Severe endotoxemia, a condition where microembolization and intravascular coagulation are thought to play important roles, was treated experimentally with prostacyclin (PGI₂). In a study of 24 dogs, 8 control animals injected with 1.75 mg·kg⁻¹ of endotoxin died within 24 h. Six animals given intravenous aspirin 100 mg/kg, 30 min after endotoxin died. 9 of 10 dogs infused with 100 ng PGI₂·kg⁻¹·min⁻¹ for 3 h, given 30 min after the injection of endotoxin survived 24 h (P < 0.025). Injection of endotoxin resulted in a: (a) maximal 62% fall in mean arterial pressure (P < 0.001); (b) transient doubling of mean pulmonary arterial pressure (P < 0.001); (c) initial 70% drop in cardiac index (P < 0.001); (d) decline in blood platelets from 213,700 to 13,700/mm³ (P < 0.001), and leukocytes from 7,719 to < 750/mm³ (P < 0.001); (e) depressed urine output (P < 0.001); (f) 34% decrease in blood fibrinogen (P < 0.01) and an increase in fibrin degradation products > 50 µg/ml (P < 0.001); (g) fivefold increase in circulating cathepsin D titer (P < 0.005) and (h) increase in blood norepinephrine (P < 0.005), dopamine (P < 0.005), and epinephrine (P < 0.001). Aspirin treatment led to an increase in mean arterial pressure (P < 0.001) and mean pulmonary arterial pressure (P < 0.005), but cardiac index, […]
Prostacyclin Reversal of Lethal Endotoxemia in Dogs

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ABSTRACT Severe endotoxemia, a condition where microembolization and intravascular coagulation are thought to play important roles, was treated experimentally with prostacyclin (PGI2). In a study of 24 dogs, 8 control animals injected with 1.75 mg·kg⁻¹ of endotoxin died within 24 h. Six animals given intravenous aspirin 100 mg/kg, 30 min after endotoxin died. 9 of 10 dogs infused with 100 ng PGI₂·kg⁻¹-min⁻¹ for 3 h, given 30 min after the injection of endotoxin survived 24 h (P < 0.025). Injection of endotoxin resulted in a: (a) maximal 62% fall in mean arterial pressure (P < 0.001); (b) transient doubling of mean pulmonary arterial pressure (P < 0.001); (c) initial 70% drop in cardiac index (P < 0.001); (d) decline in blood platelets from 213,700 to 13,700/mm³ (P < 0.001), and leukocytes from 7,719 to < 750/mm³ (P < 0.001); (e) depressed urine output (P < 0.001); (f) 34% decrease in blood fibrinogen (P < 0.01) and an increase in fibrin degradation products > 50 μg/ml (P < 0.001); (g) fivefold increase in circulating cathepsin D titer (P < 0.005) and (h) increase in blood norepinephrine (P < 0.005), dopamine (P < 0.005), and epinephrine (P < 0.001). Aspirin treatment led to an increase in mean arterial pressure (P < 0.001) and mean pulmonary arterial pressure (P < 0.005), but cardiac index, urine flow, platelets, leukocytes, fibrin degradation products, and cathepsin D levels remained similar to untreated controls. After infusion of PGI₂ there was a: (a) prompt increase of cardiac index to base-line levels; (b) late increase in mean arterial pressure (P < 0.005) after the discontinuation of PGI₂ treatment (c) restoration of urine output; (d) increase in circulating platelets to levels still below base line but above untreated control animals (P < 0.05); (e) no effect on circulating leucocyte levels; (f) fall in fibrin degradation products to 11.2 μg/ml (P < 0.05); (g) decline in cathepsin D levels to values 60% lower than the untreated controls (P < 0.025); and (h) reduction in plasma norepinephrine levels to base line at 4 h (P < 0.005). Although the mode of PGI₂ action is not clear, it is effective in the treatment of experimental endotoxemia.

INTRODUCTION

Endotoxemia is associated with thrombocytopenia, leukopenia (1–3) and the appearance of platelet and leucocyte aggregates in the microvasculature, particularly of the lungs (4–6). These hematologic events are thought to underlie the hemodynamic alterations of endotoxemia that is pulmonary hypertension, low cardiac output, and systemic hypotension. The precise mechanisms of injury are unknown, but probably include both mechanical vascular obstruction with release of vasoactive and vasotoxic agents directly from the intravascular aggregates, as well as indirect effects mediated by injured organs such as the liver (7). The salutary results of the treatment of pulmonary embolism with an infusion of the anti-aggregating and smooth muscle relaxing agent prostacyclin (8) prompted a trial of this prostaglandin in the therapy of endotoxemia; an event thought to be characterized by microemboli and disseminated intravascular coagulation.

METHODS

24 adult mongrel dogs weighing 21–40 kg were anesthetized with sodium pentobarbital 30 mg/kg, paralyzed with pancuronium bromide 0.1 mg/kg (Organon Inc., West Orange, N. J.), and intubated and ventilated with room air using a piston pump (Harvard Apparatus Co., S. Natick, Mass.). Tidal volume was set at 15 ml/kg and the rate at 12

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Received for publication 2 September 1980 and in revised form 16 December 1980.

J. Clin. Invest. © The American Society for Clinical Investigation, Inc. · 0021-9738/81/04/1118/08 $1.00
Volume 67 · April 1981 · 1118–1125
cycles/min. Adjustments in rate were made to yield a PaCO₂ of 35–40 mm Hg. Supplemental doses of pentobarbital and pancerium were added as required to maintain anesthesia and paralysis. A femoral arterial catheter was placed for blood sampling and the measure of mean arterial pressure (MAP)¹ using a strain gauge transducer (model 800, Bentley Laboratories, Irvine, Calif.). The femoral vein was cannulated for fluid and drug administration. A 7 French, thermistor-tipped flow directed pulmonary arterial catheter (Instrumentation Laboratory, Lexington, Mass.) was introduced into the external jugular vein and advanced into the pulmonary artery. This catheter was used to measure central venous (CVP), mean pulmonary arterial (MPAP) and pulmonary arterial wedge pressures (PAWP) using strain gauge transducers (Bentley Laboratories). The catheter was also used for pulmonary arterial blood sampling and cardiac output determinations by thermodilution (Instrumentation Laboratory, model 601). Arterial and mixed venous blood gases, pH, hemoglobin and oxyhemoglobin measurements were made with standard Clark and Severinghaus electrodes and by spectrophotometry (Instrumentation Laboratory, models 282 and 813). Transurethral cannulation of the urinary bladder was performed for measurement of urinary output. Pulmonary vascular resistance (PVR) was calculated from the ratio MPAP-PAWP/CI and systemic vascular resistance (SVR) from the ratio MAP-CVP/CI where CI is cardiac index expressed in ml/min/kg. Leukocyte and platelet counts were performed using EDTA anticoagulated blood and phase microscopy. Fibrinogen was estimated spectrophotometrically after conversion to fibrin according to the method of Swain and Feders (9). Fibrin degradation products (FDP) were measured by staphylococcal clumping according to the technique described by Leavelle et al. (10).

**Catecholamine assay.** Plasma content of norepinephrine, epinephrine, and dopamine was assayed by a radioenzymatic, thin layer chromatographic procedure (11). Arterial blood samples were collected in heparin and centrifugated at 5,000 g for 10 min at 4°C. Proteins in a 200-μl aliquot of plasma were precipitated by the addition of 200 μl 0.5 M perchloric acid containing 31.8 mM EDTA. The supernatant fluid was separated and an aliquot of 200 μl was incubated for 90 min with catechol-O-methyl transferase and tritiated S-adenosylmethionine (New England Nuclear Corp., Boston, Mass.). The reaction was stopped by the addition of borate buffer (pH 8.0) containing metanephrine, normetanephrine (Sigma Chemical Co., St. Louis, Mo.), and 3-methoxy-4-hydroxyphenyl-ethanalamine (Calbiochem-Behring Corp., American Hoench Corp., San Diego, Calif.). The amines were extracted into toluene:isoamyl alcohol (3:2) and then into 0.1 M acetic acid. The radioactive products were separated by thin layer chromatography and the appropriate areas separately scraped into counting vials. After periodate oxidation of the methylated compounds of metanephrine and normetanephrine to vanillin, phosphor-containing tolune was added and the tritium content assayed by liquid scintillation spectrometry.

**Cathepsin D.** was assayed by a modification of the procedure of Anson (12) and Utsunomiya et al. (13). The substrate was 2.5% denatured bovine hemoglobin (Sigma Chemical Co.) dissolved in 0.58 M acetic acid containing 0.02 M ammonium sulfate (pH 3.7). A volume of 0.25 ml plasma as added to 0.75 ml of this substrate and incubated at 37°C for 3 h. The reaction was stopped by adding 3 ml of 10% TCA. The concentration of the unprecipitated proteolytic product was measured according to the procedure of Lowry et al. (14). Results are expressed as micromoles of tyrosine liberated per milliliter of plasma per hour.

Endotoxin, prepared from E. coli (Difco Laboratories, Detroit, Mich.) was dissolved in normal saline (10 mg/ml) just before each experiment. Prostacyclin (PGI₂) supplied by Dr. Pike, Upjohn Co., Kalamazoo, Mich., was also freshly prepared. It was dissolved in 20 mM Tris buffer (pH 10) and infused using a specially designed ice-water jacketed syringe system which maintained infusate temperature <3°C. The rate of drug infusion was 100 mg/kg·min using a volume of 3.3 ml/h. Aspirin (Sigma Chemical Co.) was dissolved in 8.4% sodium bicarbonate in a concentration of 100 mg/ml (pH 9.0).

All dogs received a rapid intravenous injection of 1.75 mg/kg endotoxin. Eight animals were then given the Tris buffer without PGI₂ and served as untreated controls. 30 min after endotoxin administration, an infusion of PGI₂ was started in 10 dogs and was continued over a 3-h period. In six dogs 100 mg/kg aspirin was rapidly injected intravenously 30 min after endotoxin. Hemodynamic measurements, urine output, arterial and mixed venous blood samples were obtained before endotoxin infusion, after 6 min and then at 30-min intervals for 5 h. Hemoglobin levels were kept constant using intravenous infusions of lactated Ringer’s solution. Sodium bicarbonate (1 meq/ml) was added to maintain blood pH between 7.35 to 7.40. Heat lamps were used to stabilize body temperature. After 5 h of monitoring, anesthesia was discontinued, pancerium was reversed with neostigmine 0.06 mg/kg (Roche Diagnostics Div., Nutley, N. J.), and atropine 0.02 mg/kg (Burroughs-Wellcome Co., Research Triangle Park, N. C.). The animals were exubtated, observed in their cages for 24 h, and then killed.

Statistical analysis of differences between the three groups was based upon a one-way analysis of variance. Epinephrine values between control and PGI₂ groups were analyzed by a repeated measures analysis of variance. A paired t test was used to examine changes within a group. The Chi-square test was employed for mortality studies (15). All data are expressed as the mean ±1 se. Figures contain one, two, three or four asterisks (*), indicating a P value of less than 0.05, 0.01, 0.005 or 0.001 between PGI₂ and control groups. Crosses (†) in the figures refer to comparisons between aspirin and control animals.

**RESULTS**

**Hemodynamics.** Immediately after endotoxin infusion, MAP fell from 131±3 to 50±5 mm Hg, while MAP rose twofold (Fig. 1). The CVP and PAWP were unchanged from initial values of 4.7±0.7 and 6.9 ±0.9 mm Hg, respectively. The CI fell 70% (Fig. 2). These abnormalities were transient and after 30 min there was a partial restoration toward base line.

Infusion of PGI₂ led to a prompt increase of CI to base-line level which was significantly higher than untreated controls. Flow remained high even after cessation of the PGI₂ infusion (Fig. 2). In the aspirin group CI remained low. MAP did not change during PGI₂ but increased from 82 to 97 mm Hg after discontinuation of the drug, and was then higher

¹Abbreviations used in this paper: CI, cardiac index; CVP, central venous pressure; FDP, fibrin degradation products; MAP, mean arterial pressure; MPAP, mean pulmonary arterial pressure; PAWP, pulmonary arterial wedge pressure; PGI₂, prostacyclin; PVR, pulmonary vascular resistance; Qc/Qr, physiologic shunting; SVR, systemic vascular resistance; Tx, thromboxane; Vd/Vr, physiologic dead space.
than controls (P < 0.05). Aspirin led to a prompt rise in MAP (P < 0.001) and MPAP (P < 0.005) (Fig. 1). The prompt rise in PVR after endotoxin spontaneously returned toward base line, while PGI₂ further reduced PVR below control values (Fig. 3). In contrast, aspirin led to a significant rise in PVR. SVR did not change following endotoxin. Administration of PGI₂ led to a fall in SVR from 0.89±0.08 mm Hg·min·kg⁻¹·min⁻¹ to 0.47±0.05 mm Hg·min·kg⁻¹·min⁻¹ following endotoxin (P < 0.005). Aspirin, on the other hand, led to a rise in SVR from 0.98±0.09 mm Hg·min·kg⁻¹·min⁻¹ to 1.37±0.16 mm Hg·min·kg⁻¹·min⁻¹ (P < 0.01) at these same time intervals. There were no changes noted in the CVP or PAWP in either control or treated animals.

Following endotoxin, urine flow fell (P < 0.01, Fig. 4). Toward the end of the PGI₂ infusion and after cessation of the drug, urine volumes were restored. Eventually they significantly exceeded (P < 0.005) values in the severely oliguric dogs of the control and aspirin group.

Pulmonary function. Physiologic shunting (Qₗ/Qₗ') increased from 18±1 to 31±4% 60 min after endotoxin (P < 0.005). The physiologic dead space (Vₐ/Vₐ') had risen from 54±3 to 62±2% (P < 0.001) 6 min following endotoxin. Infusion of PGI₂ did not prevent or reverse the rise in Qₗ/Qₗ' or cause Vₐ/Vₐ' to vary from untreated control animals. Aspirin was also ineffective in reversing Qₗ/Qₗ', but Vₐ/Vₐ' decreased from 64±2% 30
Figure 4 Urine output fell after intravenous endotoxin and was unaffected by aspirin. An increase in urine flow was noted toward the end of the PGI2 infusion. This increase became more prominent after cessation of PGI2 administration. ○, control; ●, PGI2; ▲, aspirin; *, comparisons between PGI2 and control animals.

min after endotoxin to 39±3% (P < 0.001) at 5 h. In control animals V0/Vr was 56±3% at this time (P < 0.005).

Platelet and leukocyte count. 6 min after endotoxin, platelet numbers decreased to less than 10% of base line (P < 0.001) and then gradually increased, reaching a plateau of about 100,000 after 60 min in the control group (Fig. 5). Aspirin did not alter numbers, but with PGI2 platelets slowly rose and after 2.5 h the count of 122,700±10,300 was higher than controls (P < 0.05). The leukocyte count following endotoxin initially declined to <750/mm3 (P < 0.001) and then gradually rose to levels above 4,000/mm3 by 5 h. PGI2 and aspirin were without effect on the leukocyte count.

Fibrinogen and FDP. Fibrinogen levels decreased from 484±52 to 321±28 μg/dl in the control group (P < 0.01), from 483±39 to 331±24 μg/dl in the PGI2 group (P < 0.005) and from 464±64 to 227±47 μg/dl in the aspirin group (P < 0.001). Fibrinogen remained depressed in the three groups throughout the experiment. 30 min after endotoxin, FDP rose from <0.05 to 36.0±9.6 μg/ml and to 52.0±18 μg/ml at 3 h. In the PGI2 treated group, FDP peaked at 54.4±20.0 μg/ml and declined significantly (P < 0.05, Fig. 6). In the aspirin treated group, FDP increased to 53.7±20.0 μg/ml after 2 h, similar to the control group.

Cathepsin D. Endotoxin injection resulted in a fivefold rise in plasma cathepsin D from 128±79 to 812±145 μM trypsin/ml·h at 3.5 h in the control group (P < 0.001, Fig. 7). In the PGI2 group, cathepsin D levels peaked at 602±162 after 2 h (P < 0.05) and became significantly lower than untreated controls by 3.5 h (P < 0.05). Cathepsin D levels in the aspirin group were not significantly different from controls.

Catecholamines. Norepinephrine levels in untreated controls increased threefold 6 min after endotoxin,
fivefold 2 h after endotoxin infusion, and remained elevated during the remaining 3 h period \((P < 0.005, \text{ Fig. 8})\). Following PG\(_I_2\), arterial levels of norepinephrine were significantly lower and returned to base-line values by 4 h. In the aspirin group norepinephrine increased fivefold after 2 h and was significantly higher than controls after 4 h \((P < 0.05)\). Arterial dopamine initially increased 6 min following endotoxin \((P < 0.005)\), and remained elevated in all three groups (Table 1). Arterial epinephrine increased more than sevenfold following endotoxin administration \((P < 0.01)\). Neither PG\(_I_2\) nor aspirin had any significant effect on epinephrine levels.

Survival. In order to maintain a stable hemoglobin and pH, untreated control animals required 705±60 ml/h lactated Ringers solution and 10.0 ml/h bicarbonate; the PG\(_I_2\) group required 700±74 ml/h Ringers and 10.2 ml/h bicarbonate; finally, after aspirin 633±64 ml/h Ringers and 10.0 ml/h bicarbonate were needed. Watery diarrhea was observed in four control, three PG\(_I_2\) treated and two aspirin treated animals. All eight untreated dogs and six aspirin treated dogs died within 24 h following the administration of endotoxin. 9 out of 10 PG\(_I_2\) treated animals survived more than 24 h \((P < 0.025)\).

**DISCUSSION**

Lethal endotoxemia results in systemic hypotension, transient pulmonary hypertension, and reduction in cardiac output. Multiple organ failure develops: acute respiratory failure leads to a rise in \(Q_s/Q_t\); acute renal failure is heralded by persistent severe oliguria; hepatocellular dysfunction is manifest by elevation of the serum enzymes glutamic-oxaloacetic transaminase and glutamic-pyruvic transaminase as reported by Wise et al. (16), as well as increases in the acid hydrolase cathepsin D (17). These enzyme elevations are thought to be due to hepatocyte damage with lysosomal disruption caused by leukocyte and erythrocyte aggregates in hepatic sinusoids (18, 19).

Early and prominent hematologic abnormalities are thrombocytopenia and leukopenia. Endotoxin is known to cause platelet clumping (2). Platelet aggregation and neutrophil stimulation by particulates (20) lead to the generation of prostaglandins. The high levels of thromboxane \((\text{Tx})B_2\) the stable metabolite of thromboxane A\(_2\), within 30 min of the administration of endotoxin (16) is presumably a consequence of the metabolic activities of platelets and leukocytes. It is likely that TxA\(_2\) is important in promoting further platelet aggregation as well as in the mediation of the cardiovascular abnormalities observed with endotoxemia. The vasoconstrictive properties of TxA\(_2\) can account for the early pulmonary hypertension.
while negative inotropic properties of TxB₂ may explain in part the reduced flow (17, 21), although the levels of TxB₂ used in in vitro studies were far above anything which can be achieved in vivo. Pretreatment of animals with the cyclo-oxygenase inhibitors indomethacin (22) or ibuprofen (23) and thromboxane synthetase inhibitors, imidazole or 7-(1-imidazolyl)-heptanoic acid ameliorated the severe thrombotocypenia following endotoxin (24) and prevented the rise of serum acid hydrolase activity of lysosomal origin (23). Furthermore, many other salutary effects were noted after pretreatment with these cyclo-oxygenase and thromboxane synthetase inhibitors including the maintenance of hepatic function and improved long term survival (16, 17, 22, 23). These beneficial effects required the prophylactic use of antagonists. In the present study, aspirin given 30 min after endotoxin did not reverse the fall in platelets, nor was there restoration of the rise in FDP and cathepsin D levels. Further, although MAP and MPAP rose, there was no increase in CI; PVR and SVR remained high and there was a fatal outcome.

Intravascular coagulation is a prominent event in endotoxemia. Its occurrence was signaled by the fall in platelets and fibrinogen, and the rise in FDP. It is likely that platelet aggregation and disseminated intravascular coagulation were triggered by the same stimulus since imidazole has been reported by Wise et al. (16) to prevent severe thrombotocypenia, as well as limit the rise in FDP. PGI₂ is known to inhibit platelet aggregation by causing an increase in cyclic AMP (25). Our observed rise in platelet counts following PGI₂ and fall in FDP indicates the effectiveness of PGI₂ in reversing the intravascular coagulopathy.

Treatment of endotoxemia with PGI₂ significantly modified metabolic events, organ function and survival. We believe the mechanism relates directly to the ability of PGI₂ to stimulate cyclic AMP production. Thus, increases in platelet cyclic AMP prevents platelet aggregation, disseminated intravascular coagulation and the generation of negative inotropic agents such as TxB₂ (21). Our observations that aspirin was ineffective therapy argues that TxA₂ does not play an important role in the pathophysiology of endotoxemia, although it may be important in the development of increased Vₒ/Vₒ. The observed rise of cardiac output in response to PGI₂ is probably due, in part, to vasodilatation and reduction in SVR and cardiac afterload. The fact that neither the CVP nor PAWP changed makes alterations of venous return, venous capacitance, and/or compliance unlikely. Reversal by PGI₂ of flow limitations due to right ventricular failure secondary to pulmonary hypertension is also unlikely, in as much as PGI₂ had no appreciable effect on MPAP. It is possible that in addition to simulating cyclic AMP, the vasodilating effects of PGI₂, particularly with regard to the coronary vasculature (26) may have contributed to improved cardiac function.

The rapid reversal of cardiac dysfunction by PGI₂ contrasts with the slow reversal of renal failure and hepatocellular function reflected by urine flow and cathepsin D activity (Figs. 4, 7). These events may indicate improved cellular function secondary to the

<p>| Table I |
| Plasma Catecholamine Concentrations |</p>
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<thead>
<tr>
<th>Time after endotoxin</th>
<th>0</th>
<th>6 min</th>
<th>30 min</th>
<th>1 h</th>
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<th>4 h</th>
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<td></td>
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<td>Control</td>
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<td>590±70</td>
<td>694±90</td>
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<td>246±30</td>
<td>545±122</td>
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<td>607±73</td>
<td>575±109*</td>
<td>439±37*</td>
<td>255±321</td>
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<td>1,042±322</td>
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* PGI₂ group compared with control animals. P < 0.05.
† PGI₂ group compared with control animals. P < 0.005.
§ Aspirin group compared with control animals. P < 0.05.
improved perfusion. The delayed restoration of norepinephrine levels with PGI₂ may simply be a function of a slow reversal of the state of stress and the stimulus to production (Fig. 8). The selective reduction of norepinephrine and not dopamine or epinephrine may relate to a direct inhibition of norepinephrine release by PGI₂ from sympathetic nerve endings in blood vessels (27). It is also possible that endotoxin interfered with the pulmonary endothelial clearance of norepinephrine. Normally, 25% of circulating norepinephrine, but not epinephrine or dopamine, is extracted during passage through the lungs (28). PGI₂ may have restored normal pulmonary metabolic function. Surprisingly, PGI₂ did not reverse $Q_s/Q_T$ during the 5-h observation period. An infusion of PGI₂ into animals made hypoxic with pulmonary emboli led to a lowering of $Q_s/Q_T$ within 15–30 min (8). The failure of PGI₂ to promptly reverse respiratory failure in endotoxia where microemboli are thought to play a prominent role is unexpected (6) and suggests that microemboli, which may possibly have been formed in the lung, were not affected by PGI₂ during the limited 5-h period of observation. Studies in septic dogs and patients have shown that platelets and granulocytes are entrapped by the lungs (29, 30). However, these events correlate poorly with abnormalities in respiratory function. It is likely that other factors are involved in lung damage and the functional abnormalities of sepsis. Leukocytes may mediate endothelial damage (31). Neutrophils contain neutral proteases such as collagenase, elastase, and cathepsin D. Following infusion of endotoxin the decrease in leukocyte count may be due to complement-activation and release of complement (C)3a and C5a which are chemotactic and result in sequestration of leukocytes in the microvasculature (29). During the process of neutrophil activation and degranulation, lysosomal contents may be discharged not only into phagocytic vacuoles within the cell, but may inadvertently escape into plasma (32). It is conceivable that other toxic oxygen derivatives such as superoxides are also released and cause endothelial cell damage. The natural defenses against these events are the circulating antiproteases and scavengers of superoxide anions.

The potential benefit of PGI₂ regarding leukocytes may be outweighed by its inhibitory actions on chemotaxis and the hexose monophosphate shunt (33). These inhibitory effects may be hazardous during a clinical setting of bacteremia where reticuloendothelial function is important.

The mechanisms whereby PGI₂ modifies the response to endotoxia remain obscure. The results of the current investigation provide evidence of hematologic, biochemical and cardiovascular activities of PGI₂ which coincide with improved survival.

ACKNOWLEDGMENTS

This work was supported in part by National Institutes of Health grants GM24891-03, HL16714-06; U. S. Army Medical Research and Development Command contract DAMD17-78-C-5026; the Brigham Surgical Group, Inc.; and the Trauma Research Foundation.

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