IL-1, IL-6, TNF-α, and MIF in relative adrenal insufficiency in septic shock: a piglet model

Bina Akura,¹ Jose R. L. Batubara,² Zakudun Munasir,² Gunanti,³ Joedo Prihartono,⁴ Hindra Irawan Satari,² Suzanna Immanuel,⁵ Dadang Hudaya Somasetia⁶

ABSTRACT

BACKGROUND Inflammatory mediators released during septic shock are involved in the mechanism of adrenal insufficiency. This study investigated the role of interleukin (IL)-6, IL-1, tumor necrosis factor (TNF)-α, and macrophage migration inhibitory factor (MIF) in septic shock with relative adrenal insufficiency (RAI).

METHODS We conducted a 6-month experimental study in 20 piglets. Following endotoxin administration, their hemodynamics were monitored and blood samples were drawn to test the levels of cytokines IL-1, IL-6, TNF-α, and MIF every 15 min until septic shock onset as well as during a corticotropin stimulation test. Septic shock was managed by administering fluid resuscitation, inotropic drugs, and hydrocortisone. At the end of the study, the piglet models were classified as either RAI or non-RAI. Immunohistochemistry staining was performed on the hypothalamus of the RAI group.

RESULTS The level of IL-6 at 45 min was higher in the RAI group than the non-RAI group (p = 0.008), and that of IL-1 was similar in the two groups during septic shock. The RAI group had higher TNF-α levels at 15 min (p = 0.002) and at 30 min (p = 0.007) than the non-RAI group, and the MIF level during septic shock was higher in the RAI group (p = 0.003) than the non-RAI group.

CONCLUSIONS Cytokine-induced inflammatory process of adrenal gland reflected in TNF-α level in 15 min and 30 min, IL-6 in 45 min, and MIF in septic shock condition but not in IL-1.

KEYWORDS adrenal insufficiency, interleukin-1, interleukin-6, macrophage migration inhibition factors, septic shock, tumor necrosis factor-alpha

Sepsis refers to a dysfunction that can be life-threatening and is caused by immune dysregulation in response to infection.¹,² Sepsis diagnosis is based on a predisposition to infection, signs of ongoing infection, inflammation responses, and organ dysfunction or failure.¹ Management of sepsis in “Surviving Sepsis Campaign” has established an early diagnosis and prompt administration of adequate antibiotic treatment and resuscitation are the only measures that improve the prognosis.³ Despite these advances, the mortality of children with septic shock in developed countries is still above 12%.² Incidence adrenal insufficiency in sepsis patients is 30.7% in Brazil.¹ At Cipto Mangunkusumo hospital in 2009, there were 61 cases of septic shock and 28 cases (45.9%) were death.⁴ Neuroendocrine dysfunction could occur in patients with severe sepsis or septic shock.⁵ Adrenal insufficiency in septic shock is
temporary, and conditions return to normal with the improvement of sepsis. Thus, it is suspected that inflammatory mediators released during septic shock cause hypothalamus–pituitary–adrenal (HPA) axis dysfunction and may play a role in the development of adrenal insufficiency.⁵

Cytokines mediate the immune/metabolic response to external stimuli and the transition from sepsis to septic shock and then to multiple organ dysfunction syndrome.⁵⁶ The mechanism of relative adrenal insufficiency (RAI) in septic shock is exceptionally complex. It is suspected that inflammatory mediators released during septic shock play a role in HPA axis dysfunction and in the mechanism of adrenal insufficiency.⁵ In addition to their stimulatory function, the release of inflammatory mediators during sepsis could also inhibit the synthesis and release of cortisol via the action of cytokines at the HPA axis and at glucocorticoid receptors. Interleukin (IL)-6 and IL-1 stimulate cortisol secretion by affecting the components of the HPA axis.⁵⁶ Another immune mediator, macrophage migration inhibitory factor (MIF), is secreted by the anterior pituitary gland and macrophages to counteract glucocorticoid action.⁷ Because the incidence of RAI remains high, it is crucial to determine which cytokines among IL-1, IL-6, tumor necrosis factor (TNF)-α, and MIF play an important role, and this has yet to be investigated. However, it would be unethical to perform such a study in humans. In such cases, studies have been performed using Sus scrofa, due to similarities with humans in terms of physiology, anatomy, and biochemical structure.⁸–¹⁰ The primary objectives of this study were to investigate the role of cytokines IL-1, IL-6, TNF-α, and MIF in the development of RAI in septic shock and to observe the histopathological features in the adrenal glands, pituitary glands, and hypothalamus in a piglet model of septic shock with RAI.

**METHODS**

**Study design**

This 6-month experimental study (April–September 2015) was conducted in the Experimental Surgery Laboratory, Surgery and Radiology Division, Reproduction Clinic and Department of Pathology, Faculty of Veterinary, Institut Pertanian Bogor (IPB). We also used the facilities at the integrated laboratory of the Faculty of Medicine, Universitas Indonesia, and the IPB Primate Laboratory. Ethical approval was obtained from the Medical/Health Research Ethics Committee of the Faculty of Medicine, Universitas Indonesia/Cipto Mangunkusumo Hospital (No: 939/UN2.F1/ETIK/K/2015) and the Animal Ethics Committee of the Faculty of Veterinary, IPB (No: 026/KEH/SKE/IV/2015).

**Sample selection**

We used 20 piglets (Sus scrofa) from two healthy litters aged 6–8 weeks with a bodyweight of 5–10 kg, equivalent to the weight of infant and pediatric patients aged 3 months–2 years. A sample size of 20 was calculated using a single proportion formula with α = 0.05, a proportion of 0.3, and precision of 0.2.¹⁰

**Inclusion and exclusion criteria**

Piglets were only included if they were declared healthy by the veterinarian, with normal standard physical, blood, blood gas analysis, and chest X-ray examinations. Piglets were excluded if the veterinarian detected abnormal heart sounds or lung abnormalities upon X-ray. Those piglets that did not complete the study protocol or died before all study procedures were completed, those with incomplete laboratory results, and those with unstable hemodynamics were excluded.

**Pre-study screening**

A physical diagnostic examination was conducted by a veterinarian prior to study commencement, including routine blood examinations, blood gas analysis, and a chest X-ray. The piglets were given the antibiotic enrofloxacin for treatment against Escherichia coli and Salmonella, and oxfendazole for deworming.

**Study procedure**

The study procedure included sedation/anesthesia, intubation, vascular access, sampling, a corticotropin stimulation test (Synacthen®), and pathological examination of the adrenal glands, pituitary glands, and hypothalamus. Anesthesia was performed using a combination of 20 mg/kg body weight (BW) 10% ketamine HCl and 2 mg/kgBW 10% xylazine HCl administered intramuscularly in the neck muscles, followed by 1% propofol (100–300 ug/kgBW/min) and phentanyl (2 mcg/kgBW/hour).¹⁰ A central arterial catheter (Pulsiothath PV2015, Pulsion Medical Systems, Germany) was inserted into descending aorta.
through the femoral artery, and a venous catheter (Certofix® Duo Paed, B-Braun, Germany) was inserted deep into the jugular vein. Then, they were attached to a pressure transducer and pulse index continuous cardiac output (PiCCO) device (B850 General Electric, USA) to measure arterial blood pressure, mean arterial pressure (MAP), and cardiac index (CI). The heart and respiratory rates were also monitored. The heart rate, respiratory rate, temperature, MAP, and CI was determined for all piglets. The white blood cells count and levels of IL-1, IL-6, TNF-α, MIF, cortisol, and adrenocorticotropic hormone (ACTH) were measured prior to study procedure, during sepsis, and during septic shock. Blood gas analysis was also performed. The blood glucose level was measured using glucometer (GlucoDr, Allmedicus, Republic of Korea) and the lactate level was measured using i-STAT (Abbott Point of Care Inc., Abbott Park, USA). A PiCCO monitor (B850 General Electric) was used to measure heart rate, MAP, and CI to determine the septic shock state.

All animals were given 50 µg/kgBW lipopolysaccharide (LPS) endotoxin intravenously (E. coli O111:B4; Sigma-Aldrich St. Louis, USA). The piglets were intensively monitored using a PiCCO device until septic shock occurred. If septic shock had not occurred within 4 hours, a further dose of 1 µg/kgBW/hour of E. coli LPS was given. Blood samples were taken for IL-1, IL-6, TNF-α, MIF, ACTH, and cortisol analysis. The samples were drawn before the endotoxin administration and every 15 min thereafter until septic shock occurred. Sepsis signs included increasing or decreasing body temperature, vomiting, and increased heart rate, MAP, white blood cells, and lactate levels. Septic shock was considered to have occurred if the CI was <3.0 l/min/m². Septic shock was managed by administering fluid resuscitation, inotropic drugs. Hydrocortisone was given to overcome RAI after giving inotropic drugs and resuscitation.

A corticotropin stimulation test was performed after septic shock had occurred using an injection of synthetic corticotropin. The pre- and post-test cortisol levels were measured using an enzyme-linked immunosorbent assay (ELISA) cortisol kit (Abcam, UK; catalog number: ab108665). After completing the study procedure, euthanasia was performed with the intravenous administration of 400 mg phenobarbital in the auricular vein, and the adrenal gland, pituitary gland, and hypothalamus were resected for histopathological evaluation. The piglet was grouped into RAI or non-RAI group based on the result of corticotropin stimulation test. All hemodynamic parameters, cytokine levels, and hormone levels were assessed against normal piglet values.

Corticotropin stimulation test

Piglets were grouped based on corticotropin stimulation test at the end of intervention, after we got laboratory result of cortisol. A corticotropin stimulation test was performed by injecting 250 mg (equivalent to 25 IU) of corticotropin intravenously and followed by flushing with 0.9% NaCl (1 ml/kgBW; Synacthen Depot®; Novartis Pharma GmbH, Germany). The corticotropin was injected immediately after blood specimen for the pre-test cortisol was drawn (t₀). The post-test sample was taken at 30–60 min after the corticotropin injection. Elevation of the post-test cortisol level (Δ max) was calculated as the difference between the cortisol level post corticotropin stimulation test (t₃₀₋₆₀) and pre-test cortisol level (t₀). RAI was grossly defined as basal cortisol <5 µg/dl, a cortisol level after synacthen stimulation of <18 µg/dl, or Δ cortisol <9 µg/dl.

Laboratory examination

After collecting blood from the piglets into ethylenediaminetetraacetic acid tubes, they were centrifuged for 15 min at 1,000 × g within 30 min of collection before being stored at ≤−20°C. All laboratory tests were performed at Prodia Laboratory, Jakarta. A Human IL-1 Quantikine ELISA Kit (R&D Systems, USA) was used to measure the levels of IL-1. All reagents, working standards, and samples were prepared according to the manufacturer's instructions. Briefly, after adding assay diluent RD-1 to each well of a 96-well plate, 200 µl of standard, sample, or control was added to each well, covered with an adhesive strip, and incubated for 2 hours at room temperature. Thereafter, each well was aspirated and washed three times with wash buffer (400 µl). After the last wash, any remaining wash buffer was removed via aspiration. Then, 200 µl of human IL-1 conjugate was added to each well, incubated again for 2 hours, aspirated, and washed as before. Substrate solution (200 µl) was added to each well and incubated for 20 min while protected from light. Finally, 50 µl of stop solution was added. A microplate reader was used.
to determine the optical density at 450 nm for each well within 30 min. A Human IL-6 Quantikine ELISA Kit, Human TNF-α Quantikine ELISA Kit, and Human MIF Quantikine ELISA Kit (R&D Systems) were used to measure IL-6, TNF-α, and MIF, respectively, and the procedure used was similar to that described for IL-1.¹² A cortisol ELISA kit and an ACTH immunoassay kit were used to measure the cortisol and ACTH levels, respectively.¹³

**Histopathology examination**

The adrenal gland, pituitary gland, and hypothalamus tissue were examined at the IPB Primate Laboratory. The tissues were stained with hematoxylin and eosin for histopathological examination. Immunohistochemical analysis was performed using anti IL-1 antibody [EPR21086] (Abcam 9722), anti IL-6 antibody [EPR21711] (Abcam 229381), anti TNF-α antibody [EPR19147] (Abcam 183218), and anti MIF antibody [EPR 12463] (Abcam 175189).

**Statistical analysis**

All data were analyzed using SPSS version 20 (IBM Corp., USA), and the results were presented as text, tables, or graphs. We used a 95% confidence interval and a power of 80%, and p-values <0.05 were considered statistically significant. Data with a normal distribution were presented as the mean and standard deviation.

### Table 1. Variables in baseline and during septic shock between the RAI and non-RAI groups

<table>
<thead>
<tr>
<th>Variable</th>
<th>Baseline</th>
<th>During septic shock</th>
<th>p*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RAI group, mean (SD) (N = 12)</td>
<td>Non-RAI group, mean (SD) (N = 7)</td>
<td>RAI group, mean (SD) (N = 12)</td>
</tr>
<tr>
<td>Male sex, (n)</td>
<td>6</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>7.8 (1.38)</td>
<td>7.6 (1.37)</td>
<td>-</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>70.3 (5.02)</td>
<td>70.7 (4.98)</td>
<td>-</td>
</tr>
<tr>
<td>Heart rate (bpm)</td>
<td>91.6 (13.30)</td>
<td>81.0 (10.26)</td>
<td>118.6 (21.17)</td>
</tr>
<tr>
<td>Blood pressure (mmHg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systolic</td>
<td>72.9 (14.18)</td>
<td>74.1 (9.49)</td>
<td>54.2 (12.92)</td>
</tr>
<tr>
<td>Diastolic</td>
<td>40 (11.78)</td>
<td>40 (11.12)</td>
<td>35.6 (10.1)</td>
</tr>
<tr>
<td>MAP (mmHg)</td>
<td>51.0 (11.47)</td>
<td>51.4 (10.41)</td>
<td>43 (10.16)</td>
</tr>
<tr>
<td>Respiratory rate (per min)</td>
<td>31.2 (2.86)</td>
<td>29.6 (5.59)</td>
<td>38.8 (4.73)</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>33.2 (1.77)</td>
<td>33.1 (1.41)</td>
<td>36.0 (1.74)</td>
</tr>
<tr>
<td>Hemoglobin (g/dl)</td>
<td>11.7 (1.43)</td>
<td>11.0 (0.74)</td>
<td>11.6 (1.52)</td>
</tr>
<tr>
<td>Hematocrit (%)</td>
<td>34.7 (5.12)</td>
<td>34.7 (3.04)</td>
<td>34.8 (3.98)</td>
</tr>
<tr>
<td>WBCs (µl)</td>
<td>12,475 (5.483.7)</td>
<td>11,386 (5.599.7)</td>
<td>13,925 (471.1)</td>
</tr>
<tr>
<td>Platelet (10³/µl)</td>
<td>427.4 (90.02)</td>
<td>364.8 (81.93)</td>
<td>351.6 (94.11)</td>
</tr>
<tr>
<td>Lactate level (mg/dl)</td>
<td>1.08 (0.27)</td>
<td>1.26 (0.50)</td>
<td>1.43 (0.44)</td>
</tr>
<tr>
<td>Cortisol level (µg/dl)</td>
<td>11.25 (6.91)</td>
<td>17.78 (6.72)</td>
<td>11.25 (6.91)</td>
</tr>
<tr>
<td>IL-1 (pg/dl), median (min–max)</td>
<td>15.66 (9.99–55)</td>
<td>20.07 (7.77–56.54)</td>
<td>19.45 (7.77–51.47)</td>
</tr>
<tr>
<td>IL-6 (pg/dl), median (min–max)</td>
<td>0.62 (0.51–1.35)</td>
<td>0.56 (0.51–0.62)</td>
<td>0.635 (0.55–1.23)</td>
</tr>
<tr>
<td>TNF-α (pg/dl), median (min–max)</td>
<td>34.77 (12.32–68.75)</td>
<td>41.39 (16.54–165)</td>
<td>4,731 (3,754.52–5,981.97)</td>
</tr>
<tr>
<td>MIF (ng/dl), median (min–max)</td>
<td>10 (8.12–17.3)</td>
<td>15.10 (8.17–21.52)</td>
<td>25.28 (18.45–30.64)</td>
</tr>
<tr>
<td>ACTH level (pg/dl)</td>
<td>10.82 (1.30)</td>
<td>11.21 (0.64)</td>
<td>10.31 (0.42)</td>
</tr>
</tbody>
</table>

RAI=relative adrenal insufficiency; SD=standard deviation; bpm=beats per minute; MAP=mean arterial pressure; WBCs=white blood cells; IL=interleukin; TNF-α=tumor necrosis factor-α; MIF=macrophage migration inhibitory factor; ACTH=adrenocorticotropin hormone

*p<0.05 were considered statistically significant
deviation, while data with abnormal distribution were presented as median values. The Mann–Whitney U test, Pearson’s correlation coefficient, and Spearman’s rank correlation coefficient were used.

RESULTS

Characteristics of the RAI and non-RAI groups

All piglets showed septic shock 60 min after endotoxin administration, except for one, where septic shock only occurred at 105 min, and it was consequently excluded from the analysis. Thus, only 19 subjects (9 males and 10 females) were analyzed. The initial cortisol level was 11.25 (6.91) µg/dl in the RAI group and 17.78 (6.72) µg/dl in the non-RAI group. The characteristics of each group are shown in Table 1.

Characteristics of the RAI and non-RAI groups during septic shock

The characteristics of the RAI and non-RAI groups during the septic shock condition are presented in Table 1. An increased heart rate, respiratory rate, and body temperature were observed in both groups. The mean white blood cell count was slightly increased in both the RAI and non-RAI groups, and the mean levels of IL-1, IL-6, and ACTH were similar in both groups. The cortisol level in the RAI group 11.25 (6.9) µg/dl was lower than in the non-RAI group 14.04 (7.18) µg/dl during septic shock. However, after the corticotropin stimulation test, the RAI group had a lower cortisol level than the non-RAI group (Table 2). Based on the corticotropin stimulation test result, 12/19 (63%) piglets were considered to have RAI.

Comparison of IL-1, IL-6, TNF-α, MIF, cortisol, and ACTH levels between the RAI and non-RAI groups

Figures 1 shows the dynamic changes of IL-1, IL-6, TNF-α, MIF, cortisol, and ACTH in the RAI and non-RAI group. The level of IL-6 in the RAI group at 45 min was higher than that of non-RAI group (0.65 [0.5–4.32] versus 0.54 [0.51–0.61] pg/dl; p = 0.008). The level of IL-6 after synacthen administration was not significantly different between both groups. The level of IL-1 at baseline and at 15–60 min during septic shock was not significantly different between both groups. At 30 and 60 min after synacthen administration, the level of IL-1 was similar in both groups (16.03 [11.56–590.82] versus 14.21 [10.57–31.24] and 20.35 [11.97–741.37] versus 15.83 [8.3–68.63] pg/dl). The TNF-α level at 15 min during septic shock in the RAI group had a p-value of 0.002 when compared with the non-RAI group. The level of TNF-α at 30 min had a p-value of 0.007 when compared with the non-RAI group. The MIF level during septic shock in the RAI group compared with the non-RAI group showed a p-value of 0.003. After the corticotropin stimulation test, the level of MIF at 30 and 60 min in the RAI group was also similar compared with the non-RAI group (12.46 [8.03–23.32] versus 15.96 [7.7–19.88] and 11.12 [8.07–20.79] versus 15.41 [7.29–22.12] ng/dl).

Correlation of IL-1, IL-6, TNF-α, and MIF with ACTH and cortisol

IL-6 levels were positively correlated with ACTH levels at 60 min (p = 0.002, r = 0.662) but did not correlate with ACTH prior to sepsis induction until 45 min and also after the corticotropin stimulation test. IL-6 was positively correlated with the cortisol level at 15 min (p = 0.008, r = 0.586) and 60 min (p = 0.008, r = 0.590).

IL-1 levels did not significantly increase the ACTH and cortisol levels during septic shock (p = 0.994 and p = 0.258, respectively) and at 60 min after the synacthen test (p = 0.078 and p = 0.912, respectively) but were positively correlated the cortisol level during the sepsis condition (p<0.001, r = 0.728). TNF-α did not significantly increase the ACTH and cortisol levels during septic shock (p = 0.887 and p = 0.545, respectively) and at 60 min after the synacthen test (p = 0.980 and p = 0.124, respectively).

Table 2. Corticotropin stimulation test during septic shock

<table>
<thead>
<tr>
<th>Variable</th>
<th>RAI group, mean (SD) (N = 12)</th>
<th>Non-RAI group, mean (SD) (N = 7)</th>
<th>p*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal cortisol level (µg/dl)</td>
<td>11.25 (6.9)</td>
<td>14.04 (7.18)</td>
<td>0.703</td>
</tr>
<tr>
<td>Cortisol level 30 min (µg/dl)</td>
<td>17.78 (6.72)</td>
<td>28.25 (8.99)</td>
<td>0.014</td>
</tr>
<tr>
<td>Cortisol level 60 min (µg/dl)</td>
<td>18.18 (6.93)</td>
<td>58.03 (48.97)</td>
<td>0.009</td>
</tr>
</tbody>
</table>

RAI=relative adrenal insufficiency; SD=standard deviation
*p<0.05 were considered statistically significant

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The MIF level did not significantly suppress the ACTH level during septic shock ($p = 0.648, r = 0.112$) and 60 min after the synacthen test ($p = 0.096, r = 0.393$). The MIF level was correlated with ACTH during the sepsis condition ($p<0.001, r = 0.736$). MIF levels were inversely correlated with cortisol levels at 60 min after the synacthen stimulation test ($p = 0.042, r = -0.471$).

**Histopathological examination**

Histopathological examination showed inflammatory cell infiltration and hemorrhage in the adrenal gland in both the RAI and non-RAI groups, which indicated that the inflammatory process played a role in septic shock. Inflammatory cell infiltration was also observed in the hypothalamus and the pituitary glands in both groups. Immunohistochemical staining of the RAI group revealed that only the hypothalamus was positive for IL-1, IL-6, TNF-α, and MIF, indicating that the ongoing inflammatory process resulted in a relatively temporary adrenal insufficiency; hence, the lack of IL-1, IL-6, TNF-α, and MIF staining after the monitoring period ended (Figure 2).

**DISCUSSION**

RAI is a condition in which, despite a maximally ACTH-activated adrenal cortex in response to critical illness, the cortisol production is still insufficient in response to general glucocorticoid receptor
activation to maintain hemodynamic stability.¹⁹ In this study, the incidence of RAI was 63% (12/19 piglets). The cortisol level was lower in the RAI group compared with the non-RAI group during septic shock. After the corticotropin stimulation test, the cortisol levels in the RAI group were also lower compared with the non-RAI group. These results showed that in the RAI group, the cortisol levels were insufficient to maintain hemodynamic stability. Our result was similar to a study by Singh et al in pediatric subjects, which reported the incidence of RAI as 40–65%. Meanwhile, Menon et al¹⁵ found 30.2% RAI cases with baseline cortisol levels 28.6 µg/dl. The difference of lower incidence of RAI, might be due to use of a lower dose of synacthen (1 µg synacthen). Rady et al⁶ also reported a RAI incidence of 33.3% using the same dose of synacthen in this study. Hebbar et al¹⁷ reported a 50% incidence of RAI. In Cipto Mangunkusumo Hospital, the incidence of RAI in pediatric patients was reported as 20%.¹⁸ These differences from our results may be due to different responses in piglets compared with humans and the time taken to perform the corticosteroid stimulation test. In this study septic shock was managed by administering fluid resuscitation, and inotropic drugs. Hydrocortisone was also given to overcome RAI.

Cortisol acts as a stimulant of the immune response at low concentrations and a suppressor of the immune response at high concentrations.¹⁹ The basal levels of cortisol can sensitize cells to harmful stimuli, even in the absence of inflammation, by increasing the expression of cytokine receptors, pattern recognition receptors, and complement factors.¹⁹ In this study, the cortisol levels in both groups were low from the 15th to the 30th min, which might be required to stimulate an immune response.

Systemic inflammation may cause a breakdown of the blood–brain barrier (BBB), facilitating the traffic of blood-borne cytokines to deep brain structures. In an animal study, the peripheral administration of endotoxin resulted in the expression of IL-1 and TNF-α.²⁰ In patients with septic shock, postmortem examination suggested overexpression of IL-1 and TNF-α in the hypothalamic nuclei.²⁰ In our study, the IL-1 levels during septic shock were similar in both groups after endotoxin administration as well as after the corticotropin stimulation test. In both groups, the IL-1 increase was followed a cortisol increase, although the cortisol levels in the RAI group were higher than in the non-RAI group. In the sepsis condition, the IL-1 level was correlated with the cortisol level (p<0.001, r = 0.728), indicating that IL-1 played a role in increasing cortisol levels, which was attributed to activation of the HPA axis. IL-1 and TNF-α act synergistically to induce a shock-like state characterized by vascular permeability, severe pulmonary edema, and hemorrhage.²¹ IL-1 was also identified as mediator for the development of fever.²¹ In our study, IL-1 levels increased in the 30th min in the RAI and non-RAI groups, and IL-1 levels were correlated with the cortisol levels in the sepsis condition. Based on this result, IL-1 was involved in stimulating cortisol production, which, in turn, could stimulate immune and inflammation responses, which is needed in the
sepsis condition. In our study, IL-1 levels decreased after the corticotropin stimulation test so that the inflammatory response was not excessive. IL-1 could also indirectly increase the cortisol level due to IL-6 production. Our immunohistochemical investigations showed IL-1 in the hypothalamic region, which proved that IL-1 played a role in activating the HPA axis to release corticotropin-releasing hormone (CRH) and vasopressin from the hypothalamus.

IL-6 is also an activator of the HPA axis. This inflammatory mediator can reach the portal circulation in the median eminence, located outside the BBB, via the anterior hypothalamic arteries.¹³ In our study, IL-6 was correlated with ACTH at the 60th min, which indicated that IL-6 played a role in stimulating the HPA axis. IL-6 was also correlated with cortisol at the 60th min, which indicated that IL-6 also stimulated cortisol production by increasing ACTH production. Furthermore, the IL-6 level in the RAI group was higher than in the non-RAI group from the 15–60th min, which showed that IL-6 acted as a stimulator of inflammation from the beginning. However, a significant difference was observed between the RAI group and the non-RAI group at the 45th min which was related to the immune response to eliminate the endotoxin. The increased IL-6 level also showed that it played a role in inducing cortisol production so that an excessive response to inflammation did not occur. Matsumoto et al²² found that IL-6 on day-2 and -4 in the critically ill patients was significantly increased compared to those in the non-critically ill patients. IL-6 serves as an important mediator during the acute phase of response to inflammation in sepsis. Song et al²³ found that IL-6 could discriminate sepsis from control with cut-off value 52.60 pg/ml, 80.4% sensitivity, and 88.9% specificity. Karrow et al²⁴ showed that the LPS level could induce a peak cortisol level in 2 hours and a peak IL-6 level in 1 hour. Our immunohistochemical investigations found IL-6 in the hypothalamus, which proved that IL-6 might play a role in hypothalamic stimulation.

The proinflammatory cytokine TNF-α also contributes to activating the HPA axis. TNF-α overexpression in hypothalamic nuclei has been reported in postmortem examinations in patients with septic shock.¹⁵,²⁰ In our study, immunohistochemical staining showed that TNF-α was found in the hypothalamic region, proving that TNF-α was involved in stimulating the hypothalamic region. Animal experiments have suggested that TNF-α-induced release of corticosterone is a CRH-dependent mechanism.²⁰ TNF-α is also produced in adrenal tissues by resident macrophages and adrenocortical cells.²⁰ The presence within the adrenals of TNF-α and its receptors in the adrenal glands suggests that this cytokine plays a role in adrenal function in stimulatory steroidogenesis.²⁰ In our study, there was no correlation between TNF-α and both cortisol and ACTH, indicating that cortisol production occurred indirectly by stimulating the hypothalamic region. Cortisol production in the early stages of inflammation can be increased due to an increase of IL-1.²³ Our study found that TNF-α was higher from the 15–30th min during septic shock in the RAI group than in the non-RAI group. The release of TNF-α from macrophages begins within 30 min after the inciting event, following gene transcription and RNA translation.²⁵ In our study, the TNF-α levels in the non-RAI group were increased after the 15th min during septic shock and decreased after septic shock.

MIF was initially described as a T lymphocyte product that inhibited the random migration of macrophages.⁷ MIF functions as corticosteroid contraregulator and modulates immune responses and inflammation.⁷,²⁵ A low level of corticosteroids can induce MIF release, which reduces immune suppression and the anti-inflammatory effects of glucocorticoids.⁷ In our study, MIF levels were found to correlate with ACTH levels in the sepsis condition, leading to the production of ACTH in the pituitary gland, which stimulated cortisol production.⁷ We also found that MIF levels were correlated with cortisol levels at the 60th min after corticotropin injection, indicating that MIF functioned as a corticosteroid contraregulator, maintaining them at lower concentrations so that cortisol could exert its anti-inflammatory effects. We observed higher MIF levels in the RAI group, indicating macrophage accumulation at the inflammation site. In our study, the MIF levels in the RAI group were higher than in the non-RAI group in septic shock condition. An exaggerated early-phase response, which occurs due to the expression of proinflammatory mediators, can lead to early mortality as a result of shock.²⁵ This can be indicated by increased levels of MIF, which acts as a key mediator of the systemic inflammatory response and is a predictive factor of early death from severe sepsis.²⁵
The role of IL-1, IL-6, TNF-α, and MIF in inflammation and cortisol production in the RAI group can be seen in Figure 1. In this group, IL-1 increased to stimulate IL-6, in the beginning to the 15th min. TNF-α levels also increased in the 15th min as proinflammatory mediator. The higher concentration of TNF-α in the RAI group compared with the non-RAI suppressed cortisol production. After 15 min, IL-6 concentration levels decreased in RAI group compared with the non-RAI group. The IL-1 levels continued to increase, which stimulated cortisol production. The cortisol levels from the 30-60th min were higher compared with the ACTH levels. A low plasma ACTH in the presence of high plasma cortisol concentrations has been interpreted as non-ACTH driven cortisol production, in which cytokines could play a role.³ The increased availability of systemic cortisol during critical illness seems to be largely driven by decreased cortisol breakdown in the liver and kidneys.¹⁹ In the septic shock conditions in our study, MIF levels were increased so that plenty of inflammatory cells would become concentrated at the inflammatory site. After the corticotropin stimulation test, cortisol levels were not increased, showing that the adrenal gland was no longer capable of cortisol production. The levels of TNF-α also contributed to the suppression of cortisol production and prolonging the septic shock condition. The ACTH levels were relatively stable from the onset of sepsis until the septic shock condition in the RAI group. In this case, the proinflammatory cytokines might have played a lesser role in hypothalamic stimulation or other cytokines could have been involved in suppressing ACTH levels.²⁰

In conclusion, the levels of IL-1, IL-6, TNF-α, and MIF in inflammation, cortisol, and ACTH production in the RAI and non-RAI group is shown in Figure 1. In this group, IL-1 levels also increased to stimulate IL-6, which subsequently stimulated TNF-α production. The IL-6 increase also stimulated cortisol production to prevent an overt inflammation reaction. In the 15th min, IL-1 decreased in the non-RAI group, which showed that the stimulatory effect of IL-1 was less prominent in the 15th min. Cortisol levels increased after septic shock, indicating its anti-inflammatory role. In the 30th min, IL-6 levels decreased to prevent an overt inflammation reaction. The IL-6 levels increased again after the 30th min, and TNF-α levels decreased after septic shock so that cortisol could assert its anti-inflammatory role. MIF levels also increased after the 60th min, resulting in an accumulation of inflammatory cells. In our study, IL-6 mainly increased in the RAI group.

RAI occurs when the degree of HPA axis activation is assumed to be insufficient to cover cortisol requirements for survival, even when plasma cortisol levels are higher than under healthy conditions. Hypotension refractory to fluid resuscitation and vasopressors may be signs of RAI.³⁴-⁵³ Diagnostic criteria for RAI is based on an increased cortisol increment response of <9 µg/dl after the injection of 250 µg ACTH.⁸ The corticotropin stimulation test is sometimes difficult to perform due to the extremely rare availability of synthetic ACTH. Thus, other parameters are required to diagnose RAI. The differences in cytokines between RAI and non-RAI that we observed in our study should be considered as potential biomarkers of RAI or as indicators of the risk of RAI.

Our study has several limitations. Before undertaking this study, we conducted a preliminary study to assess normal vital signs in piglets during sepsis until septic shock. We also assessed CI, intrathoracic blood volume index, and extravascular lung water index to determine the septic shock condition. This was the first time that our procedure was conducted in the animal laboratory used in our study. The other problems encountered included difficulties in inserting the PICCO catheter and central venous catheter because they were not designed for piglets, sedation problems with the piglets, and hypoglycemia due to fasting before the procedure. Our study was conducted in piglets, which might not be similar to humans. This study was also an experimental study, and a different study design is necessary to conduct similar research in humans. Further research needs to be conducted to determine the MIF cut-off point that can cause RAI.

In conclusion, the levels of IL-1, IL-6, and TNF-α were similar during septic shock. The TNF-α level in our piglet model of septic shock with RAI was increased at the 15th and 30th min. The MIF level in the piglet model of septic shock with RAI was significantly increased during septic shock. The IL-6 level in the piglet model of septic shock with RAI was higher at the 45th min. Immunohistochemistry revealed that IL-1, IL-6, TNF-α, and MIF were only positive in the hypothalamus from the piglet model of septic shock with RAI. Hydrocortisone treatment can be given earlier, based
on IL-6, TNF-α, and MIF levels in pediatric patients with septic shock. Cytokines IL-6, TNF-α, and MIF could be used as predictors of the incidence of RAI in septic shock.

Conflict of Interest
José R. L. Batubara is the business manager but was not involved in the review or decision process for the article.

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