Different effects of endotoxic shock on the respiratory function of liver and heart mitochondria in rats

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Kozlov, Andrey V., Katrin Staniek, Susanne Haindl, Christina Piskernik, Wolfgang Ohlinger, Lars Gille, Hans Nohl, Soheyl Bahrami, and Heinz Redl. Different effects of endotoxic shock on the respiratory function of liver and heart mitochondria in rats. Am J Physiol Gastrointest Liver Physiol 290: G543–G549, 2006; doi:10.1152/ajpgi.00331.2005.—This study was designed to clarify whether mitochondrial function/dysfunction and reactive oxygen species (ROS) production have a temporal relationship with organ failure during endotoxic shock. Adult male Sprague-Dawley rats were divided into three groups receiving 1) isotonic saline (control group, n = 16); 2) 8 mg/kg lipopolysaccharide (LPS; n = 8); or 3) 20 mg/kg LPS (n = 8) intraperitoneally under short anesthesia with 3.5% of isoflurane. After 16 h, animals were killed to analyze plasma, rat liver mitochondria (RLM), and rat heart mitochondria (RHM). In accordance with plasma analysis, LPS-treated rats were divided into “responders” and “nonresponders” with high and low levels of alanine aminotransferase and creatine, respectively. RHM from responders had significantly lower respiratory activity in state 3, suggesting a decreased rate of ATP synthesis. In contrast, RLM from responders had significantly higher respiratory activity in state 3 than both nonresponders and the control group. This increase was accompanied by a decrease in phosphate-to-oxygen ratio values, which was not observed in RHM. ROS generation determined with a spin probe, 1-hydroxy-3-carboxypyrrolidine, neither revealed a difference in RHM between LPS and control groups nor between responders and nonresponders. Our data demonstrate that 1) RHM and RLM respond to endotoxic shock in a different manner, decreasing and increasing respiratory activity, respectively, and 2) there is a temporal relationship between ROS production in RLM (but not in RHM) and tissue damage in rats subjected to LPS shock.

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There is ample evidence suggesting that ROS are produced in excess during sepsis and that they are involved in cellular damage within vital organs (5, 22, 23, 31). These conclusions have mainly been drawn from the imbalance of antioxidant enzyme activities (22) during sepsis and the beneficial effects of antioxidants (23). Only one group (31) has attempted to directly confirm the increase in ROS in liver mitochondria by measuring \( \text{H}_2\text{O}_2 \), a direct product of \( \text{O}_2^- \) dismutation, and \( \cdot \text{OH} \), a product of the interaction between \( \text{H}_2\text{O}_2 \) and iron ions (31). However, they have not shown a connection between mitochondrial function and organ failure. Whether radical production is elevated only in liver mitochondria or in other organs as well remains unclear.

Another point that has not yet been addressed is the underlying mechanism of increased free radical production. It has been suggested that mitochondrial electron transport is inhibited during the acute phase of sepsis, thereby contributing to inefficient oxygen utilization and the attendant increase in ROS production (5). Another hypothesis recently published suggests that organ failure is a potentially protective, reactive mechanism involving an activation of mitochondrial metabolism (26). In contrast to the previous study, the latter suggests that an increase in ROS production could be due to increased mitochondrial electron flow, reflected by increased mitochondrial transmembrane potential (17, 18).

Our recent study (15) demonstrated an increase in ROS levels in vivo during endotoxic shock in rats. This increase was significant only in 3 of 10 tissues: those of the heart, liver, and lung (15). These data suggest that mitochondrial ROS formation contributes to increased ROS levels in the heart, liver, and lung. However, the pathophysiological role of increased mitochondrial ROS production remains unclear.

The aim of this study was to clarify whether heart and liver mitochondria respond to endotoxic shock in a similar manner and, if so, whether these changes coincide with tissue damage.

MATERIALS AND METHODS

Animals. The study was approved by the local Committee on Animal Experiments of Vienna, Austria, and all experiments were performed under conditions described in the National Institutes of Health Guide for the Care and Use of Laboratory Animals (NIH Pub. No. 86-23, Revised 1985). Adult male Sprague-Dawley rats weighing 280 ± 21 g (Animal Research Laboratories, Himberg, Austria) were divided into three groups: a control group receiving saline intraperitoneally (n = 16), a group receiving 8 mg lipopolysaccharide (LPS)/kg ip (E. coli 026:B6, n = 8, Difco; Detroit, MI), and a group receiving 20 mg LPS/kg ip (n = 8). One control and one LPS-treated rat were killed per experimental day 16 h after the intraperitoneal injection, and blood was collected in heparinized tubes for biochemical analysis. The liver and heart were quickly extracted and stored in ice-cold preparation buffer.

Histological investigation. Liver tissue was fixed in 10% formaldehyde solution for 1–2 wk. The paraffin blocks and later sections were prepared. Sections were stained with hematoxylin and eosin. Blood parameters. Plasma levels of alanine aminotransferase (ALT) and creatinine were measured as described previously (10). Briefly, 1 ml of heparinized blood (10 IU/ml) was centrifuged at 1,000 g for 10 min, and plasma was frozen until use. ALT and creatinine were analyzed with a Cobas Fara analyzer using reagents from Roche Diagnostic.

Statistics. All data are presented as means ± SE. Statistical analysis was performed by one-way ANOVA followed by a post hoc test for the least-significant difference. Significance was based on a value of \( P < 0.05 \). Calculations were made with SPSS 11.5 software for Windows (SPSS) and MS Excel (Microsoft).

RESULTS

Organ damage. On the basis of the plasma levels of ALT and creatinine, individual responses of rats subjected to LPS-induced endotoxic shock showed a strong variation. Therefore, rats receiving LPS were divided in two groups in accordance with plasma ALT and creatinine (Fig. 1) but not in accordance with the LPS dose administered. The highest plasma concen-
tration of ALT in the control group (93 IU/l) was set as the limiting value for LPS-treated rats, defining “nonresponders” as ALT < 93 IU/l (LPS1 group) and “responders” as ALT > 93 IU/l (LPS2 group). Consequently, both LPS groups received endotoxin, but only the LPS2 group responded with organ damage. After this redistribution, the LPS1 group included five animals treated with 8 mg LPS/kg and one animal treated with 20 mg LPS/kg, whereas the LPS2 group included seven animals treated with 20 mg LPS/kg and three animals treated with 8 mg LPS/kg.

Histological examination of the liver. Plasma levels of ALT and creatinine were in accordance with histological findings. Focal necroses were found in responders only. Cellular infiltration was found in both the LPS1 and LPS2 groups (Fig. 2). All other histological parameters were similar in all three groups.

Function of RHM. Four parameters [oxygen consumption in state 4 and 3, the phosphate-to-oxygen ratio (P/O), and ROS generation] were compared in RHM obtained from the three groups. In the presence of glutamate/malate, oxygen consumption in state 3 respiration was lower in RHM from the LPS2 group compared with the control group (Fig. 3). In contrast, respiratory parameters of succinate-respiring RHM were not significantly influenced by LPS treatment. There was no difference between responders (LPS2) and nonresponders (LPS1) independently of the substrates used for respiration. Furthermore, there was no difference in ROS generation in RHM between the three groups (Fig. 3).

Function of RLM. In contrast to RHM, liver mitochondria isolated from LPS-treated rats showed an increase in state 3 respiration with both succinate and glutamate/malate (Fig. 4). At the same time, P/O values were decreased in responders (LPS2; Fig. 4). Oxygen consumption rates in state 4 respiration were neither influenced by LPS treatment in RLM (Fig. 4) nor in RHM (Fig. 3). ROS generation in RLM was increased in the LPS2 group but not in the LPS1 group compared with the control group.
A particularly high difference in ROS levels was observed when glutamate/malate was used as the substrate (Fig. 4).

**Mitochondrial content in preparations.** To prove whether the composition of mitochondrial preparations was affected by LPS or not, the contents of the four most important carriers of the respiratory chain (cytochromes $a$, $b$, $c$, and $c_1$) were compared between mitochondrial preparations in the three groups studied. No significant difference was found among the

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**Fig. 3.** Respiratory parameters of rat heart mitochondria isolated from the control, LPS1, and LPS2 groups. **A:** oxygen uptake in state 4; **B:** oxygen uptake in state 3; **C:** inorganic phosphate-to-oxygen ratio ($P/O$) values; **D:** ROS generation. All parameters were determined with glutamate/malate, substrates of complex I, and succinate, a substrate of complex II. #$$P < 0.01$$ compared with the control group.

**Fig. 4.** Respiratory parameters of rat liver mitochondria (RLM) isolated from the control, LPS1, and LPS2 groups. **A:** oxygen uptake in state 4; **B:** oxygen uptake in state 3; **C:** $P/O$ values; **D:** ROS generation. All parameters were determined with glutamate/malate, substrates of complex I, and succinate, a substrate of complex II. #$$P < 0.05$$, $$P < 0.01$$, and $$P < 0.001$$ compared with the control group; *$$P < 0.05$$ and **$$P < 0.01$$, compared with the LPS group.
is likely that there is a ROS-independent mechanism affecting mitochondrial function in RHM.

Respiration versus ROS in RLM. In contrast to RHM, RLM had a significantly increased respiration rate in state 3 in the LPS2 group with both glutamate/malate or succinate. Unexpectedly, increased state 3 respiration was accompanied by decreased P/O values, indicating that the efficiency of oxidative phosphorylation was reduced. Although the exact mechanism remains unclear at this point, there are two possible explanations for this phenomenon: 1) an increase in state 3 respiration and a decrease in P/O are coming from two different populations of mitochondria or 2) there is an additional mechanism of oxygen consumption not related to ATP synthesis in state 3.

Mitochondrial ROS generation was measured to find out whether increased oxygen consumption could be attributed to excessive ROS production. ROS production was significantly increased in glutamate/malate-respiring RLM as well as in succinate-respiring RLM isolated from LPS-treated rats with severe organ damage compared with control rats. This increase in ROS levels is probably not due to a decrease in the antioxidant capacity of mitochondria, because previous reports have shown an increase in SOD activity in liver tissue (2), and particularly in Mn-SOD typical for mitochondria (12, 16), in response to endotoxic shock.

In highly coupled mitochondria, the leakage of protons through the inner mitochondrial membrane is relatively small, so that a high transmembrane potential can be established. An increase in transmembrane potential in mitochondria has been shown to cause increased ROS production (17, 18), indicating that part of the electrons deviates from the respiratory chain to cause a one-electron reduction of oxygen, yielding ROS instead of participating in ATP synthesis.

A possible explanation as to why mitochondria isolated from LPS-treated animals have increased ROS production simultaneously with increased respiratory activity comes from studies (17, 18) demonstrating that an increase in transmembrane potential in mitochondria results in an increase of ROS production. A recent study by Starkov and Fiskum (28) suggests that ROS production by mitochondria oxidizing physiological NADH-dependent substrates is regulated by membrane potential. Therefore, mitochondria having higher respiratory activity are expected to have higher membrane potential and consequently higher ROS production. On the one hand, this supports our data, because we found the highest increase in ROS generation with glutamate/malate, a NADH-dependent substrate. On the other hand, the data presented in Fig. 4 show that there is no temporal relationship between the increased respiration rate in state 3 and ROS production in the LPS1 group. Therefore, the exact mechanism leading to increased ROS formation still needs to be clarified.

Independently of the mechanism leading to increased ROS formation in RLM, we clearly found a temporal relationship between increased mitochondrial ROS production and liver damage. This finding suggests the involvement of mitochondrial ROS generation in endotoxin-induced liver damage.

Recently, Suliman and co-workers (29) disclosed a new aspect of ROS in endotoxic shock. They demonstrated a duality of ROS effect in the cardiac response to LPS in which oxidative mitochondrial damage is opposed by oxidant-in-
duced stimulation of biogenesis in terms of mitochondrial DNA recovery (29).

Molecular mechanisms underlying endotoxin-induced changes in RLM. The changes observed in RLM can result from decreased liver perfusion and consequent hypoxia, as reflected by our model (10), or from partial inhibition of respiration by ROS and reactive nitrogen species (3). An important issue is whether the changes in mitochondrial respiration are the result or cause of free radical generation. Many authors have reported that free radical attack results in damage of mitochondrial membranes accompanied by leakage of protons (uncoupling), increased oxygen consumption in state 4, and decreasing efficiency of ATP synthesis. In contrast to those authors, we found that the state 4 respiration was not affected and the rates in state 3 were even higher than in control rats. Thus the changes we found in liver mitochondria are probably not the result of free radical attack. Our data are in line with a hypothesis recently published by Singer et al. (26), suggesting that the changes in mitochondria are primarily a defense reaction similar to that induced by thyroid hormones. It has also been suggested (by Singer et al. and others) that mitochondria respond to endotoxemia in a biphasic manner, with an initial increase in respiration followed by a decline. The duration of both phases has not yet been clarified, particularly for our model. In accordance with Singer et al.’s hypothesis, we observed the first phase in our experiments, whereas a decline in mitochondrial function (second phase) appears to cause death quickly and cannot be easily detected. These different phases of endotoxic shock may explain the controversial results obtained from different mitochondrial studies, ranging from impaired (6, 7) to unchanged (11, 31) and even to improved mitochondrial function (32).

There is also another explanation for the stimulation of high respiratory activity of mitochondria by endotoxin. It is possible that 16 h are sufficient to account for removal of malfunctioning mitochondria (i.e., autophagy) and cells (necrosis or apoptosis), such that the most damaged mitochondria are cleared from the organs or even that new mitochondria are produced soon after LPS treatment (29).

Purity of RLM. The changes in parameters normalized to protein concentration described above, e.g., state 4, state 3, and ROS generation, could be due to LPS-induced modification in the composition of mitochondrial preparation. Because oxygen consumption and ROS formation originates from the inner mitochondrial membrane, levels of the most important carriers of the respiratory chain (cytochromes a, b, c, and c1) were determined. Because no difference was found among the groups studied, the changes in mitochondrial parameters are related to their affected function and not to a modified composition of mitochondrial preparations.

In our study, we focused on the function of the main mitochondrial fraction. There is another mitochondrial fraction, however, the so-called light mitochondrial fraction, which has been found to behave differently in apoptotic muscle (34). We did not study this light fraction because it is strongly contaminated by peroxisomes and lysosomes, particularly in the liver. However, we performed preliminary experiments in the liver homogenate and in mitochondria separated from the same liver homogenate and did not find a significant difference in P/O values and respiratory control, a ratio between oxygen consumption in state 3 to state 4 (data not presented).

In summary, our data demonstrate that 1) RHM and RLM respond to endotoxic shock differently, decreasing and increasing respiratory activity, respectively; and 2) there is a temporal relationship between ROS production in RLM (but not in RHM) and tissue damage in rats subjected to LPS shock.

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REFERENCES


