Prevention of endotoxaemia by non-absorbable antibiotics in heat stress

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SUMMARY Four anaesthetised monkeys were given oral kanamycin (15 mg 1 kg 12 hourly) over five consecutive days before being heat stressed. Four other anaesthetised monkeys served as controls. The plasma lipopolysaccharide concentration in control primates increased initially from 0.044 (SEM 0.004) ng/ml to 0.062 (0.006) ng/ml as the rectal temperature increased from 37.5 to 39.5°C. A second increase in lipopolysaccharides started at 42°C and reached 0.308 (0.038) ng/ml ($p < 0.01$) at 44.5°C. Before heat stress the plasma lipopolysaccharide concentration in the primates who had been pretreated with kanamycin was 0.007 (0.006) ng/ml, and despite heating these animals to 44.5°C no increase in plasma lipopolysaccharide concentrations were seen in this group. The cardiovascular variable during heat stress were more unstable in the control group and began to deteriorate at a lower temperature than in the group receiving antibiotic. These data suggest that the increased plasma lipopolysaccharide concentration during heat stress originates mainly from the gut.

Recent evidence shows that endotoxins (lipopolysaccharides or LPS), the highly toxic components of the outer cell membrane of Gram negative bacteria, may have a role in heat stroke pathophysiology.^{1–6} The lumen of the mammalian gut always contains Gram negative bacteria, and hence LPS. Normally, the gut wall is impermeable or slightly permeable to LPS. Small amounts of LPS that may leak into the portal circulation are detoxified by the reticuloendothelial system.⁷ Damage to the gut wall by ischaemia, trauma, hyperthermia, vasoactive agents, ionising radiation, hypoxia, and viral gastroenteritis, however, enables LPS to leak rapidly into the portal and systemic circulations.^{3,8–13} Should the reticuloendothelial system of the liver and spleen become overwhelmed by the rapidly rising blood LPS concentrations or should the reticuloendothelial system function be inadequate to remove the LPS, then the plasma LPS concentration in the systemic circulation would rise and persist in the circulation, eventually causing vascular collapse, shock, and death.^{9,14}

In a previous study we determined the time course of changes in circulating plasma LPS concentrations and cardiovascular variables in heat stressed monkeys.¹ Furthermore, high concentrations of plasma LPS have been detected in a few cases of fatal heat

stroke.^{2,5} In addition, reduction of gut flora with antibiotics has been found to increase an 18 hour survival in heat stressed dogs⁴ and to reduce the prevalence of endotoxaemia in heat stressed rabbits.⁶ We believe that during heat stress the reduced blood flow to the visceral regions^{15,16} coupled with the high core temperature leads to damage to the permeability properties of the gut mucosa and results in leakage of LPS into the portal and lymphatic circulation.

In this study an attempt has been made to show that the increase in LPS that occurs during heat stress is intestinal. The amount of endogenous Gram negative flora and hence LPS in the gut can be reduced by the oral administration of a non-absorbable antibiotic before heat stress.

Material and methods

Eight monkeys (*Cercopithecus aethiops*) of either sex, weighing between 2.7 and 6.8 kg were used. They were anaesthetised with ketamine (10 mg/kg, given intramuscularly). Thereafter, incremental intravenous bolus doses (5–10 mg/kg intravenously) of ketamine were used to maintain anaesthesia. The animals were divided into two groups. Four of them received kanamycin (15 mg/kg) (Kantrexil suspension, the B-M Group Ltd) every 12 hours over five consecutive days via a nasogastric tube prior to heat stress; four others served as controls.

After cleansing both the femoral areas with chlor-

hexidine gluconate catheters were introduced into both femoral arteries and a peripheral vein. One of the arterial catheters was connected to a B188 Stat-ham transducer for recording of blood pressure, while blood samples were collected at various times from the opposite catheter. Only equipment without pyrogen was used, and each heparinised plastic tube into which the blood was collected was stored on ice until centrifuged for LPS and anti-LPS IgG analyses. After each withdrawal of blood sample an equal volume of physiological saline was reinfused. Arterial pressure was recorded using a Honeywell CM 130 patient monitor system at five minute intervals during the experiment. Heart rate, systolic, diastolic, and mean arterial pressures were calculated electronically and presented as a printout with the blood pressure recording. The mean arterial pressure (MAP) was measured automatically from integration of the area under the arterial pressure curve.

Rectal temperatures were recorded continuously using a rectal probe inserted about 10 cm into the rectum, and a telethermometer (Yellow Springs Instrument 46-TUC) connected to a chart recorder.

After surgery a 30 minute stabilisation period was allowed and then baseline rectal temperature, arterial blood pressures, and room temperature were recorded, and 1 ml blood sample for LPS and anti-LPS analyses and 3 ml for serum enzyme analyses were collected in heparinised and non-heparinised tubes, respectively. Each animal was then positioned in a forced draft incubator, where the environmental temperature was maintained at 41.0 (0.3)°C and relative humidity close to 100%. During heat stress, blood samples for LPS and anti-LPS IgG analyses were taken at 15–30 minute intervals and for serum enzyme analyses when the rectal temperature reached 40, 42, and 43°C.

The blood samples for LPS and anti-LPS IgG assay were stored in ice until the end of each experiment. After centrifugation of the samples the plasma was removed under sterile conditions in a laminar flow hood. The samples were either analysed immediately or stored at –20°C for up to a week until analysed. Plasma LPS concentrations were determined using the chromogenic substrate modification of the limulus amoebocyte lysate (LAL) technique (MA Bioproducts).^{17,18} We previously found a 95.1% recovery from spiked plasma samples using this method, calibrating the standard curve with LPS prepared from *Escherichia coli* 0111:B4.¹⁹ Relative plasma anti-LPS IgG concentrations were determined using an enzyme linked immunoabsorbent assay (ELISA).²⁰ The concentration of anti-LPS IgG at a rectal temperature of 37.5°C for each animal was taken as 100%. A detailed description of the procedure adopted has already been described.¹ Boehringer kits were used for deter-

mining the activities of aspartate aminotransferase (AST), alanine aminotransferase (ALT), L-γ-glutamyl-transferase, alkaline phosphatase and the concentrations of bilirubin, albumin, and total protein in the serum.

Rectal swabs for bacteriological examination were taken from all animals after anaesthesia but before experimental heat stress. These sterile rectal swabs were initially moistened with sterile saline and care was taken to avoid perianal contamination. After storing in nutrient broth the swabs were individually plated out on deoxycholate citrate (DCA) MacConkey, and nutrient agars. These plates were then incubated aerobically for 18–24 hours at 37°C and further subcultured on to DCA. Twenty four hours later each plate was examined for non-lactose fermenting colonies which were then isolated and identified by Gram stain, biochemical reactions, colony form and pigmentation.

Immediately after the termination of each experiment the abdomen of each animal was opened. A 6–7 cm section of the transverse colon was tied off at each end and removed. One gram of fecal contents was then emulsified in 100 ml of sterile peptone water under a laminar flow hood. Serial dilutions of 10²–10⁸ were made up using an initial 1/100 dilution. Triplicate pour plates of 1 ml of each in nutrient agar were made for bacterial enumeration. Plates were incubated inverted at 37°C for 18–24 hours. Bacterial colonies were enumerated and results were reported as the number of colony forming units/g faeces.

All data were presented as a mean and (SEM) and compared using Student's *t* test, the analysis of variance (ANOVA), and Duncan's multiple range test²¹; a *p* value of <0.05 was taken as significant.

Results

The figure shows an initial plasma LPS concentration of 0.044 (0.004) ng/ml in the control group similar to the low values we have previously seen.²¹ As the rectal temperature rose there was a small but insignificant increase in plasma LPS concentration near 39.5°C followed by a large rise at about 42°C and reaching 0.308 (0.038) ng/ml (*p* < 0.01) (ANOVA and Duncan's multiple range test) at about 44.5°C. Within a few minutes of reaching this rectal temperature each animal succumbed. In contrast, the group treated with kanamycin showed no significant change in plasma LPS concentrations during the entire heat stress period. Before this latter group was subjected to heat stress the plasma LPS concentration 0.007 (SEM 0.008) ng/ml was significantly lower than that of the controls (*p* < 0.02) and after heat stress it never rose significantly above baseline, and a concentration of 0.005 (0.002) ng/ml was measured just

Figure Mean (SEM) changes in plasma LPS concentration (circles), mean arterial pressure (squares), and heart rate (triangles) in control (broken lines) and treated (solid lines) groups at progressively raised rectal temperature in monkeys exposed to environmental temperature of 41.0 (0.3)°C and 100% relative humidity.

before the monkeys died. The primates in the group treated with kanamycin succumbed at a significantly lower rectal temperature than those in the control group (44.1 v 44.6°C) ($p < 0.025$).

As the core temperature rose the MAP in the control group (figure) increased from 85 (SEM 4.2) mm Hg at a rectal temperature of 37.5°C to 100 (5) mm Hg at 39–41°C. Above 41°C the MAP gradually declined until a rectal temperature of about 43°C when there was a rapid decline. This rapid fall in MAP coincided with a rapid rise in heart rate and shortly before the rapid rise in plasma LPS. In the group treated with kanamycin the MAP curve was similar to that of the controls but at a level about 10–20 mm Hg higher than the controls throughout the whole temperature range.

As the rectal temperature rose the heart rate (figure) in the control group increased rapidly from 113 (SEM 3) beats/minute at a rectal temperature of 37.5°C to 152 (SEM 16) beats/minute at 39°C. This increase was followed by a slight decline in heart rate to 128 (SEM 9) beats/minute at 40°C before rising steadily to 155 (SEM 9) beats/minute at 42°C. Thereafter, the heart rate increased rapidly to reach a peak of 303 (SEM 6) beats/minute ($p < 0.001$) at 44°C after which it declined rapidly until a temperature of about 44.5°C was recorded. In the group treated with kanamycin the heart rate increased steadily from

126 (SEM 7) beats/minute at 37.5°C to 309 (SEM 7) beats/minute at 43.5°C, with a dip at 38°C. For any given rectal temperature between 39°C and 43.5°C, both the MAP and heart rate were higher than those recorded for the controls.

Except for a significant increase in serum AST concentration ($p < 0.01$) which increased from 47.55 (SEM 3.25) IU/l at 37°C to 75.9 (SEM 2.9) IU/l at 43°C in the control group, no significant changes in the serum enzymes ALT, L- γ -glutamyltransferase, and alkaline phosphatase were observed in either groups (table). Albumin, total protein, bilirubin concentrations and anti-LPS IgG titres were also not found to have changed significantly during heat stress (table).

Bacterial examination of rectal swabs from control animals yielded *Escherichia coli*, *Pseudomonas* sp, *Coliform bacilli*, *Proteus* sp, *Serratia* sp, *Staphylococcus* sp and *Lactobacilli* sp. In contrast, pretreatment with kanamycin resulted in an overgrowth of the Gram positive *Staphylococcus* sp and *Lactobacillus*, although *E coli* was found in some animals. Plate counts in the controls yielded a total of 12.56 (SEM 1.83) colony forming units $\times 10^9$ /g faeces of Gram negative and Gram positive bacteria. In the group treated with kanamycin plate counts showed a significant reduction to 0.183 (SEM 0.04) colony forming units $\times 10^9$ /g faeces ($p < 0.001$). This count would have been much lower had it not been for the overgrowth of Gram positive bacteria.

Discussion

Heat stroke is characterised by high body temperature, loss of consciousness, irritability, diarrhoea, vomiting and other symptoms.²¹ These symptoms are similar to those in endotoxic shock caused by high plasma concentrations of LPS.^{22–24} Hence LPS has been postulated to play a part in the pathophysiology of heat stroke.^{1–6} We have recently shown the time course of endotoxaemia in heat stressed monkeys.¹

In the control group of this study the plasma LPS concentration began to increase when the rectal temperature reached 42°C (figure). Initially this increase was gradual up to 43°C when a rapid rise occurred, reaching 0.308 (0.038) ng/ml ($p < 0.001$) just before death. The changes in plasma LPS concentration seen here were similar to those previously reported.¹ On the other hand, in the experimental group pretreatment with the oral non-absorbable antibiotic completely prevented any significant increase in plasma LPS concentration. The active ingredients of Kantrexil suspension are kanamycin and kaolin. Although kanamycin is sensitive for most Gram negative bacteria and aerobic bacteria, together with kaolin, it suppresses the plasma LPS concentration.

Table Changes in concentration of serum enzymes, bilirubin, albumin, total protein and anti-LPS (IgG) in control and treated groups

	Concentration at rectal temperatures of:			
	37°C	40°C	42°C	43°C
Control group:				
AST (IU/l)	47.55 (3.25)	58.0 (17.2)	68.2 (9.1)	75.9 (2.9)*
ALT (IU/l)	6.2 (0)	10.9 (5.0)	40.8 (36.55)	39.1 (34.0)
Alkaline phosphatase (IU/l)	376.1 (7.8)	367.8 (31.85)	418.4 (13.2)	406.9 (36.0)
L-γ-glutamyltransferase (IU/l)	22.5 (3.3)	21.2 (2.8)	24.2 (3.0)	24.3 (2.0)
Bilirubin (μmol/l)	3.5 (0.5)	3.0 (1.0)	5.0 (2.0)	4.5 (0.5)
Albumin (g/l)	31.25 (3.35)	29.45 (0.55)	34.3 (0.7)	32.2 (3.9)
Total protein (g/l)	48.9 (10.2)	57.05 (2.15)	59.45 (0.35)	60.25 (0.35)
Anti-LPS (IgG)%	100	—	61.8 (7.2)	94.1 (28.3)
Treated group:				
AST (IU/l)	34.85 (7.85)	32.0 (11.71)	31.4 (6.17)	31.83 (8.12)
ALT (IU/l)	5.73 (2.38)	8.68 (1.06)	10.25 (3.86)	4.85 (1.19)
Alkaline phosphatase (IU/l)	431.2 (78.8)	372.0 (64.7)	413.1 (101.6)	437.6 (105.9)
L-γ-glutamyltransferase (IU/l)	26.53 (3.23)	26.15 (3.65)	27.78 (4.35)	26.38 (3.6)
Bilirubin (μmol/l)	4.18 (0.14)	2.63 (0.86)	3.5 (0.75)	4.85 (0.83)
Albumin (g/l)	27.8 (1.05)	27.68 (2.38)	27.85 (1.65)	27.48 (1.83)
Total protein (g/l)	54.78 (2.57)	53.4 (3.19)	56.48 (3.42)	54.9 (3.74)
Anti-LPS (IgG)%	100	—	87.8 (14.8)	80.9 (21.3)

*p < 0.05.

The LPS of anaerobic Gram negative bacteria which, incidentally, make up a large proportion of the gut flora, lack certain characteristics of classic endotoxins and as such are less toxic.^{25 26} In view of this no attempts were made either to suppress their activity in the gut or to determine their count in the faeces. Moreover, prophylaxis with kanamycin only has been advocated and used for sterilisation of the gut during surgery.^{27 28} Furthermore, pretreatment with oral kanamycin has been shown to reduce the incidence of persisting endotoxaemia, lung lesions, and mortality from 90% to 32% during temporary occlusion of the superior mesenteric artery, intravenous injection of endotoxin or bradykinin, and intraperitoneal injection of *E coli* in rabbits.²⁹ Excessive and indiscriminate use of antimicrobes active against the anaerobic Gram negative gut flora may also reduce or eliminate the "interference phenomenon" and encourage invasion by pathogenic bacteria.²⁶ Although prophylaxis with kanamycin used in this study significantly reduced the total bacterial count (p < 0.001), at the same time it promoted an overgrowth of the Gram positive bacteria. The reduction in count from 12.56 (1.83) colony forming units × 10⁹/g faeces to 0.183 (0.04) colony forming units × 10⁹/g faeces of total bacterial flora might, therefore, not be sufficient to have caused the reduction in the plasma LPS concentration observed in this study. The count shown would have been much lower had it not been for the overgrowth of the Gram positive bacteria.

In this study as the rectal temperature increased so did the MAP in both the groups. In the control group not only were the MAPs lower for any given rectal temperature but the MAP also began a downward

trend at a lower rectal temperature than the group treated with kanamycin (40.5°C v 42°C) (p < 0.05). Gorman and Proppe³⁰ also noticed a similar decline in MAP in the early period of heat stress in baboons. The higher MAP in the group treated with kanamycin may be partly explained by the anticholinergic properties of aminopentamide, one of the constituents of Kantrexil suspension³¹; and this could also explain why the heart rates were higher in those primates pretreated with kanamycin, and also possibly why they succumbed at a lower rectal temperature.^{31 32} Gorman and Proppe also found that the heart rates for any given blood temperature were higher in heat stressed baboons who had received a cholinergic blocking agent than those who were not treated.³⁰

Hyperthermia not only causes an increased blood flow to the skin but also a decreased visceral blood flow.^{15 16} These could result in an ischaemic gut wall and hence raised plasma LPS.^{1 13} High concentrations of plasma LPS have been reported in patients with fatal heat stroke^{2 5} and a reduction of gut flora with antibiotics and enemas have been found to increase the incidence of an 18 hour survival in dogs subjected to heat stress from 20% to 70.6%.⁴ Furthermore, rabbits pretreated with oral antibiotics have a reduced tendency toward developing endotoxaemia than untreated heat stressed rabbits.⁶ The standard treatment for heat stroke is rapid cooling, correction of fluid and electrolyte disturbances, and treatment of shock.^{21 33}

Our study suggests that the origin of the increased plasma LPS concentration seen during heat stress is mainly derived from the gut. Furthermore, gut derived LPS may be an important contribution to the

pathophysiology of heat stroke, and the use of anti-LPS antibodies may prove beneficial in heat stroke.

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