

## New Developments in Septic Acute Kidney Injury

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### Summary

The kidney is a common "victim organ" of various insults in critically ill patients. Sepsis and septic shock are the dominant causes of acute kidney injury, accounting for nearly 50 % of episodes of acute renal failure. Despite our substantial progress in the understanding of mechanisms involved in septic acute kidney injury there is still a huge pool of questions preclusive of the development of effective therapeutic strategies. This review briefly summarizes our current knowledge of pathophysiological mechanisms of septic acute kidney injury focusing on hemodynamic alterations, peritubular dysfunction, role of inflammatory mediators and nitric oxide, mitochondrial dysfunction and structural changes. Role of proteomics, new promising laboratory method, is mentioned.

### Key words

Acute kidney injury • Sepsis • Pathophysiology • Proteomics

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### Introduction

Sepsis is the leading cause of death at non-coronary intensive care units and the mortality and morbidity resulting from sepsis remain enormous despite our substantial progress in diagnostic tools, monitoring and new therapeutic approaches (Angus *et al.* 2001, Van Der

Poll 2001, Reinhart *et al.* 2006). Sepsis is complex syndrome resulting from the response of an organism to overwhelming infection with cytokine release, activation of pro- and anti-inflammatory pathways, immunological dysregulation, coagulation and endothelial activation and usually leads to multiorgan dysfunction. Acute kidney injury (AKI) is one of the most feared complications in septic critically ill patients because it further worsens prognosis and increases cost of care (Chertow *et al.* 2005). In addition, sepsis and septic shock are the dominant causes of AKI, accounting for nearly 50 % of episodes of AKI (Schrier and Wang 2004). The incidence of acute kidney injury proportionally rises with the severity of sepsis, occurring in 19 % of patients with sepsis, 23 % patients with severe sepsis and 51 % patients with septic shock (Rangel-Frausto *et al.* 1995, Schrier and Wang 2004). Of note, even a slight decline in renal functions results in higher morbidity and mortality (Chertow *et al.* 2006), highlighting the potentially important role of the kidney dysfunction during the natural history of critical illness. The above mentioned reasons increase the urgent need to improve our understanding of its pathophysiology and to develop new treatment. There is now emerging evidence that the pathogenesis of septic AKI involves distinct mechanisms as compared to non-septic causes of AKI. Therefore, the purpose of this brief review is to discuss the most recent advances in the understanding of the pathogenesis of sepsis-induced AKI.

### Pathophysiology of septic AKI

In general, the pathophysiology of sepsis

involves a multitude of systemic and cellular processes as well as mediators. In most cases, AKI develops as a part of multiple organ dysfunction syndrome (MODS) sharing many common pathophysiological mechanisms that are also involved in the dysfunction of other organs. However, the nephron is highly organized structure and may, therefore, have unique response to injury. Indeed, within the kidney there are multiple levels at which significantly different changes might occur. These include alterations in renal blood flow, glomerular and peritubular microcirculation, tubular cell function and structure as well as derangements in cellular bioenergetics and renal proteome. It is important to note that much of our insights into the pathophysiology of septic AKI have been derived from experimental studies. Therefore, one should consider the available evidence still as hypothesis-generating rather than confirmatory.

### **Renal hemodynamics in sepsis: new paradigms**

Whereas systemic hemodynamic changes in sepsis are well defined, the behavior of renal blood flow in human sepsis is not clearly understood, in particular due to the lack of reliable methods allowing continuous renal blood flow measurement. Undoubtedly, hypovolemia caused by increased venous capacitance and venous pooling, increased vascular permeability with fluid leak into the tissue interstitium and hypotension resulting from septic vasoplegia are the dominant hemodynamically-mediated and, therefore, potentially reversible causes of septic AKI. However, if renal hypoperfusion persists and compensatory kidney reserve is exhausted or absent, AKI progresses from “pre-renal” state to established structural tubular injury (Schrier *et al.* 2004, Macedo and Mehta 2009). Unfortunately, not every drop in renal perfusion pressure is clinically visible and renal hypoperfusion might occur even in the absence of marked hypotension, especially in high risk patients with chronically disturbed intrarenal autoregulatory mechanisms (Abuelo 2007).

While human data on renal hemodynamics in sepsis are scarce and unreliable (Schrier and Wang 2004), recent comprehensive review of the available experimental evidence showed that renal blood flow reported in these studies is highly variable (Langenberg *et al.* 2006b). It has to be stressed, however, that majority of studies reporting a reduction in renal blood flow were derived from heterogeneous, usually short-term and

mostly hypodynamic models characterized by a reduced cardiac output, which clearly limits the inference that could be drawn. In fact, cardiac output appears to be the dominant predictor of renal blood flow. This has been demonstrated in a study by Australian research group in a sheep sepsis model, in which hyperdynamic and normotensive circulation was accompanied by significant renal vasodilatation and increased renal artery blood flow (Langenberg *et al.* 2006a, 2007). These data from sheep model have recently been reproduced by our group in a porcine model of peritonitis-induced septic AKI (Chvojka *et al.* 2008). Our study was the first to tackle the issue of directly measured renal venous pressure allowing both the determination of renal vascular resistance and true renal perfusion pressure in a large animal sepsis model. In keeping with previous reports (Langenberg *et al.* 2006a, 2007), our study provided further evidence against the widely held concept that early sepsis increases renal vascular resistance (Schrier and Wang 2004). In summary, utilizing animal models that better mimic human disease challenged the conventional presumption suggesting that renal vasoconstriction is not necessarily a prerequisite for AKI to develop during hyperdynamic sepsis (Wan *et al.* 2008).

### **Renal venous congestion: an underestimated factor?**

Not only renal inflow but also renal outflow, if impeded, might be involved in septic AKI. The renal venous congestion has been increasingly recognized as key mechanism driving AKI in decompensated heart failure patients (Damman *et al.* 2009, Mullens *et al.* 2009). In the case of sepsis, aggressive fluid resuscitation in the terrain of severe capillary leak might lead to the development of tissue edema and abdominal hypertension. It is well recognized that the kidney is especially vulnerable to the increased intraabdominal pressure and tissue edema (Shear and Rosner 2006). In this context, we observed gradually and significantly increased renal venous pressure during progressive porcine sepsis resulting in reduced renal perfusion pressure despite clinically acceptable mean arterial pressure (70 mm Hg) (Chvojka *et al.* 2008). Hence, it is plausible to speculate that renal venous congestion (i.e. congestive kidney disease) might be unrecognized factor contributing to the fall in glomerular filtration in septic AKI. Further research is needed to establish whether this concept is applicable in other models of septic AKI.

## Renal glomerular injury in sepsis

There is widely held concept of a fall in transcapillary hydraulic pressure due to afferent arteriolar vasoconstriction leading to the reduction in glomerular filtration rate (GFR) in sepsis (Schrier and Wang 2004, Abuelo 2007). This concept is based on studies from the eighties showing that the afferent arteriole is primarily affected by a preglomerular vasoconstriction resulting in a decrease in cortical flow and reduced GFR in rats challenged with large endotoxin bolus (Lugon *et al.* 1989). However, the absolute lack of data from humans and experimental models of hyperdynamic, well-resuscitated sepsis questions the robustness of this paradigm. Although it seems reasonable to argue that changes in the intraglomerular hemodynamics are likely involved in the deterioration of glomerular filtration, at least at early stages, the exact response of both afferent and efferent arterioles in the course of sepsis is completely unknown. Interestingly, significant renal vasodilatation, increased renal artery blood flow and reduced glomerular filtration with preserved tubular functions observed in the above mentioned large animal studies (Langenberg *et al.* 2006a, 2007) offer a provocative hypothesis: decreased rather than increased glomerular vascular resistance affecting both the afferent and efferent arterioles, with the effect predominating on the latter vessels, might explain the fall in glomerular filtration, and the opposite changes in intraglomerular circulation might account for the restoration of glomerular filtration (Langenberg *et al.* 2007). The lack of effectiveness or even worse outcome in clinical trials investigating various vasodilators in septic AKI (De Vriese and Bourgeois 2003, Friedrich *et al.* 2005) and, conversely, less severe kidney dysfunction with higher urine output achieved by vasopressin-mediated action on efferent arteriole in a porcine model of fecal peritonitis-induced septic shock (Simon *et al.* 2009) fit well with the above hypothesis. The latter experimental observation has recently been supported by a *post hoc* analysis of a randomized, controlled trial in which septic patients at risk for AKI (risk category according to RIFLE criteria) treated with vasopressin were less likely to progress to renal failure than their noradrenaline-treated counterparts (Gordon *et al.* 2010). Collectively, an imbalance in intraglomerular vasomotor control and yet undefined disharmony of glomerular vascular balancing mediators (Langenberg *et al.* 2006a, Yamaguchi *et al.* 2006) may represent a form of vasomotor nephropathy as a primary

cause of early, “functional” AKI, preceding an intrinsic renal structural injury (Matějovič *et al.* 2007). Nevertheless, whether the septic kidney dysfunction is a unique, namely hyperemic form of AKI as originally proposed by Rector *et al.* (1973) and recently reaffirmed (Chvojka *et al.* 2008, Wan *et al.* 2008), remains to be confirmed by further studies.

Not only impaired glomerular hemodynamic autoregulation, but also inflammatory changes affecting glomerular microvasculature may facilitate septic AKI. Although the human data are very scarce and reporting only mild structural alterations of the glomerulus (Hotchkiss *et al.* 1999), experimental studies revealed leukocyte infiltration in the glomerular capillaries, apoptotic death of glomerular endothelial cells (Messmer *et al.* 1999) as well as formation of microvascular thrombosis (Welty-Wolf *et al.* 2006).

## Renal peritubular microcirculation: the culprit of septic acute kidney injury

Sepsis is a disease of microcirculation. New imaging techniques, such as orthogonal spectral imaging or side-stream dark field, opened the way to directly investigate the microcirculatory network perfusion and its derangement at the bedside. Using orthogonal spectral imaging the correlation between microcirculation alterations and prognosis was observed. Microvascular flow disturbances quantified by distinct parameters as microvascular flow index or functional capillary density were markedly impaired in non-survivors compared to survivors (Trzeciak *et al.* 2007). Well-maintained or even increased renal blood flow in sepsis is insufficient for predicting renal tissue oxygenation, because it does not necessarily reflect changes in cortical and medullary microcirculation. Although the distribution of blood flow from the cortex towards medulla has been suggested by several studies (Gullichsen *et al.* 1989, Millar and Thiernemann 1997, Cohen *et al.* 2001), contradictory results have also been reported (Di Giantomaso *et al.* 2003). Regardless of these inconsistencies, peritubular microcirculation has recently received considerable attention as a possible causative element in septic AKI and several experimental studies provided direct evidence for the role of peritubular capillary injury in septic AKI. In the study by Wu *et al.* (2007b), an early and marked decline in cortical peritubular capillary perfusion with a significant shift in the percentage of vessels with continuous flows to vessels with intermittent or no flow

pattern developed in mice challenged with endotoxin. These microvascular disturbances preceded the development of AKI. Interestingly, despite a full recovery of renal function at 48 h, functional capillary density recovered only partially (Wu *et al.* 2007b). Moreover, areas of compromised cortical microvascular perfusion correlated with renal tubular cell stress in corresponding regions as assessed by NADP(H) autofluorescence, suggesting important link between altered peritubular microcirculation and epithelial cell dysfunction. These findings has been corroborated by a study of Gupta *et al.* (2007), in which quantitative two-photon intravital microscopy revealed markedly reduced peritubular capillary blood flow in an endotoxemia model in rats. The consequence of these peritubular microvascular alterations is renal tissue hypoxia. However, microcirculatory perfusion defects might not be uniform throughout the kidney and regions suffering from hypoxia might be overlooked. In support of this notion, a recent study of Johannes *et al.* (2009a) in endotoxemic rats provided the evidence for the presence of microvascular hypoxic areas despite renal oxygen consumption was not significantly reduced and no hypoxia was detected in the average microcirculatory pO<sub>2</sub> measurements. Of great importance, the acute renal microvascular injury may persist for a long period even after resolution of initial insult, resulting in chronic microvascular alterations and rarefaction. Consequently, this persistent peritubular capillary failure and subsequent microvascular dropout predisposes survivors of an episode of AKI to the development of chronic kidney disease (Horbelt *et al.* 2007). Taken together, the maintenance of peritubular microcirculation seems to be an important therapeutic target to improve the renal outcome in patients with AKI.

### **Molecular mechanisms of renal microvascular and tubular injury: the role of nitric oxide**

In sepsis/septic shock, the exposure of endothelium to cytokines and their downstream effectors results in profound alterations in many of physiological endothelial function (endothelial dysfunction). These changes encompass altered balance between endothelial vasoactive compounds (i.e. nitric oxide, carbon monoxide, endothelins, prostacyclin etc.) resulting in loss of vascular tone and microvascular perfusion heterogeneity, expression of adhesion molecules, further

production of cytokines and reactive nitrogen-oxygen species (RNOS), and imbalance between pro- and anticoagulant mechanisms (Le Dorze *et al.* 2009, Sutton 2009). The excessive inflammation and associated endothelial dysfunction lead to the activation of coagulation system and production of RNOS, and vice-versa, activation of these pathways may affect inflammatory response progressing into a vicious cycle on a downward spiral to vascular injury and tissue dysfunction (Sharfuddin *et al.* 2009). There is now emerging evidence supporting the role of nitric oxide (NO) derived from inducible NO synthase (iNOS) and oxidative stress in mediating these abnormalities in septic AKI (Hauser *et al.* 2005, Heemskerk *et al.* 2009a). Wu *et al.* (2007a) demonstrated in mice cecal ligation and puncture model real-time generation of RNOS by renal tubules and linked decreased peritubular capillary perfusion to overproduction of NO and RNOS and tubular injury. Moreover, the potential of selective iNOS inhibition to markedly attenuate abnormalities in peritubular vasculature indicated the contribution of iNOS-dependent pathway in the development of septic AKI (Tiwari *et al.* 2005, Wu *et al.* 2007a). These data obtained from rodent models have been supported by our series of experiments demonstrating that both selective iNOS inhibition (L-NIL) and free radical scavenger (Tempol) maintained renal function in bacteremic swine (Matějovič *et al.* 2004, 2005). The association between iNOS-generated NO-dependent pathways and tubular injury has recently been confirmed in human endotoxemia and sepsis (Heemskerk *et al.* 2006). This study documented an increased iNOS mRNA expression in cells isolated from urine of both septic patients and healthy volunteers challenged with endotoxin and showed that renal iNOS-associated proximal tubule injury is preventable through the selective iNOS inhibition. Finally, in another clinical study performed by the same group of investigators, infusion of alkaline phosphatase attenuated iNOS induction and renal NO production and prevented further renal injury (Heemskerk *et al.* 2009b). In conclusion, it seems that timely intervention focused on the elimination or prevention of excessive or toxic iNOS activity might be beneficial, although some contradictory experimental findings have been reported (Johannes *et al.* 2009b). Certainly, any therapeutic intervention in this pathway must take into account a delicate balance of preserving essential activities of NO while inhibiting its toxic effects (Hauser *et al.* 2005).

## Intrarenal inflammation

Sepsis is characterized by overproduction of a broad spectrum of proinflammatory cytokines. Besides their systemic effects many of them can cause direct or indirect damage to the kidney. For example, tumor necrosis factor alpha (TNF- $\alpha$ ) has direct toxic effect on tubular cells (Baud *et al.* 1989). In LPS-induced AKI in rats, neutralization with soluble TNF receptor prevented renal dysfunction (Knotek *et al.* 2001). Cunningham *et al.* (2002) documented protection against renal injury in TNF gene-deficient mice. Unfortunately, no beneficial effect of selective anti-TNF treatment was found in human clinical studies (Cohen and Carlet 1996). Anti-inflammatory, antithrombotic and cytoprotective properties of activated protein C (APC) have recently been demonstrated by Gupta *et al.* (2007, 2009). These authors documented the ability of APC to protect both the kidney vessel and tubular cells from insult in rats challenged with endotoxin (Gupta *et al.* 2007, 2009). Nevertheless, the data from clinical studies using APC in septic shock remains conflicting and more studies are needed to elucidate the role of APC in septic AKI.

Despite the existing confounding results, a growing body of evidence suggests that AKI in sepsis has a prominent inflammatory component both in initiation and extension phase of the kidney injury. Several large cohorts of critically ill patients demonstrated that interleukin-6 is a predictor of AKI (Chawla *et al.* 2007, Liu *et al.* 2009). Although the exact molecular mechanism whereby inflammation mediates renal tissue injury remains only partly understood, several recent studies highlighted the importance of intrarenal, both vascular and interstitial inflammation. Administration of endotoxin has been shown to trigger an influx of neutrophils into the kidney interstitium, which contributed to the deterioration of renal function (Cunningham *et al.* 2004). It has been shown that such interstitial neutrophil infiltration occurs particularly in the peritubular capillary network of the outer medulla as early as 30 min after ischemia/reperfusion injury (Li *et al.* 2008). There is evidence that the activation of adhesion molecules, both on the renal endothelium and epithelial cells, leads to the enhanced leukocyte adhesion, followed by the influx of activated leukocytes into the renal interstitium (Wu X. *et al.* 2007). The mechanism by which renal intracapillary and interstitial inflammation mediates the tissue injury includes local ischemia due to capillary plugging and direct tubular cell injury resulting

from injurious proteases, cytokines and RNOS released by activated leukocytes (Sutton 2009). Hence, kidney leukocyte infiltration, which is often seen in biopsies from septic patients (Lerolle 2009), might not be just an innocent bystander in the pathogenesis of septic AKI (Bolisetty and Agarwal 2009). Moreover, local inflammation within the kidney is increasingly recognized as a factor contributing to distant inflammatory injury in remote organs (Li *et al.* 2009).

## Acute tubular injury: necrosis, apoptosis or adaptive metabolic shutdown?

The available evidence suggests that the tubular injury in sepsis is triggered by both ischemic and inflammatory component. Nevertheless, very little is known of the cellular events leading to the loss of renal epithelial cells in the setting of sepsis. The complex tubular cell dysfunction ranges from sublethal to lethal injury depending on the severity and duration of the insults. Although the term acute tubular necrosis (ATN) has almost been the synonyme for sepsis-induced renal failure for many years, there is in fact no published study in septic patients, which would provide conclusive histopathological evidence for the presence of ATN in the course of sepsis-induced AKI (Langenberg *et al.* 2008). The problem is that a series of kidney biopsies would be needed to prove the underlying histopathological substrate for septic AKI. Obviously, the practical and in particular ethical issues make this approach unjustifiable in critically ill septic patients. Nevertheless, early postmortem studies of patients dying in intensive care units from sepsis and AKI showed that only gentle histological changes in more than 90 % of the kidneys (Hotchkiss and Karl 2003). In keeping with this study, a recent systematic review revealed that there were only mild, non-specific renal histological changes in human and animal sepsis, and ATN was a relatively uncommon finding (Langenberg *et al.* 2008). These results were supported by our group in a clinically relevant porcine model of peritonitis-induced septic shock, where immediate postmortem analysis showed only subtle histological changes (loss of tubular brush border and intracellular vacuoles) even in the presence of marked microvascular and metabolic stress (Chvojka *et al.* 2008). However, considering the dynamic nature of AKI, the assessment of renal morphology at a single time period (usually postmortem) provides a limited perspective. Another problem arising from the interpretation of

morphological changes is that the same histology may result from completely different molecular mechanisms.

A plausible explanation for the apparent discrepancy between histological evidence of injury and the degree of renal dysfunction could be apoptotic cell death, which is difficult to appreciate on routine histologic sections. Apoptosis is mediated by a genetically determined biochemical pathway and is characterized by cell shrinkage, membrane blebbing, condensation of nuclear chromatin and nuclear fragmentation into fragments of same DNA length (Hengartner 2000). Although there is rapidly developing evidence to suggest that increased apoptotic processes may play a determining role in the outcome of ischemia/reperfusion injury (Saikumar and Venkatachalam 2003), its role has not been extensively documented in septic AKI and only few experimental studies explored this issue (Messmer *et al.* 1999, Guo *et al.* 2004). Nevertheless, recent clinical data demonstrate that plasma from septic burn patients with AKI contains pro-apoptotic factors capable of inducing tubular apoptosis and pro-apoptotic proteins while reducing apoptosis inhibitors (Mariano *et al.* 2008). However, given the contradictory results (Hotchkiss and Karl 2003, Dear *et al.* 2006), the causative contribution of apoptosis to renal dysfunction in sepsis is currently unknown.

Finally, the absence of gross structural cell damage and the capability of failing kidneys to recover generated a new conceptual paradigm, considering organ dysfunction in sepsis as an adaptive phenomenon (Singer *et al.* 2004, Mongardon *et al.* 2009). According to this theory, the development of organ dysfunction (e.g. AKI) represents an attempt to cope with prolonged and significant insult. As mitochondria are the primary consumers of cellular oxygen (more than 90 % of total body oxygen consumption) used predominantly for ATP production *via* oxidative phosphorylation, increasing attention has been paid to the role of mitochondrial dysfunction in the establishment of organ dysfunction in sepsis. In analogy to the process of hibernation, decreased mitochondrial activity resulting in reduced ATP production evokes a transient state of metabolic shutdown manifested clinically as organ dysfunction. This hypometabolic state might not necessarily represent devastating process but rather an adaptive mechanism protecting the cells from lethal bioenergetic collapse and allowing the cells to recover after the injurious insult dismisses (Mongardon *et al.* 2009). A number of pathogenic mechanisms have been implicated in this

process, including inhibition of key mitochondrial enzymes involved in either the tricarboxylic acid (TCA) cycle or the electron transport chain, uncoupling of oxidative phosphorylation, diminished delivery of a key substrate (i.e. pyruvate) into the TCA cycle or activation of the nuclear enzyme poly (ADP-ribose) synthase (Singer 2007). Accumulating data support the view that increased production of NO and RNOS is, at least partly, responsible for impaired cellular bioenergetics in sepsis (Hauser *et al.* 2005). In an animal model of burn-induced prolonged critical illness, Vanhorebeek *et al.* (2009) demonstrated significant reduction in renal cortex mitochondrial respiratory chain activity in hyperglycemic animals, thereby supporting the role of bioenergetic failure in the pathogenesis of AKI. In addition, the kidney protective potential of hibernation-like state has recently been documented in a model of bilateral renal ischemia/reperfusion injury (Bos *et al.* 2009). In this model, pharmacologically (hydrogen sulphide) induced hypometabolic and oxygen demand reducing state afforded striking beneficial effects on survival, renal function, apoptosis, and inflammation. Other recent experimental studies demonstrating renoprotective effects of hydrogen sulphide suggested temperature-independent cytoprotection (Tripatara *et al.* 2009, Wagner *et al.* 2009). Although the increasing evidence points toward the critical role of mitochondrial damage during AKI (Brooks *et al.* 2009), some contradictory experimental results have been reported (Porta *et al.* 2006, May *et al.* 2007). Nevertheless, unraveling the fate and role of renal bioenergetic dysfunction both in the development of and recovery from septic AKI might pave the way for new treatment targets in sepsis-induced kidney dysfunction.

### The power of proteomics in septic AKI

The process of AKI in sepsis involves the complex of dynamically interacting multiple factors and it is clear that renal dysfunction, similar to dysfunction of other organs in sepsis, is not caused by a single mechanism. Limited ability to exactly analyze the renal molecular mechanisms and pathophysiology in humans emphasizes the need for complex, dynamic and clinically relevant animal studies (Doi *et al.* 2009). Implementing new powerful technologies of molecular biology into the renal research should allow to put the data into a relevant complex picture. Proteomics represents a powerful post-genomic biotechnology used for simultaneous examination of a large number of proteins or the

proteome. Applying proteomics to clinically relevant models of sepsis can fill important gaps in our understanding of AKI in sepsis. Indeed, virtually all disease states are caused by alterations in protein expression and modifications. The identification of these changes by proteomic analysis is of utmost importance to reveal relevant drug targets, therapeutic proteins and disease biomarkers (Devarajan 2008, Karvunidis *et al.* 2009, Smith *et al.* 2009, Thongboonkerd *et al.* 2009). With an effort to discover novel biomarkers and potential drug targets, Holly *et al.* (2006) compared the urinary proteomics in the cohort of peritonitis-induced septic rats with AKI and in the subgroup of those who did not develop AKI. They identified changes in a number of urinary proteins, including albumin, serine protease inhibitors and “kidney-specific” brush-border enzyme meprin-1 $\alpha$ . Meprin-1 $\alpha$  was suggested as a potential biomarker and drug target as treatment of mice with actinonin, an inhibitor of the brush-border enzymes (especially meprin-1 $\alpha$ ), prevented the development of septic AKI. Difference in-gel electrophoresis has also been used to characterize protein changes in the liver of mice with sepsis (Dear *et al.* 2007). In this study, dynamic changes in the liver proteome revealed many altered proteins with a wide range of functions such as acute phase response, oxidative stress, nitric oxide metabolism, coagulation, apoptosis, and mitochondrial functions. Importantly, the comparison of early (6 h) and late (24 h) protein changes enabled the authors to identify and validate candidate markers. The inhibition of the receptor (CD147) for one of these proteins, cyclophilin, attenuated sepsis-induced AKI and inflammatory response. In the future, dynamic tissue-specific (e.g. kidney) and cell-specific (e.g. tubular cells) proteomics holds the promise to provide convincing new mechanisms with potential clinical relevance.

## References

- ABUELO JG: Normotensive ischemic acute renal failure. *N Engl J Med* **357**: 797-805, 2007.
- ANGUS DC, LINDE-ZWIRBLE WT, LIDICKER J, CLERMONT G, CARCILLO J, PINSKY MR: Epidemiology of severe sepsis in the United States: analysis of incidence, outcome, and associated costs of care. *Crit Care Med* **29**: 1303-1310, 2001.
- BAUD L, OUDINET JP, BENS M, NOE L, PERALDI MN, RONDEAU E, ETIENNE J, ARDAILLOU R: Production of tumor necrosis factor by rat mesangial cells in response to bacterial lipopolysaccharide. *Kidney Int* **35**: 1111-1118, 1989.
- BOLISSETY S, AGARWAL A: Neutrophils in acute kidney injury: not neutral any more. *Kidney Int* **75**: 674-676, 2009.

## Conclusions

Growing body of experimental and clinical evidence suggests the sepsis-induced AKI being the unique form of acute renal dysfunction. Despite the fact that historically embedded theory of ischemic acute tubular necrosis has been challenged, hemodynamic parameters including the emerging concept of renal venous congestion are still of crucial importance for maintaining kidney functions. Contemporary studies reveal the complex network of simultaneously acting pathways with microcirculatory alterations and intrarenal inflammation being considered key factors. It needs to be elucidated, whether septic AKI represents dominantly functional or structural organ dysfunction, but the absence of a proof of major histological changes makes the theory of mitochondrial dysfunction plausible. Because of the growing burden of sepsis, the need to develop new pharmacological treatments and therapeutic interventions is of paramount importance. Undoubtedly, clinically relevant large animal models will continue to play a crucial role in the elucidation of biological pathways involved in AKI. Moreover, the implementation of powerful techniques (e.g. genomics and proteomics) into the clinical and experimental research should allow us to understand the complex pathogenesis of AKI and develop useful diagnostic and treatment techniques in near future.

## Conflict of Interest

There is no conflict of interest.

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- BOS EM, LEUVENINK HG, SNIJDER PM, KLOOSTERHUIS NJ, HILLEBRANDS JL, LEEMANS JC, FLORQUIN S, VAN GOOR H: Hydrogen sulfide-induced hypometabolism prevents renal ischemia/reperfusion injury. *J Am Soc Nephrol* **20**: 1901-1905, 2009.
- BROOKS C, WEI Q, CHO SG, DONG Z: Regulation of mitochondrial dynamics in acute kidney injury in cell culture and rodent models. *J Clin Invest* **119**: 1275-1285, 2009.
- CHAWLA LS, SENEFF MG, NELSON DR, WILLIAMS M, LEVY H, KIMMEL PL, MACIAS WL: Elevated plasma concentrations of IL-6 and elevated APACHE II score predict acute kidney injury in patients with severe sepsis. *Clin J Am Soc Nephrol* **2**: 22-30, 2007.
- CHERTOW GM, BURDICK E, HONOUR M, BONVENTRE JV, BATES DW: Acute kidney injury, mortality, length of stay, and costs in hospitalized patients. *J Am Soc Nephrol* **16**: 3365-3370, 2005.
- CHERTOW GM, SOROKO SH, PAGANINI EP, CHO KC, HIMMELFARB J, IKIZLER TA, MEHTA RL: Mortality after acute renal failure: models for prognostic stratification and risk adjustment. *Kidney Int* **70**: 1120-1126, 2006.
- CHVOJKA J, SÝKORA R, KROUŽECKÝ A, RADŽJ J, VARNEROVÁ V, KARVUNIDIS T, HES O, NOVÁK I, RADERMACHER P, MATĚJOVIČ M: Renal haemodynamic, microcirculatory, metabolic and histopathological responses to peritonitis-induced septic shock in pigs. *Crit Care* **12**: R164, 2008.
- COHEN J, CARLET J: INTERSEPT: an international, multicenter, placebo-controlled trial of monoclonal antibody to human tumor necrosis factor-alpha in patients with sepsis. International Sepsis Trial Study Group. *Crit Care Med* **24**: 1431-1440, 1996.
- COHEN RI, HASSELL AM, MARZOUK K, MARINI C, LIU SF, SCHARF SM: Renal effects of nitric oxide in endotoxemia. *Am J Respir Crit Care Med* **164**: 1890-1895, 2001.
- CUNNINGHAM PN, DYANOV HM, PARK P, WANG J, NEWELL KA, QUIGG RJ: Acute renal failure in endotoxemia is caused by TNF acting directly on TNF receptor-1 in kidney. *J Immunol* **168**: 5817-5823, 2002.
- CUNNINGHAM PN, WANG Y, GUO R, HE G, QUIGG RJ: Role of Toll-like receptor 4 in endotoxin-induced acute renal failure. *J Immunol* **172**: 2629-2635, 2004.
- DAMMAN K, VAN DEURSEN VM, NAVIS G, VOORS AA, VAN VELDHUISEN DJ, HILLEGGE HL: Increased central venous pressure is associated with impaired renal function and mortality in a broad spectrum of patients with cardiovascular disease. *J Am Coll Cardiol* **53**: 582-588, 2009.
- DEAR JW, YASUDA H, HU X, HIENY S, YUEN PS, HEWITT SM, SHER A, STAR RA: Sepsis-induced organ failure is mediated by different pathways in the kidney and liver: acute renal failure is dependent on MyD88 but not renal cell apoptosis. *Kidney Int* **69**: 832-836, 2006.
- DEAR JW, LEELAHAVANICHKUL A, APONTE A, HU X, CONSTANT SL, HEWITT SM, YUEN PS, STAR RA: Liver proteomics for therapeutic drug discovery: inhibition of the cyclophilin receptor CD147 attenuates sepsis-induced acute renal failure. *Crit Care Med* **35**: 2319-2328, 2007.
- DE VRIESE AS, BOURGEOIS M: Pharmacologic treatment of acute renal failure in sepsis. *Curr Opin Crit Care* **9**: 474-480, 2003.
- DEVARAJAN P: Proteomics for the investigation of acute kidney injury. *Contrib Nephrol* **160**: 1-16, 2008.
- DI GIANTOMASSO D, MORIMATSU H, MAY CN, BELLOMO R: Intrarenal blood flow distribution in hyperdynamic septic shock: effect of norepinephrine. *Crit Care Med* **31**: 2509-2513, 2003.
- DOI K, LEELAHAVANICHKUL A, YUEN PS, STAR RA: Animal models of sepsis and sepsis-induced kidney injury. *J Clin Invest* **119**: 2868-2878, 2009.
- FRIEDRICH JO, ADHIKARI N, HERRIDGE MS, BEYENE J: Meta-analysis: low-dose dopamine increases urine output but does not prevent renal dysfunction or death. *Ann Intern Med* **142**: 510-524, 2005.
- GORDON AC, RUSSELL JA, WALLEY KR, SINGER J, AYERS D, STORMS MM, HOLMES CL, HÉBERT PC, COOPER DJ, MEHTA S, GRANTON JT, COOK DJ, PRESNEILL JJ: The effects of vasopressin on acute kidney injury in septic shock. *Intensive Care Med* **36**: 83-91, 2010.
- GULLICHSEN E, NELIMARKKA O, HALKOLA L, NIINIKOSKI J: Renal oxygenation in endotoxin shock in dogs. *Crit Care Med* **17**: 547-550, 1989.
- GUO R, WANG Y, MINTO AW, QUIGG RJ, CUNNINGHAM PN: Acute renal failure in endotoxemia is dependent on caspase activation. *J Am Soc Nephrol* **15**: 3093-3102, 2004.



- GUPTA A, RHODES GJ, BERG DT, GERLITZ B, MOLITORIS BA, GRINNELL BW: Activated protein C ameliorates LPS-induced acute kidney injury and downregulates renal INOS and angiotensin 2. *Am J Physiol* **293**: F245-F254, 2007.
- GUPTA A, GERLITZ B, RICHARDSON MA, BULL C, BERG DT, SYED S, GALBREATH EJ, SWANSON BA, JONES BE, GRINNELL BW: Distinct functions of activated protein C differentially attenuate acute kidney injury. *J Am Soc Nephrol* **20**: 267-277, 2009.
- HAUSER B, BRACHT H, MATEJOVIC M, RADERMACHER P, VENKATESH B: Nitric oxide synthase inhibition in sepsis? Lessons learned from large-animal studies. *Anesth Analg* **101**: 488-498, 2005.
- HEEMSKERK S, PICKKERS P, BOUW MP, DRAISMA A, VAN DER HOEVEN JG, PETERS WH, SMITS P, RUSSEL FG, MASEREEUW R: Upregulation of renal inducible nitric oxide synthase during human endotoxemia and sepsis is associated with proximal tubule injury. *Clin J Am Soc Nephrol* **1**: 853-862, 2006.
- HEEMSKERK S, MASEREEUW R, RUSSEL FG, PICKKERS P: Selective iNOS inhibition for the treatment of sepsis-induced acute kidney injury. *Nat Rev Nephrol* **5**: 629-640, 2009a.
- HEEMSKERK S, MASEREEUW R, MOESKER O, BOUW MP, VAN DER HOEVEN JG, PETERS WH, RUSSEL FG, PICKKERS P: Alkaline phosphatase treatment improves renal function in severe sepsis or septic shock patients. *Crit Care Med* **37**: 417-423, 2009b.
- HENGARTNER MO: The biochemistry of apoptosis. *Nature* **407**: 770-776, 2000.
- HOLLY MK, DEAR JW, HU X, SCHECHTER AN, GLADWIN MT, HEWITT SM, YUEN PS, STAR RA: Biomarker and drug-target discovery using proteomics in a new rat model of sepsis-induced acute renal failure. *Kidney Int* **70**: 496-506, 2006.
- HORBELT M, LEE SY, MANG HE, KNIPE NL, SADO Y, KRIBBEN A, SUTTON TA: Acute and chronic microvascular alterations in a mouse model of ischemic acute kidney injury. *Am J Physiol* **293**: F688-F695, 2007.
- HOTCHKISS RS, KARL IE: The pathophysiology and treatment of sepsis. *N Engl J Med* **348**: 138-150, 2003.
- HOTCHKISS RS, SWANSON PE, FREEMAN BD, TINSLEY KW, COBB JP, MATUSCHAK GM, BUCHMAN TG, KARL IE: Apoptotic cell death in patients with sepsis, shock, and multiple organ dysfunction. *Crit Care Med* **27**: 1230-1251, 1999.
- JOHANNES T, MIK EG, INCE C: Nonresuscitated endotoxemia induces microcirculatory hypoxic areas in the renal cortex in the rat. *Shock* **31**: 97-103, 2009a.
- JOHANNES T, MIK EG, KLINGEL K, GOEDHART PT, ZANKE C, NOHÉ B, DIETERICH HJ, UNERTL KE, INCE C: Effects of 1400W and/or nitroglycerin on renal oxygenation and kidney function during endotoxaemia in anaesthetised rats. *Clin Exp Pharmacol Physiol* **36**: 870-879, 2009b.
- KARVUNIDIS T, MAREŠ J, THONGBOONKERD V, MATĚJOVIČ M: Recent progress of proteomics in critical illness. *Shock* **31**: 545-552, 2009.
- KNOTEK M, ROGACHEV B, WANG W, ECDER T, MELNIKOV V, GENGARO PE, ESSON M, EDELSTEIN CL, DINARELLO CA, SCHRIER RW: Endotoxemic renal failure in mice: role of tumor necrosis factor independent of inducible nitric oxide synthase. *Kidney Int* **59**: 2243-2249, 2001.
- LANGENBERG C, WAN L, EGI M, MAY CN, BELLOMO R: Renal blood flow in experimental septic acute renal failure. *Kidney Int* **69**: 1996-2002, 2006a.
- LANGENBERG C, BELLOMO R, MAY CN, EGI M, WAN L, MORGERA S: Renal vascular resistance in sepsis. *Nephron Physiol* **104**: 1-11, 2006b.
- LANGENBERG C, WAN L, EGI M, MAY CN, BELLOMO R: Renal blood flow and function during recovery from experimental septic acute kidney injury. *Intensive Care Med* **33**: 1614-1618, 2007.
- LANGENBERG C, BAGSHAW SM, MAY CN, BELLOMO R: The histopathology of septic acute kidney injury: a systematic review. *Crit Care* **12**: R38, 2008.
- LE DORZE M, LEGRAND M, PAYEN D, INCE C: The role of the microcirculation in acute kidney injury. *Curr Opin Crit Care* **15**: 503-508, 2009.
- LEROLLE M, NOCHY D, GUÉROT E, BRUNEVAL P, FAGON JY, DIEHL JL, HILL G: Histopathology of septic shock induced acute kidney injury: apoptosis and leukocytic infiltration. *Intensive Care Med* **36**: 471-478, 2010.

- LI L, HUANG L, SUNG SS, VERGIS AL, ROSIN DL, ROSE CE, JR, LOBO PI, OKUSA MD: The chemokine receptors CCR2 and CX3CR1 mediate monocyte/macrophage trafficking in kidney ischemia-reperfusion injury. *Kidney Int* **74**: 1526-1537, 2008.
- LI X, HASSOUN HT, SANTORA R, RABB H: Organ crosstalk: the role of the kidney. *Curr Opin Crit Care* **15**: 481-487, 2009.
- LIU KD, ALTMANN C, SMITS G, KRAWCZESKI CD, EDELSTEIN CL, DEVARAJAN P, FAUBEL S: Serum Interleukin-6 and interleukin-8 are early biomarkers of acute kidney injury and predict prolonged mechanical ventilation in children undergoing cardiac surgery: a case-control study. *Crit Care* **13**: R104, 2009.
- LUGON JR, BOIM MA, RAMOS OL, AJZEN H, SCHOR N: Renal function and glomerular hemodynamics in male endotoxemic rats. *Kidney Int* **36**: 570-575, 1989.
- MACEDO E, MEHTA RL: Prerenal failure: from old concepts to new paradigms. *Curr Opin Crit Care* **15**: 467-473, 2009.
- MARIANO F, CANTALUPPI V, STELLA M, ROMANAZZI GM, ASSENZIO B, CAIRO M, BIANCONE L, TRIOLO G, RANIERI VM, CAMUSSI G: Circulating plasma factors induce tubular and glomerular alterations in septic burns patients. *Crit Care* **12**: R42, 2008.
- MATĚJOVIČ M, KROUŽECKÝ A, MARTÍNKOVÁ V, ROKYTA R, JR, KRÁLOVÁ H, TRESKA V, RADERMACHER P, NOVÁK I: Selective inducible nitric oxide synthase inhibition during long-term hyperdynamic porcine bacteremia. *Shock* **21**: 458-465, 2004.
- MATĚJOVIČ M, KROUŽECKÝ A, MARTÍNKOVÁ V, ROKYTA R, JR, RADĚJ J, KRÁLOVÁ H, TRESKA V, RADERMACHER P, NOVÁK I: Effects of tempol, a free radical scavenger, on long-term hyperdynamic porcine bacteremia. *Crit Care Med* **33**: 1057-1063, 2005.
- MATĚJOVIČ M, RADERMACHER P, JOANNIDIS M: Acute kidney injury in sepsis: is renal blood flow more than just an innocent bystander? *Intensive Care Med* **33**: 1498-1500, 2007.
- MAY C, WAN L, WILLIAMS J, WELLARD MR, PELL G, LANGENBERG C, JACKSON G, BELLOMO R: A technique for the simultaneous measurement of renal ATP, blood flow and pH in a large animal model of septic shock. *Crit Care Resusc* **9**: 30-33, 2007.
- MILLAR CG, THIEMERMANN C: Intrarenal haemodynamics and renal dysfunction in endotoxaemia: effects of nitric oxide synthase inhibition. *Br J Pharmacol* **121**: 1824-1830, 1997.
- MESSMER UK, BRINER VA, PFEILSCHIFTER J: Tumor necrosis factor-alpha and lipopolysaccharide induce apoptotic cell death in bovine glomerular endothelial cells. *Kidney Int* **55**: 2322-2337, 1999.
- MONGARDON N, DYSON A, SINGER M: Is MOF an outcome parameter or a transient, adaptive state in critical illness? *Curr Opin Crit Care* **15**: 431-436, 2009.
- MULLENS W, ABRAHAMS Z, FRANCIS GS, SOKOS G, TAYLOR DO, STARLING RC, YOUNG JB, TANG WH: Importance of venous congestion for worsening of renal function in advanced decompensated heart failure. *J Am Coll Cardiol* **53**: 589-596, 2009.
- VAN DER POLL T: Immunotherapy of sepsis. *Lancet Infect Dis* **1**: 165-174, 2001.
- PORTA F, TAKALA J, WEIKERT C, BRACHT H, KOLAROVA A, LAUTERBURG BH, BOROTTO E, JAKOB SM: Effects of prolonged endotoxemia on liver, skeletal muscle and kidney mitochondrial function. *Crit Care* **10**: R118, 2006.
- RANGEL-FRAUSTO MS, PITTET D, COSTIGAN M, HWANG T, DAVIS CS, WENZEL RP: The natural history of the systemic inflammatory response syndrome (SIRS). A prospective study. *JAMA* **273**: 117-123, 1995.
- RECTOR F, GOYAL S, ROSENBERG IK, LUCAS CE: Sepsis: a mechanism for vasodilatation in the kidney. *Ann Surg* **178**: 222-226, 1973.
- REINHART K, MEISNER M, BRUNKHORST FM: Markers for sepsis diagnosis: what is useful? *Crit Care Clin* **22**: 503-519, ix-x, 2006.
- SAIKUMAR P, VENKATACHALAM MA: Role of apoptosis in hypoxic/ischemic damage in the kidney. *Semin Nephrol* **23**: 511-521, 2003.
- SCHRIER RW, WANG W: Acute renal failure and sepsis. *N Engl J Med* **351**: 159-169, 2004.
- SHARFUDDIN AA, SANDOVAL RM, BERG DT, McDOUGAL GE, CAMPOS SB, PHILLIPS CL, JONES BE, GUPTA A, GRINNELL BW, MOLITORIS BA: Soluble thrombomodulin protects ischemic kidneys. *J Am Soc Nephrol* **20**: 524-534, 2009.

- SHEAR W, ROSNER MH: Acute kidney dysfunction secondary to the abdominal compartment syndrome. *J Nephrol* **19**: 556-565, 2006.
- SIMON F, GIUDICI R, SCHEUERLE A, GROGER M, ASFAR P, VOGT JA, WACHTER U, PLONER F, GEORGIEFF M, MOLLER P, LAPORTE R, RADERMACHER P, CALZIA E, HAUSER B: Comparison of cardiac, hepatic, and renal effects of arginine vasopressin and noradrenaline during porcine fecal peritonitis: a randomized controlled trial. *Crit Care* **13**: R113, 2009.
- SINGER M: Mitochondrial function in sepsis: acute phase versus multiple organ failure. *Crit Care Med* **35**: S441-S448, 2007.
- SINGER M, DE SANTIS V, VITALE D, JEFFCOATE W: Multiorgan failure is an adaptive, endocrine-mediated, metabolic response to overwhelming systemic inflammation. *Lancet* **364**: 545-548, 2004.
- SMITH MP, BANKS RE, WOOD SL, LEWINGTON AJ, SELBY PJ: Application of proteomic analysis to the study of renal diseases. *Nat Rev Nephrol* **5**: 701-712, 2009.
- SUTTON TA: Alteration of microvascular permeability in acute kidney injury. *Microvasc Res* **77**: 4-7, 2009.
- TIWARI MM, BROCK RW, MEGYESI JK, KAUSHAL GP, MAYEUX PR: Disruption of renal peritubular blood flow in lipopolysaccharide-induced renal failure: role of nitric oxide and caspases. *Am J Physiol* **289**: F1324-F1332, 2005.
- THONGBOONKERD V, CHIANGJONG W, MARES J, MORAVEC J, TUMA Z, KARVUNIDIS T, SINCHAIKUL S, CHEN ST, OPATRYN K, MATEJOVIC M: Altered plasma proteome during an early phase of peritonitis-induced sepsis. *Clin Sci* **116**: 721-730, 2009.
- TRIPATARA P, PATEL NS, BRANCALEONE V, RENSHAW D, ROCHA J, SEPODES B, MOTA-FILIFE H, PERRETTI M, THIEMERMANN C: Characterisation of cystathionine gamma-lyase/hydrogen sulphide pathway in ischaemia/reperfusion injury of the mouse kidney: an in vivo study. *Eur J Pharmacol* **606**: 205-209, 2009.
- TRZECIAK S, DELLINGER RP, PARRILLO JE, GUGLIELMI M, BAJAJ J, ABATE NL, ARNOLD RC, COLILLA S, ZANOTTI S, HOLLENBERG SM: Early microcirculatory perfusion derangements in patients with severe sepsis and septic shock: relationship to hemodynamics, oxygen transport, and survival. *Ann Emerg Med* **49**: 88-98, 2007.
- WAGNER F, ASFAR P, CALZIA E, RADERMACHER P, SZABÓ C: Bench-to-bedside review: Hydrogen sulfide – the third gaseous transmitter: applications for critical care. *Crit Care* **13**: 213, 2009.
- VANHOREBEEK I, GUNST J, ELLGER B, BOUSSEMAERE M, LERUT E, DEBAVEYE Y, RABBANI N, THORNALLEY PJ, SCHETZ M, VAN DEN BERGHE G: Hyperglycemic kidney damage in an animal model of prolonged critical illness. *Kidney Int* **76**: 512-520, 2009.
- WAN L, BAGSHAW SM, LANGENBERG C, SAOTOME T, MAY C, BELLOMO R: Pathophysiology of septic acute kidney injury: what do we really know? *Crit Care Med* **36**: S198-S203, 2008.
- WELTY-WOLF KE, CARRAWAY MS, ORTEL TL, GHIO AJ, IDELL S, EGAN J, ZHU X, JIAO JA, WONG HC, PIANTADOSI CA: Blockade of tissue factor-factor X binding attenuates sepsis-induced respiratory and renal failure. *Am J Physiol* **290**: L21-L31, 2006.
- WU L, GOKDEN N, MAYEUX PR: Evidence for the role of reactive nitrogen species in polymicrobial sepsis-induced renal peritubular capillary dysfunction and tubular injury. *J Am Soc Nephrol* **18**: 1807-1815, 2007a.
- WU L, TIWARI MM, MESSER KJ, HOLTHOFF JH, GOKDEN N, BROCK RW, MAYEUX PR: Peritubular capillary dysfunction and renal tubular epithelial cell stress following lipopolysaccharide administration in mice. *Am J Physiol* **292**: F261-F268, 2007b.
- WU X, GUO R, WANG Y, CUNNINGHAM PN: The role of ICAM-1 in endotoxin-induced acute renal failure. *Am J Physiol* **293**: F1262-F1271, 2007.
- YAMAGUCHI N, JESMIN S, ZAEDI S, SHIMOJO N, MAEDA S, GANDO S, KOYAMA A, MIYAUCHI T: Time-dependent expression of renal vasoregulatory molecules in LPS-induced endotoxemia in rat. *Peptides* **27**: 2258-2270, 2006.