Diaphragm and cardiac mitochondrial creatine kinases are impaired in sepsis

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Callahan LA, Supinski GS. Diaphragm and cardiac mitochondrial creatine kinases are impaired in sepsis. J Appl Physiol 102: 44–53, 2007—Previous studies indicate that ATP formation by the electron transport chain is impaired in sepsis. However, it is not known whether sepsis affects the mitochondrial ATP transport system. We hypothesized that sepsis inactivates the mitochondrial creatine kinase (MtCK)-high energy phosphate transport system. To examine this issue, we assessed the effects of endotoxin administration on mitochondrial membrane-bound creatine kinase, an important trans-mitochondrial ATP transport system. Diaphragms and hearts were isolated from control (n = 12) and endotoxin-treated (8 mg·kg⁻¹·day⁻¹; n = 13) rats after pentobarbital anesthesia. We isolated mitochondria using techniques that allow evaluation of the functional coupling of mitochondrial creatine kinase MtCK activity to oxidative phosphorylation. MtCK functional activity was established by 1) determining ATP/creatine-stimulated oxygen consumption and 2) assessing total creatine kinase activity in mitochondria using an enzyme-linked assay. We examined MtCK protein content using Western blots. Endotoxin markedly reduced diaphragm and cardiac MtCK activity, as determined both by ATP/creatine-stimulated oxygen consumption and by the enzyme-linked assay (e.g., ATP/creatine-stimulated mitochondrial respiration was 173.8 ± 7.3, 60.5 ± 9.3, 210.7 ± 18.9, was 67.9 ± 7.3 nanomols O₂·min⁻¹·mg⁻¹ in diaphragm control, diaphragm septic, cardiac control, and cardiac septic samples, respectively; P < 0.001 for each tissue comparison). Endotoxin also reduced diaphragm and cardiac MtCK protein levels (e.g., protein levels declined by 39.5% in diaphragm mitochondria and by 44.2% in cardiac mitochondria; P < 0.001 and P = 0.009, respectively, comparing sepsis to control conditions). Our data indicate that endotoxin markedly impairs the MtCK-ATP transporter system; this phenomenon may have significant effects on diaphragm and cardiac function.

ATP/creatine stimulated respiration; mitochondrial creatine kinase activity; endotoxin; heart; respiratory muscles

Despite the utilization of increasingly sophisticated and potent antibiotic and adjunctive therapies, sepsis remains a leading cause of death (20). In many cases, the organ failure that accompanies this syndrome is the result of the direct and indirect damage to parenchymal organs by host defenses rather than to the direct effects of the infecting agents (11). Recent studies suggest, moreover, that sepsis-induced alterations in mitochondrial function play an important role in the genesis of the tissue injury seen in this syndrome (3–6, 8, 11, 16, 25, 29). There are several mechanisms by which mitochondria have been postulated to contribute to tissue dysfunction in sepsis, including 1) mitochondrial generation of toxic substances, i.e., free radical species, that can damage cell organelles directly (by reaction with cellular constituents) and indirectly (by activating signaling pathways) (3, 5, 29); 2) triggering of mitochondrial-dependent pathways of cellular apoptosis (2); and 3) reduction in cellular high-energy compound stores due to impairment of mitochondrial metabolic pathways (3–5).

The majority of the published reports that have examined mitochondrial dysfunction in sepsis have focused on the role of sepsis-induced alterations in one or more properties of the electron transport chain (3, 5, 8, 29). Inhibition of electron flow through the transport chain (5, 6, 8, 29, 30) and uncoupling of electron transport from ATP synthesis have been described in sepsis (3); both defects act to reduce ATP generation. However, these previous studies have largely ignored one important aspect of mitochondrial function that is vital for optimum cellular performance in several key organs. Once synthesized, ATP cannot directly cross the inner mitochondrial membrane but must be transported by means of an enzyme-linked carrier system. In most tissues, the adenine nucleotide transporter system is the principal means by which ATP is transported from the matrix space to the intermembrane space and from there through outer mitochondrial voltage-dependent anion channels (VDAC or porin) to the cytosol (13). On the other hand, in organs or cells that require extremely high rates of trans-mitochondrial ATP transport (the brain, the heart, skeletal muscle, kidney, and spermatozoa), a mitochondrially based creatine kinase isoenzyme provides the major means of ATP transport (15). There are two tissue-specific mitochondrial creatine kinase (MtCK) isoenzymes: 1) sarcomeric MtCK, which is present in striated muscle, and 2) ubiquitous MtCK, which is present in most other tissues or cells such as the kidney, brain, and spermatozoa.

Of note, MtCK can be easily inactivated by free radicals (reactive oxygen species), with a more than 10-fold lower level of susceptibility to in vitro inactivation by reactive oxygen species than components of the electron transport chain (28, 32). Moreover, recent work indicates that mitochondrial free radical generation is increased in sepsis (3, 5). Taking these two observations into account, we postulated that sepsis may be associated with the in vivo inactivation of the MtCK-high energy phosphate transport system. The purpose of the present experiment, therefore, was to test this hypothesis by examining the effect of sepsis on skeletal and cardiac muscle MtCK functional activity and protein content. Studies were performed with a rat model of endotoxin-induced sepsis, and analyses of MtCK were conducted on samples removed from these animals at 48 h after the initial injection of either saline (control animals) or endotoxin (administered as 8 mg·kg⁻¹·day⁻¹ of endotoxin injected intraperitoneally).

Experimental protocols

Experiments were performed with adult male Sprague-Dawley rats (Harlan) weighing between 250 and 350 g. Protocols were approved...
The function of the mitochondrial ATP-creatine kinase shuttle (step 1). ADP generated from this reaction then drives mitochondrial oxygen consumption through the electron transport (ET) chain (step 2). Standard assays of oxygen consumption rates in isolated mitochondria routinely measure ADP-stimulated respiration (step 2) and thereby do not take into account the function of the mitochondrial ATP-creatine kinase shuttle (step 1).

by the Institutional Animal Care and Use Committee. Rats were housed in the Animal Resource Center; food and water were allowed ad libitum. Animals were divided into two groups: 1) control animals injected intraperitoneally with saline (0.5 ml) at time 0 and again at 24 h and 2) animals injected intraperitoneally with endotoxin (8 mg·kg⁻¹·day⁻¹, Escherichia coli lipopolysaccharide; Sigma, St. Louis, MO) at time 0 and at 24 h. All animals were also given subcutaneous doses of saline (60 ml·kg⁻¹·day⁻¹) to prevent dehydration. At 48 h after the first injection of saline or endotoxin, animals were anesthetized with pentobarbital sodium (50 mg/kg ip), a midline abdominal incision was made, and the abdominal aorta was flushed with 60 ml of isolation buffer (0.3 M sucrose, 10 mM HEPES, 2 mM EDTA, pH 7.2 at 4°C). After this, either the diaphragms or hearts were removed and quickly weighed, and mitochondria were isolated as described below. For diaphragm studies, groups consisted of six control animals and six endotoxin-treated animals; for cardiac studies, groups consisted of six control animals and seven endotoxin-treated animals. We used this regimen of endotoxin administration to induce sepsis because in previous studies we found that this (8 mg·kg⁻¹·day⁻¹ of endotoxin for 48 h) reproducibly elicits severe reductions in mitochondrial ATP generation (5, 6).

**Mitochondrial isolation.** After removal, tissues were rinsed, placed in ice-cold isolation buffer (1:10 wt/vol), finely minced, and homogenized with a Polytron set to one-half speed for 10 s. An aliquot of the total homogenate was reserved for measurement of MtCK. Homogenates were centrifuged at 1,000 g for 10 min at 4°C. The resulting supernatant was centrifuged at 8,000 g for 15 min at 4°C. An aliquot of the resulting supernatant was reserved for measurement of cytosolic proteins and cytosolic levels of MtCK. The remaining pellet was washed and resuspended in isolation buffer containing 1 mg/ml BSA to a final protein concentration of ~20 mg/ml. Mitochondrial isolates were used for assessment of MtCK functional activity utilizing the two techniques described in the next paragraph, as well as for determination of MtCK protein content utilizing Western blot techniques.

**MtCK functional and activity assays.** MtCK functional activity was evaluated in two ways. First, MtCK activity was assessed by determining the oxygen consumption of isolated mitochondrial suspensions in response to addition of increasing doses of ATP (0–1,000 μM) in the presence or absence of creatine (20 mM) (7). It is important to note that most standard assessments of mitochondrial oxidative phosphorylation routinely utilize ADP to stimulate maximal oxygen consumption; however, this method only assesses oxygen consumption as a function of the electron transport chain and does not consider the activity of the mitochondrial ATP transport system (see Fig. 1). On the other hand, the assay that we employed directly assesses the functional activity of MtCK and its coupling to oxidative phosphorylation. As such, in the absence of MtCK activity, addition of ATP alone or ATP and creatine will elicit no increase in mitochondrial oxygen consumption. However, in the presence of functionally active MtCK, addition of ATP will stimulate oxidative phosphorylation (because of the presence of endogenous levels of creatine within the mitochondrial intermembrane space) with subsequent generation of ADP; the ADP so generated then drives oxidative phosphorylation. Moreover, addition of both ATP and exogenous creatine will further stimulate oxidative phosphorylation because both are substrates for the enzyme (see Fig. 1). Therefore, the magnitude of the increment of oxygen consumption observed with ATP and creatine addition is a function of MtCK activity. For these determinations, mitochondrial samples (200 μg) in buffer (120 mM KCl, 5 mM KH₂PO₄, 5 mM MOPS, 1 mM EDTA, 10 mM pyruvate, 2.5 mM malate, pH 7.25 at 30°C) were placed in a closed chamber containing a Clark-type electrode to assess oxygen consumption rates. Resting oxygen consumption was measured, and oxygen consumption rates were reassessed after addition of various concentrations of ATP (0–1,000 μM). In separate determinations, in which we used additional aliquots of mitochondrial suspensions, oxygen consumption rates were measured in the presence of both ATP and creatine (20 μM).

We also determined the total MtCK activity for mitochondrial samples using an enzyme-linked assay as previously described (22). For this assay, mitochondrial samples were incubated with a mixture containing hexokinase, glucose, and glucose-6-phosphate dehydrogenase. Active creatine kinase will produce NADH, which can be assessed spectrophotometrically by measuring absorbance at 340 nm. We used a spectrophotometer (Shimadzu Scientific Instruments, Columbia, MD) to perform assays, with addition of 20 μl of mitochondria in a 1-ml reaction chamber at a temperature of 25°C. Change in absorbance over time at 340 nm was measured, and the NADH generation rate was determined by use of the millimolar absorbivity of NADH (6, 22). Results were expressed in activity units, with one unit defined as production of one micromole of NADH per minute.

**Western blot analysis of MtCK protein levels.** Dual protein gels were used to perform Western blot analyses for determination of MtCK protein levels in diaphragm and cardiac mitochondrial isolates (12). For each determination, mitochondrial samples were diluted with an equal volume of loading buffer (126 mM Tris-HCl, 20% glycerol, 4% SDS, 1.0% 2-mercaptoethanol, 0.005% bromphenol blue, pH 6.8). Samples were then loaded onto tandem Tris-glycine polyacrylamide gels (12.5 μg of protein/lane), and proteins were separated by electrophoresis (Novex Minicell II, Carlsbad, CA). Proteins from one gel were visualized with Silver Stain Plus (Bio-Rad Laboratories, Hercules, CA), and approximate molecular weights were determined with scan software (SigmaScan Gel, Chicago, IL) and known standard molecular weight markers. Mitochondrial proteins from the second SDS-PAGE gel were then transferred to nitrocellulose membranes. After electroblotting was completed, membranes were washed twice in PBS, blocked for 1.5 h at room temperature in PBS containing 3% BSA and 0.05% Tween 20, and incubated over night at 4°C with a monoclonal anti-sarcomeric MtCK antibody (kindly provided as a gift by Dr. Z. Khachtra, St. Louis, MO) diluted to 1 μg/ml in PBS-BSA. Subsequently, membranes were incubated with anti-mouse horseradish peroxidase-conjugated IgG (1:2,000 for 1.5 h at room temperature. Antibody binding to proteins was detected by enhanced chemiluminescence (NEN Life Science Products, Boston, MA). Gel densitometry was performed with a Microtek scanner (Carson, CA) and Un-Scan-IT software (Silk Scientific, Orem, UT).

Additional Western blot analyses of mitochondrial protein and cytosolic protein content were performed to exclude the possibility that sepsis-induced alterations in MtCK were either caused by 1) a generalized reduction in mitochondrial protein content or 2) leakage of the protein from damaged or swollen mitochondria. To accomplish this, we utilized similar techniques as described above. Specifically, we evaluated
protein levels of complex I subunit NDUFS3 and complex IV subunit 1 (COX-1) in diaphragm and cardiac mitochondrial isolates using anti-mouse monoclonal antibodies (MitoScience, Eugene, OR). To determine the distribution of MtCK, we compared protein levels in total homogenates, mitochondrial fractions, and cytosolic fractions of diaphragm and cardiac samples from control and endotoxin-treated animals. We also assessed cytosolic MM creatine kinase protein content in cytosolic fractions of muscle homogenates from the diaphragms and hearts of control and septic animals to establish whether endotoxin administration produced alterations in this critical component of the phosphocreatine shuttle (actin levels served as a loading control).

Electron microscopy. Mitochondrial integrity was assessed by evaluation of tissue sections from the diaphragms and hearts of control and endotoxin-treated animals. Muscle samples were fixed in 2% paraformaldehyde-2% glutaraldehyde in 0.1 M cacodylate buffer in sucrose and postfixed for 1 h with osmium tetroxide. Processing and embedding of tissue in Epon 812 (EM-bed)-Araldite-502 (Electron Microscopy Sciences, Fort Washington, PA) were performed according to previously published techniques (17).

Statistical analyses. Oxygen consumption for mitochondrial isolates was plotted as a function of the level of added ATP. Separate plots were made for samples assayed with and without added creatine (20 mM). Comparison of oxygen consumption values between control and septic (i.e., endotoxin-treated) animals was accomplished by ANOVA. Unpaired t-tests were used to compare total MtCK activity, mitochondrial protein levels of sarcomeric creatine kinase, complex I subunit NDUFS3, complex IV subunit 1 (COX-1), and cytosolic protein levels of MtCK, MM creatine kinase, and actin between control and endotoxin-treated groups (SigmaStat software, Chicago, IL). Data are expressed as means ± SE; a P value of <0.05 was taken as indicating statistical significance.

RESULTS

Mitochondrial function. Addition of ATP to diaphragm mitochondrial isolates from control animals resulted in a large increase in oxygen consumption (Fig. 2, top). Respiration rates increased to $133 ± 6$ natoms O$_2$/min/g protein in response to high levels of ATP (i.e., ATP concentrations of 1,000 μM) in

![Fig. 2. Diaphragm mitochondrial oxygen consumption for samples from control (top) and endotoxin-treated septic animals (bottom) (n = 6 animals/group). Curves represent oxygen consumption as a function of addition of increasing concentrations of ATP in the presence and absence of creatine. Samples from control animals demonstrated a large increase in oxygen consumption in response to increasing concentrations of ATP and incrementally increased with the addition of creatine. In contrast, samples from endotoxin-treated animals demonstrated a markedly reduced response to increasing ATP concentrations and virtually no increment in oxygen consumption in response to addition of ATP + creatine. Data are presented as means ± SE.](http://jap.physiology.org/)

![Fig. 3. Cardiac mitochondrial oxygen consumption for samples from control (top) and endotoxin-treated animals (bottom). Samples from control animals (n = 6) demonstrated a large increase in oxygen consumption in response to increasing ATP concentrations and a further increment in response to addition of creatine, whereas samples from endotoxin-treated animals (n = 7) had little response to either ATP or ATP and creatine.](http://jap.physiology.org/)
ATP + creatine for cardiac mitochondrial samples from control and endotoxin-treated animals compared with control animals.  

**MtCK activity assays.** We also assessed activity levels of MtCK for mitochondrial isolates using the commonly employed hexokinase/glucose-6-phosphate dehydrogenase-linked enzyme assay. For diaphragm mitochondrial samples, MtCK activity levels were significantly lower in the endotoxin-treated group (P < 0.025 for comparison, Fig. 5). Similar decrements in MtCK activity levels were found for cardiac mitochondrial isolates from endotoxin-treated animals compared with control animals (P = 0.003; Fig. 5).  

**MtCK protein levels.** MtCK protein levels, assessed by Western blotting, were significantly lower for both diaphragm and cardiac mitochondrial samples taken from endotoxin-treated animals than in samples from control animals. A representative blot comparing samples taken from control and endotoxin-treated animals is shown in Fig. 6, top, whereas mean levels for protein concentrations for Western blots, assessed by densitometric analysis, are shown in Fig. 6, bottom. On average, densitometric values for MtCK levels in diaphragm mitochondrial samples from endotoxin-treated animals were 39.5% lower than those from controls (P < 0.001), whereas MtCK protein levels for cardiac mitochondria from endotoxintreated animals were 44.2% lower than isolates from control animals (P = 0.009). Densitometric analysis of concommitantly performed silver-stained protein gels from dia-

![Fig. 4. Maximal oxygen consumption rates of ATP + creatine-stimulated respiration in diaphragm and cardiac mitochondrial samples from control (n = 6) and endotoxin-treated animals (n = 7). Mitochondrial respiration was stimulated by the addition of 1000 µM ATP and 20 mM creatine. Sepsis markedly inhibits ATP + creatine-stimulated respiration in both diaphragm and cardiac mitochondria (*P < 0.001 compared with control conditions for each tissue).](link)

Fig. 4. Maximal oxygen consumption rates of ATP + creatine-stimulated respiration in diaphragm and cardiac mitochondrial samples from control (n = 6) and endotoxin-treated animals (n = 7). Mitochondrial respiration was stimulated by the addition of 1000 µM ATP and 20 mM creatine. Sepsis markedly inhibits ATP + creatine-stimulated respiration in both diaphragm and cardiac mitochondria (*P < 0.001 compared with control conditions for each tissue).

![Fig. 5. MtCK activity in diaphragm and cardiac mitochondrial isolates from control and endotoxin-treated animals as measured using the enzyme-linked assay. Endotoxin markedly reduced MtCK activity in isolated diaphragm and cardiac mitochondria compared with mitochondrial samples from control animals. *Statistically different (P < 0.05).](link)

Fig. 5. MtCK activity in diaphragm and cardiac mitochondrial isolates from control and endotoxin-treated animals as measured using the enzyme-linked assay. Endotoxin markedly reduced MtCK activity in isolated diaphragm and cardiac mitochondria compared with mitochondrial samples from control animals. *Statistically different (P < 0.05).
phragm and cardiac mitochondrial samples indicated that average total protein loads were similar for paired diaphragm samples from control and endotoxin-treated animals and for paired cardiac samples from control and septic animals (Fig. 7). Additional Western blots were performed on diaphragm and cardiac mitochondrial isolates for complex I subunit NDUFS3 and complex IV subunit 1 (COX-1) to exclude the possibility that sepsis produces a widespread depletion of mitochondrial proteins (Fig. 8). We found that levels of NDUFS3 and COX-1 were similar in diaphragm and cardiac samples compared with controls (P < 0.001 and P < 0.009, respectively).

Fig. 6. Top: representative Western blots of Mtk protein levels for diaphragm (left) and cardiac (right) mitochondrial samples from control and endotoxin-treated animals. Bottom: group mean densitometric data demonstrating Mtk levels for diaphragm (left) and cardiac (right) mitochondrial samples from control and septic animals. Endotoxin administration evoked significant reductions in Mtk protein levels for both diaphragm and cardiac samples compared with controls (P < 0.001 and P < 0.009, respectively).

Fig. 7. Representative silver-stained protein gels of diaphragm (left) and cardiac (right) mitochondrial isolates from control and endotoxin-treated animals. Equal amounts of mitochondrial proteins were loaded in each lane. As shown, many mitochondrial proteins show no change in response to endotoxin administration, whereas several proteins appear to increase or decrease in sepsis. These data indicate that sepsis is not associated with generalized depletion of mitochondrial proteins in either the diaphragm or the heart.
mitochondrial isolates from control and endotoxin-treated animals. These data argue that sepsis does not result in depletion of all mitochondrial proteins; rather, it induces selective reduction of several mitochondrial proteins.

To determine whether sepsis induced changes in MtCK content by eliciting leakage from the mitochondrial membranes, we compared MtCK levels in total homogenates and in mitochondrial and cytosolic fractions from diaphragm and cardiac samples in control and septic animals. If MtCK leaked out of the mitochondria, one might expect that cytosolic levels of the protein would increase. As shown in Fig. 9, we found that the cytosolic levels of MtCK in both diaphragm and cardiac samples did not increase in response to endotoxin. These data do not support the possibility that the sepsis-induced alterations in MtCK activity or protein levels are because of leakage from structurally damaged mitochondria.

Finally, we determined whether endotoxin administration also produced alterations in cytosolic MM creatine kinase, the creatine kinase isoform in striated muscle that is responsible for delivery of high-energy phosphates to the myosin ATPase. As demonstrated in Fig. 10, we found no sepsis-induced alterations in cytosolic MM creatine kinase protein levels in diaphragm or cardiac tissues compared with tissues from control animals.

Electron microscopy. We also assessed mitochondrial integrity in diaphragm and cardiac muscle samples using electron microscopy. Representative electron micrographs from the diaphragms and hearts of control and septic animals are shown in Fig. 11. Our results demonstrate, in both diaphragm and cardiac mitochondria, that the cristae appear less densely packed. These findings are consistent with other reports of changes in mitochondrial morphology in sepsis (4, 8). In addition, a recent report by Speer et al. (26) indicates that MtCK is an important structural protein that stabilizes mitochondrial membrane architecture by cross-linking inner and outer mitochondrial membranes at contact sites. Our results,
which demonstrate that MtCK functional activity and protein content are severely altered in sepsis, potentially provide an explanation for the sepsis-induced alterations in mitochondrial ultrastructure, since lack of MtCK would be expected to result in disruption of inner and outer mitochondrial membrane contact sites and destabilization of membrane architecture.

**DISCUSSION**

We found a marked reduction in the ability of creatine to stimulate mitochondrial respiration for diaphragm and cardiac muscle samples taken from endotoxin-treated animals compared with samples from saline-treated controls. Similarly, ATP plus creatine administration to isolated mitochondria, which increases oxygen consumption by linkage to a MtCK-catalyzed reaction, had little stimulatory effect when added to mitochondrial samples from endotoxin-treated animals but produced a large increase in respiration when added to samples from control animals. These findings are consistent with an effect of endotoxin-induced sepsis to markedly reduce MtCK functional activity in the diaphragm and the heart. These sepsis-induced reductions in functional MtCK activity were paralleled by the concomitant finding of sepsis-induced reductions using a conventional enzyme-linked creatine kinase activity assay. We also observed a significant reduction in MtCK protein content in cardiac and diaphragm mitochondrial isolates from endotoxin-treated animals compared with samples from controls, suggesting that the reduced functional capacity of MtCK is due, in part, to a sepsis-induced reduction in protein content.

MtCK. The existence of MtCK was first discovered by Jacobus and Lehninger (15), who recognized that this enzyme was responsible for the often observed effect of creatine to stimulate respiration when added to suspensions of isolated mitochondria. MtCK catalyzes the reaction of creatine with mitochondrial ATP to form phosphocreatine and ADP. The ADP so generated diffuses back to the electron transport chain where this molecule stimulates oxygen consumption, whereas the phosphocreatine produced by this reaction is directed to the adjacent cytosol. MtCK is localized to the outer mitochondrial membrane, enabling this enzyme to effectively facilitate the conversion of mitochondrial ATP to cytosolic phosphocreatine (21, 23). In cardiac and skeletal muscle, this enzyme is situated so that the phosphocreatine produced need only diffuse a short distance to reach the contractile proteins, whereas another creatine kinase isozyme (cytosolic MM creatine kinase) uses phosphocreatine to replenish ATP levels in the vicinity of the myosin ATPase (21, 23). Effectively, these two enzyme systems act together to provide a physiologically and structurally linked enzyme system that can rapidly move high-energy compounds from the site of generation (the mitochondria) to the site of major usage (the contractile proteins). An elegant review describing the functional importance of MtCK and the phosphocreatine shuttle in human health and disease has recently been published by Schlattner et al. (24).

Other work suggests that this enzyme plays a critical role in facilitating rapid restoration of cytosolic phosphocreatine lev-

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**Cytosolic Levels of Actin and MM-Creatine Kinase**

![Fig. 10. Representative Western blots of MM creatine kinase (CK) in cytosolic fractions from diaphragm (left) and cardiac (right) samples from control and septic animals (actin was used as a loading control). Densitometric analyses of cytosolic levels of these proteins (data not shown) were not significantly different between the 2 groups.](image-url)
els in highly metabolic tissues (i.e., the heart, skeletal muscle, and brain) during periods of intense activity. For example, ~90% of the transport of high-energy phosphate compounds out of mitochondria in the active heart is mediated by the activity of this transport system (27). As a result, an impairment of this transport system would be expected to reduce cytosolic phosphocreatine levels and increase free phosphate ion concentrations. Increasing phosphate concentrations, in turn, would be expected to have a direct effect to inhibit contractile protein interactions, reducing muscle force generation and muscle shortening capacity (19).

A number of recent studies have examined the biochemical properties of purified MtCK in vitro. This work shows that the enzyme consists of identical protein chains that associate to form either octamers or dimers; the octamer has been shown to be the most physiologically relevant form of MtCK (28, 32). Exposure of octameric creatine kinase to either nitric oxide or peroxynitrite results in a rapid breakdown of the octameric structure and subsequent inactivation of the enzyme (28, 32). Importantly, irreversible inactivation of this enzyme can occur at extremely low levels of nitric oxide or peroxynitrite exposure (i.e., a 10-fold lower level of peroxynitrite than required to alter electron transport chain function) (28, 32).

In keeping with these in vitro observations, two recent studies found a marked reduction in MtCK activity in the presence of disease processes associated with the generation of high levels of oxidants in tissues. In the first of these studies, MtCK and cytosolic MM creatine kinase activities were reported to decrease in cardiac tissue in an animal model of congestive heart failure (10). In another study, mitochondria isolated from neurons of animals with an experimental model of amyotrophic lateral sclerosis also demonstrated a marked impairment in ubiquitous and cytosolic BB creatine kinase functional activity compared with controls (31).

The present study represents the first evidence that this enzyme system can also be inactivated by an acute disease process, i.e., endotoxin-induced sepsis. Moreover, the magnitude of the reductions in MtCK function observed in the present study appears to be comparable to those observed previously in the heart during heart failure or in neurons after the development of amyotrophic lateral sclerosis (10, 31). Although it is impossible to directly compare the impact that these alterations in enzyme function and content may have on tissue function in these three very dissimilar disease processes, it is nevertheless impressive that sepsis evoked a very sizable reduction in MtCK activity in a very short period of time (48 h).

We should note that the magnitudes of the functional reductions that we found (65% reductions in ATP/creatine stimulation of respiration, 85% reductions in the direct assessment of enzyme function using an enzyme-linked activity assay) were greater than the observed reductions in MtCK content (39–44%), as assessed by Western blotting. This combination of findings would seem to suggest that some of the protein detected by Western blotting may be functionally inactive. Such a possibility would be consistent with the findings of previous in vitro studies (28, 32). We and

Fig. 11. Representative electron micrographs of diaphragm (top, original magnification = ×10,000) and cardiac samples from control (left) and endotoxin-treated (right, original magnification = ×5,000) animals. Mitochondrial density and size are well-preserved after 48 h in this model of endotoxin-induced sepsis, although the cristae appear less densely packed than those of control samples.
others have previously suggested that sepsis leads to enhanced generation of reactive oxygen species (e.g., peroxynitrite) by mitochondria (3, 5, 18), and reactive oxygen species have been shown to rapidly inactivate sarcomeric creatine kinase in vitro (28, 32). In addition, a recent study (1) has shown that, with endotoxin administration, a number of diaphragm proteins, including MtCK, undergo oxidative modification. It is known that oxidative modification of proteins can result in protein unfolding and enhanced susceptibility to proteolytic degradation (9). It is therefore possible that sepsis results in structural modification of MtCK, which first causes reduction in enzymatic activity and subsequently facilitates protein degradation and removal. This could explain the pattern of our results, as this mechanism of inactivation of MtCK during sepsis should theoretically result in large functional reductions but smaller reductions in protein content.

Potential implications. The sepsis syndrome is associated with significant derangements in tissue blood flow, oxygen delivery, oxygen extraction, and organ function (4, 11). The pathogenesis of these alterations has been the subject of intense study, and a variety of potential mechanisms have been postulated (i.e., alterations in mitochondrial function within tissues, alterations in blood flow due to changes in blood coagulation cascades, alterations in microvascular control) (3–6, 8, 29). In most of these previous studies, examination of mitochondrial function was confined to assessment of conventional indexes of mitochondrial respiration, e.g., state 3 respiration rate, characterized by the amount of oxygen used and the amount of ATP generated when ADP is added to mitochondrial isolates (3, 5, 6, 8, 29). These conventional methods of assessing mitochondrial function do not measure or take into account MtCK activity.

The new finding of the present work is that MtCK activity is essentially lost in the heart and skeletal muscle during the development of sepsis. The negative effects resulting from loss of MtCK would be expected to interact with and potentiate the deleterious effects of the other abnormalities thought to occur in this syndrome. Reductions in tissue oxygen delivery, due to alterations in microvascular flow regulation or localized clotting, and inhibition of the electron transport chain could result in reduced mitochondrial ATP generation. In this setting, the superimposition of a sepsis-induced reduction in MtCK activity would be expected to result in a marked impairment in the ability of cardiac and skeletal muscles to maintain adequate high-energy phosphate stores (phosphocreatine) in the cellular spaces adjacent to the contractile proteins at times of heightened contractile activity.

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