167–185.
19. Rodbell, M. 1967. Metabolism of isolated fat cells. V. Preparation of "ghosts" and their properties: adenylate cyclase and other enzymes. *J. Biol. Chem.* **242**: 5744–5752.
20. Salomon, Y., C. Londos, and M. Rodbell. 1974. A highly sensitive adenylate cyclase assay. *Anal. Biochem.* **58**: 541–548.

21. Lowry, O. H., N. Y. Rosebrough, A. L. Farr, and R. J. Randall. 1951. Protein measurement with the Folin phenol reagent. *J. Biol. Chem.* **193**: 265–275.
22. Jaffe, E. A., R. L. Nachman, C. G. Becker, and C. R. Minick. 1973. Culture of human endothelial cells derived from umbilical cord veins. *J. Clin. Invest.* **52**: 2745–2756.
23. Weibel, E. R., and G. E. Palade. 1964. New cytoplasmic components in arterial endothelia. *J. Cell Biol.* **23**: 101–110.
24. Jaffe, E. A., L. W. Hoyer, and R. L. Nachman. 1974. Synthesis of vanWillebrand factor by cultured human endothelial cells. *Proc. Natl. Acad. Sci. U. S. A.* **71**: 1906–1909.
25. Jaffe, E. A., L. W. Hoyer, and R. L. Nachman. 1973. Synthesis of antihemophilic factor antigen by cultured human endothelial cells. *J. Clin. Invest.* **52**: 2757–2764.
26. Buonassisi, V., and J. G. Venter. 1976. Hormone and neurotransmitter receptors in an established vascular endothelial cell line. *Proc. Natl. Acad. Sci. U. S. A.* **73**: 1612–1616.
27. Weksler, B., C. W. Ley, and E. A. Jaffe. 1978. Stimulation of endothelial cell prostacyclin production by thrombin, trypsin, and the ionophore A23187. *J. Clin. Invest.* **62**: 923–930.
28. Hamberg, M., J. Svensson, and B. Samuelsson. 1974. Prostaglandin endoperoxides. A new concept concerning the mode of action and release of prostaglandins. *Proc. Natl. Acad. Sci. U. S. A.* **71**: 3824–3828.
29. Nugteren, D. H. 1975. Arachidonate lipoxygenase in blood platelets. *Biochim. Biophys. Acta* **380**: 299–307.
30. Miller, O. V., J. W. Aiken, R. J. Shebuski, and R. R. Gorman. 1980. 6-Keto-Prostaglandin E<sub>1</sub> is not equipotent to prostacyclin (PGI<sub>2</sub>) as an antiaggregatory agent. *Prostaglandins*. **20**: 391–400.
31. Minkes, M., N. Stanford, M.-Y. Chi, G. J. Roth, A. Raz, P. Needleman, and P. W. Majerus. 1977. Cyclic adenosine 3',5'-monophosphate inhibits the availability of arachidonate to prostaglandin synthetase in human platelet suspensions. *J. Clin. Invest.* **59**: 449–454.