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A p38MAPK/MK2 signaling pathway leading to redox stress, cell death and ischemia/reperfusion injury

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Abstract

Background: Many diseases and pathological conditions are characterized by transient or constitutive overproduction of reactive oxygen species (ROS). ROS are causal for ischemia/reperfusion (IR)-associated tissue injury (IRI), a major contributor to organ dysfunction or failure. Preventing IRI with antioxidants failed in the clinic, most likely due to the difficulty to timely and efficiently target them to the site of ROS production and action. IR is also characterized by changes in the activity of intracellular signaling molecules including the stress kinase p38MAPK. While ROS can cause the activation of p38MAPK, we recently obtained in vitro evidence that p38MAPK activation is responsible for elevated mitochondrial ROS levels, thus suggesting a role for p38MAPK upstream of ROS and their damaging effects.

Results: Here we identified p38MAPKα as the predominantly expressed isoform in HL-1 cardiomyocytes and siRNA-mediated knockdown demonstrated the pro-oxidant role of p38MAPKα signaling. Moreover, the knockout of the p38MAPK effector MAPKAP kinase 2 (MK2) reproduced the effect of inhibiting or knocking down p38MAPK. To translate these findings into a setting closer to the clinic a stringent kidney clamping model was used. p38MAPK activity increased upon reperfusion and p38MAPK inhibition by the inhibitor BIRB796 almost completely prevented severe functional impairment caused by IR. Histological and molecular analyses showed that protection resulted from decreased redox stress and apoptotic cell death.

Conclusions: These data highlight a novel and important mechanism for p38MAPK to cause IRI and suggest it as a potential therapeutic target for prevention of tissue injury.

Keywords: p38MAPK signaling, Ischemia/reperfusion injury (IRI), Reactive oxygen species (ROS), Apoptosis, Kidney

Background

Ischemia/reperfusion injury (IRI) contributes to morbidity and mortality in a wide range of pathologies including acute coronary syndrome, stroke, acute kidney injury, sickle cell disease and is particularly unavoidable during solid organ transplantation [1]. ROS are central to the initiation and progression of damage to organs throughout ischemia/reperfusion (IR). In particular, during the early phase of reperfusion excessive amounts of ROS are produced, which through direct damage to biomolecules or indirectly through the activation of intracellular signaling pathways cause progression of the injury. ROS have been linked to inflammasome activation [2,3] and autophagy [4,5], and once produced they thus have important pacemaker function on the path to full-blown IRI. Both, mitochondrial and non-mitochondrial (i.e. NADPH-dependent oxidases, NOXs) ROS producing systems are involved in IRI. Strikingly, eliminating a single system already resulted in a therapeutic benefit. Thus genetic ablation of the...
mitochondrial ROS producing enzyme p66SHC [6] or the inhibition of complex I of the mitochondrial electron transport chain (ETC), a major source for ROS, through S-nitrosation [7] prevented IRI in the heart, which could also be achieved by the knockout of NOX2 or NOX4 [8]. Ablation of both NOX isoforms exacerbated IRI, stressing the importance of maintaining basal ROS signaling [8].

Despite the acknowledged role of ROS, the use of antioxidants failed to yield a convincing therapeutic benefit [9]. ROS are short-lived and highly reactive and thus much of the damage happens rapidly and in close proximity to the site of production and scavenging mitochondrial ROS is thus technically challenging. Most desirable, therefore, are strategies to prevent excessive ROS generation. Intracellular signaling pathways are increasingly realized for the control they can exert over mitochondria. Oxidative phosphorylation (OXPHOS), a main source of mitochondrial ROS, depends on respiratory super complexes in mitochondria [10], whose reversible phosphorylation and other forms of posttranslational modifications provide important layers of regulation [11]. This is best understood for protein kinase A (PKA) that phosphorylates components of the mitochondrial electron transport chain (ETC), and thereby decreases ROS production under cellular stress [12]. Activation of intracellular signaling molecules including mitogen-activated protein kinases (MAPKs) during IR is well documented [13,14]. MAPK comprise a family of related kinases, which function downstream of similarly evolutionary conserved upstream signaling components [15]. The initially characterized signaling proteins ERK1, 2 are targets of mitogenic signaling downstream of growth factor receptors, RAS, RAF and MEK [16,17], while the related MAPKs p38MAPK and JNK, also referred to as stress kinases, serve important functions in cytokine signaling but also cell death induction [15]. In various cell and organ systems p38MAPK activity is increased upon reoxygenation/reperfusion and we recently provided first evidence that its activity may be linked to ROS generation. These ROS were also essential for cell death induction in vitro [14] (and unpublished data), a major consequence of p38MAPK signaling during IR [14,18-21]. To confirm p38MAPK as inducer of ROS-initiated damage to cells and organs, we used two experimental approaches, hypoxia/reoxygenation (HR) in vitro on HL-1 cardiomyocytes and mouse embryonic fibroblasts (MEFs) and kidney clamping in the rat, a well established model for the study of ischemia/reperfusion injury (IRI) in vivo.

**Results**

p38MAPKα regulates mitochondrial ROS accumulation during hypoxia/reoxygenation (HR)

We have shown previously that ischemia in a heterotopic heart transplant model and hypoxia in cardiomyocytes in vitro increased p38MAPK activity, which was further enhanced during reperfusion and reoxygenation, respectively [14]. Strikingly, p38MAPK inhibition reduced mitochondrial ROS levels and prevented cell death [14]. To corroborate these findings we first established the expression pattern of p38MAPK isoforms in HL-1 cells by quantitative real time PCR. This work identified p38MAPKα as the predominantly expressed isoform in these cells (Figure 1A). These results were also confirmed at the protein level (data not shown). To substantiate the involvement of p38MAPKα in regulating mitochondrial ROS levels under cellular stress siRNAs were used to decrease p38MAPKα expression (Figure 1B). We observed activation of p38MAPK during HR as monitored by the phosphorylation of its substrates MAPKAP kinase 2 (MK2) [22] and activating transcription factor-2 (ATF2) (Figure 1C). MK2 phosphorylation was significantly reduced following downregulation of p38MAPKα, however, the phosphorylation of the other p38MAPK substrate tested, ATF2 [22], was not affected (Figure 1C), suggesting alternative pathways for activating ATF2. As reported previously [14], HR resulted in increased ROS levels in HL-1 cells, which were significantly decreased in cells transfected with siRNAs against p38MAPKα (Figure 1D).

**Role of MAPKAP kinase 2 (MK2) in signaling downstream of p38MAPK**

Since siRNA knockdown of p38MAPKα affected MK2 but not ATF2 phosphorylation, we included MK2-deficient mouse embryonic fibroblasts (MEFs) [23] in our analyses and exposed them to HR. As noticed previously in MK2-deficient mice [23] MEFs also expressed lower levels of p38MAPK protein compared to wild-type controls. However, p38MAPK and MK2 activation occurred normally during HR and the treatment with BIRB796 showed the expected decrease in their activities (Figure 2A). While we did not observe a difference in basal ROS production between wild-type and MK2 knockout cells, the increase in HR-induced ROS levels was significantly lower in MK2-deficient cells (Figure 2B, C). Consistent with a role of MK2 downstream of p38MAPK, ROS production could also be decreased in wild-type cells through the application of BIRB796 but not in MK2-deficient cells (Figure 2B, C). However, application of the antioxidant N-acetyl-cysteine (NAC) was more potent in decreasing ROS levels (Figure 2B, C), arguing for additional p38MAPKα/MK2-independent modes of regulation. To exclude the possibility that down-regulation of p38MAPKα rather than the knockout of MK2 caused decreased ROS levels, we carried out the conditional knockdown of MK2 in HL-1 cells. While we were able to efficiently decrease MK2 protein levels in these cells, p38MAPK expression remained unaffected (Figure 2D). Knockdown of MK2 inevitably reduced phosphorylation of the MK2 substrate HSP25 under HR (Figure 2D). Again we observed decreased ROS
levels as a result of MK2 knockdown, further supporting that the regulation of ROS via p38MAPK proceeded through MK2 (Figure 2E, F).

p38MAPK inhibition protects from ischemia/reperfusion injury (IRI)

To test whether p38MAPK inhibition may provide a clinically feasible approach for the prevention of IRI we used kidney clamping in the rat, a model that has been extensively characterized and allows monitoring of the damage progression by using reliable markers [1,24,25]. In our in vitro and in vivo models studied previously we had consistently observed maximum signaling activity between 10 and 15 min after reperfusion and reoxygenation, respectively [14] (and data not shown), and we thus again performed a first analysis at this time point. Clamping of the renal artery for 1 hour followed by 15 min of reperfusion resulted in a pronounced activation of p38MAPK (Figure 3A, B). The overall pattern of p38MAPK activation is comparable with the one observed in HL-1 cells under HR and in the previously published heterotopic heart transplant model [14]. Intraperitoneal application of BIRB796 (5 mg/kg BW), one hour before clamping, reduced p38MAPK activity to the
background levels observed in sham-operated animals (Figure 3A, B). The changes in p38MAPK activity were also mirrored in the phosphorylation of its substrate MK2 (Figure 3A, B). No effect of the p38MAPK inhibitor on the activation of the related MAPKs ERK and JNK was observed (Figure 3A, C), indicating that within this group of kinases the expected specificity was achieved.

To monitor kidney function serum creatinine and urea levels were monitored over a period of seven days following renal IR. While setting up the model system we had chosen an ischemia time, which resulted in a pronounced deterioration of kidney function that was largely recoverable within a seven days period as based on the parameters chosen here. As shown in Figure 4A and B, serum creatinine and urea increased over two days of reperfusion.
to peak at day 3 in animals treated with DMSO (carrier). Treatment with the p38MAPK inhibitor prevented this increase, suggesting that functional damage to the kidney had been averted. Since the use of both biomarkers has been reviewed critically [26], we also included in our analyses two additional recently characterized marker proteins cystatin C [27] and NGAL [26,28]. The increase in cystatin C serum levels was significantly less pronounced in p38MAPK inhibitor-treated animals (Figure 4C). Similar results were obtained with NGAL (Figure 4D). Taken together, all markers tested responded to ischemia/reperfusion with the expected increase, which was sensitive to the inhibition by BIRB796. In a recent report HSP70 was suggested as an early and sensitive biomarker of acute kidney injury (AKI), suitable also for monitoring of renoprotective strategies [29]. IR caused a pronounced increase in HSP70 protein levels by day 2, while application of BIRB796 dramatically decreased the effect on HSP70 expression, indicating reduced incidence of AKI with this treatment (Figure 4E).

While various methods can be used to measure ROS directly in isolated cells and tissues, no robust methods are available for in vivo application. Thus the use of markers for the oxidation of lipids, nucleic acids or proteins provides indirect means to gain insight into the generation of ROS [30]. First, cell lysates were probed with antibodies directed against 3-nitrotyrosine, a marker for oxidized proteins. The analysis of day 2 samples revealed increased

**Figure 3** Effect of p38MAPK (p38) inhibition on intracellular signaling following IR. Rats were pretreated with the carrier DMSO or BIRB796 (B-796) (5 mg/kg BW) for 1 hour and subjected to 1 hour of renal ischemia followed by different time points of reperfusion (15 min, 2 days, 7 days). Kidneys were harvested at given time points of reperfusion and total tissue lysates were used to determine activation pattern of MAPKs (p38MAPK, JNK, ERK) and the downstream target of p38MAPK (MK2) by phosphorylation specific antibodies. A representative immunoblot (A) and summary graphs (B, C) are shown. Results are given as mean ± SEM (n = 3). **p < 0.01, ***p < 0.001 vs. sham-operated group; §p < 0.01, #p < 0.001 vs. IR-15 min group.
**Figure 4** (See legend on next page.)
levels of this redox modification, which were significantly reduced in inhibitor-treated animals (Figure 4F), indicating lower levels of ROS/NO. We also tested in the same samples a biomarker for oxidized lipids, 4-hydroxynonenal (4-HNE) [30]. As shown in panel G of Figure 4, lipid peroxidation was already visible at the earliest reperfusion time point analyzed and again at day 7, suggesting 4-HNE as an early marker of redox stress. In all cases signal intensity decreased to background levels in animals receiving the p38MAPK inhibitor. As a final parameter we also analyzed the phosphorylation modification of histone 2A family member X (H2AX), which serves as an indicator of endogenous oxidants [31]. As in the case of 3-nitrotyrosine, phosphorylation was most prominent on day 2 and again almost completely abolished by p38MAPK inhibition (Figure 4H). Together, these data demonstrate that application of BIRB796 prevents functional impairment usually associated with IR in the model chosen here. Finally, we also analyzed the effects of p38MAPK inhibition on cell death in the kidney by analyzing the processing of inactive caspase-3 in total kidney lysates (Figure 5A) and by TUNEL staining (Figure 5B, C). Strikingly, p38MAPK inhibition strongly blocked caspase 3 activation (Figure 5A) and in inhibitor-treated animals a significant decrease in the number of apoptotic tubular cells, particularly in the corticomedullary region, was also observed (Figure 5B, C).

Discussion
While excessive ROS production is responsible for the development of IRI, the use of antioxidants in the clinic has been faced with little success for its prevention [13,32]. Accumulating evidence suggests that signaling proteins may be targeted to modulate mitochondrial processes including ROS production [13,14,32,33]. In our work we focused on p38MAPK, which gets activated during IR and for which potent low molecular weight inhibitors are available. This kinase has been implicated in the development of IRI [14,18-21], mainly through induction of cell death. However, while ROS have been implicated in the activation of MAPKs [34], we show here that this early activation of p38MAPK during reperfusion actually works upstream of changes in cellular ROS levels. We firmly establish p38MAPK as inducer of cellular redox stress by performing siRNA-mediated knockdown of the predominantly expressed p38MAPKα isoform in HL-1 cells and provide evidence for a role of MK2 as a possible downstream effector in this process. Most importantly, we can show that p38MAPK is an important inducer of pro-oxidant stress in vivo and that inhibition of p38MAPK activation in a rat model of renal IRI prevented the functional deterioration caused by IR.

The development of strategies for the prevention of renal ischemia/reperfusion injury (IRI) is essential as this condition is one of the most common causes of acute renal failure resulting in increased morbidity and mortality [35]. In particular the early phase of reperfusion, when the major ROS release occurs, is critical for the further course of events. Once produced, ROS directly damage proteins, lipids and nucleic acids [34] and they trigger various forms of cell death, resulting in the release of endogenous ligands (damage-associated molecular patterns, DAMPs) that activate signaling pathways, including the stress kinases JNK and p38MAPK [36]. DAMP-activated Toll-like receptor 4 (TLR-4) signaling, leading to the production of ROS through NOX4, has been implicated in the apoptosis of post-hypoxic TLR4-expressing renal tubule epithelial cells (RTECs) [37]. Moreover, ROS themselves have been linked to the activation of MAPKs and cell injury [38]. One scheme involves apoptosis signal-regulating kinase 1 (ASK1) [39,40], from which the negative redox sensor thioredoxin dissociates, resulting in the formation of an active ASK1 complex after the recruitment of TNF receptor-associated factors 2 (TRAF2) and 6 (TRAF6) and the activation of Jun N-terminal kinase (JNK) [41] or p38MAPK [42]. Thus halting the early ROS production holds the promise to prevent or limit further damage amplification. Our findings suggest that preventing p38MAPK activation, which occurs early during reperfusion, may achieve this goal. We currently do not know what activates p38MAPK in this setting, whether this reflects DAMP signaling or is induced by a first wave of ROS production, which then is further amplified by p38MAPK activation. p38MAPK may be a highly suitable target for intervention as it is also involved in inflammation...
signaling [43], which additionally contributes to the development of IRI [1]. In this regard inhibiting p38MAPK may be superior to interfering with NFκB signaling, which efficiently blocked inflammation during intestinal ischemia/reperfusion but at the same time also caused severe damage to the reperfused mucosa due to the lack of NFκB survival activity [44].

p38MAPK and some of its upstream components have been implicated in the regulation of cellular stress-induced cell and organ damage. Cardioprotection during IR has been reported following the disruption of a single copy of the p38MAPKα gene [45]. Inhibition of the p38MAPK upstream kinase MAP3K TGFβ-activated kinase 1 (TAK1) protected against oxygen and glucose deprivation (OGD) in primary cortical neurons and reduced the infarct volume after middle cerebral artery occlusion in vivo [46]. However, only short term, but not prolonged inhibition of TAK1 was protective by inferring with the activation of p38MAPK and JNK and the formation of superoxide. In cultured cardiac myocytes the MAP2K MKK6 directly stimulated p38MAPK through phosphorylation and activated p38MAPK promoted cell survival, while activation by the related MKK3 resulted in death [47,48]. Consequently, MKK6 transgenic mouse hearts were protected against IR through a mechanism which involved upregulation of the small heat shock protein alpha B-crystallin [49]. The fact that inhibition of stress kinase signaling may be protective in the setting of ischemia/reperfusion by preventing cell death has been pointed out before. Thus the cardioprotective action of Sirt1 during IR results from reducing the activation of JNK and p38 [21]. Similarly the protective effects of curcumin in left anterior descending coronary artery (LAD) occlusion goes along with the attenuation of p38 and JNK activity [20]. The protective effect was further enhanced by simultaneous activation of several prosurvival kinases [20]. Direct p38MAPK inhibition
decreased cardiomyocyte apoptosis and helped to maintain cardiac function in the Langendorff-perfused rabbit heart [50]. In our work [14] we previously have obtained evidence that p38MAPK signaling is activated during IR and pilot studies in cardiomyocytes undergoing hypoxia/reoxygenation showed that p38MAPK inhibition not only reduces ROS levels but also cell death [14]. However, none of the published reports placed p38MAPK above ROS production, thus making it a suitable target for the prevention of IRI, which cannot be prevented by antioxidants.

How does the inhibition of p38MAPK prevent IRI? Most strikingly, in our experiments protection by BIRB796 was afforded under severe ischemic conditions (ischemia time of 1 hour), as documented by the established functional markers creatinine and urea. While serum creatinine and urea provide measures of kidney function, increase in Hsp70 [29] and in particular NGAL [51,52] are indicators of renal epithelial injury [53]. These findings are also corroborated by the observed protective effect of p38MAPK inhibition on the survival of tubular epithelial cells (Figure 5B, C). Apoptosis is usually caused by the acute ischemic or nephrotoxic events that are not severe enough to induce tubular necrosis and result in a different degree of impairment and acute renal failure (ARF). Therapeutic interventions that inhibit apoptosis of renal tubular cells have the potential of minimizing deterioration of renal function.

Biochemical analyses also suggested the prevention of oxidative damage in the tissues of p38MAPK inhibitor-treated animals (Figure 4). Damage caused by IR has been linked predominantly to mitochondrial ROS, although there is evidence for the involvement of non-mitochondrial ROS sources [54]. In our in vitro experiments we used MitoTracker Red CM-H2XRos a ROS-sensitive dye, which should specifically detect ROS located in the mitochondria. Since increased ROS levels and cell death depended on p38MAPK activity and the antioxidant N-acetyl cysteine (NAC) prevented apoptosis [14], p38MAPK may cause damage by increasing mitochondrial ROS levels. The highly reactive and short-lived nature of ROS makes it difficult to measure them in vivo and surrogate markers are commonly used. Nitrination of tyrosine residues by peroxynitrites, generated by the rapid interaction of superoxides with nitric oxide (NO), leads to the formation of nitrotyrosine [55]. Our data showed increase in 3-nitrotyrosine formation at day 2 of reperfusion, which was significantly reduced following the treatment with BIRB796 (Figure 4F). These findings could be confirmed by using 4-HNE as a marker for lipid peroxidation (Figure 4G). The reduction in oxidative damage following p38MAPK inhibitor treatment also correlated with the reduced functional impairment of the kidney following IR, supporting a direct role for ROS in causing damage to the kidney. Similar results were obtained using a third marker, the phosphorylation modification of H2AX (Figure 4H).

It is still an open question how the damage signal is propagated downstream of p38MAPK. Our work suggested that this at least in part may involve MK2. MK2-deficient hearts subjected to 30 min ischemia followed by 2 hours of reperfusion in the Langendorff model were resistant to myocardial IRI and also showed a diminished number of apoptotic cardiomyocytes [56]. This view was contrasted by findings obtained in a later study [23], which used a related approach. Similar infarct sizes were observed in wild-type and MK2 deficient hearts, however, these could be decreased by the p38MAPK inhibitor SB203580 [23], suggesting p38MAPK targets outside of MK2. Protection again was observed in a model of cerebral ischemic injury in MK2-deficient mice [48]. Future work will have to chart possible signaling connections between MK2 and mitochondrial ROS production.

Conclusions

ROS are causal for development of ischemia/reperfusion injury and consequential organ dysfunction or failure. Here we demonstrate for the first time that inhibition of p38MAPK prevents the early ischemia/reperfusion-associated decline in organ function, which may halt further deterioration. Our data hint that reducing redox stress and cell death may be the underlying cause. p38MAPK inhibition may thus be an alternative to antioxidants, which failed in the clinic for the prevention of redox stress-associated organ damage.

Methods

Cell culture and hypoxia/reoxygenation (HR) induction

The HL-1 cardiomyocyte cell line has been derived from AT-1 mouse atrial myocytes, obtained from transgenic mice expressing SV40 large T antigen under the control of atrial natriuretic factor (ANF) promoter [57,58]. Cells were maintained in Claycomb medium (Sigma Aldrich, Schnelldorf, Germany) supplemented with 10% fetal calf serum (FCS) (PAA Laboratories, Pasching, Austria), penicillin (100 U/ml) (PAA Laboratories, Pasching, Austria), streptomycin (100 μg/ml) (PAA Laboratories, Pasching, Austria), 0.1 mM norepinephrine (Sigma Aldrich, St. Louis, MO, USA) and 2 mM L-glutamine (GIBCO Invitrogen, Grand Island, NY, USA), as described previously [57]. Murine embryonic fibroblasts (MEFs), isolated from WT and MK2 deficient mice [59] (provided by Matthias Gaestel, Hannover, Germany), were cultivated in DMEM (PAA Laboratories, Pasching, Austria) containing 10% FCS, 2 mM L-glutamine, penicillin (100 U/ml) and streptomycin (100 μg/ml). Cells were subjected to hypoxia/reperfusion (HR) as described previously [14]. Briefly, for
induction of hypoxia (H) cells were maintained in starvation medium (DMEM or Claycomb medium, containing 0.05% FCS) and exposed to 0.5% O₂ at 37°C for 1 or 6 hours using a Modular Incubator Chamber (Billups-Rothenberg, Del Mar, CA, USA). For subsequent reoxygenation (R), starvation medium was replaced by standard culture medium. BIRB796, a highly potent ATP-competitive type II inhibitor of p38MAPK [60] (commercially obtained from Axon MedChem, Groningen, The Netherlands or kindly provided by Boehringer Ingelheim Pharmaceuticals, Ridgefield, CT, USA), was used in all in vitro and in vivo experiments described here.

**Immunoblotting**

Whole cell and tissue lysates were prepared using ice cold NP40 lysis buffer (25 mM TRIZMA base, 150 mM NaCl, 10 mM Na₄P₂O₇, 25 mM cold NP40 lysis buffer (25 mM TRIZMA base, 150 mM NaCl, pH 7.5) and exposed to 0.5% O₂ at 37°C for 1 or 6 hours in 5% BSA in PBS. After capping with 2% agarose, membranes were transferred to nitrocellulose membrane. The membranes were blocked in 5% skim milk powder (Fluka, Buchs, Switzerland), dissolved in TBST (50 mM TRIZMA base, 150 mM NaCl, pH 7.2) and probed overnight with appropriate primary antibodies, diluted in 5% BSA or skim milk powder as recommended by the provider, followed by incubation for one hour in HRP-conjugated secondary antibody, diluted in 5% skim milk. Primary antibodies against phospho-p38MAPK (9211), phospho-MAPKAP kinase 2 (3044), MAPKAP kinase 2 (3042), phospho-ATF2 (9221), Caspase-3 (9662), phospho-H2AX and phospho-HSP25 (2401) were obtained from Cell Signaling Technology, Boston, MA, USA. Immunoblotting was performed as described previously [14,61]. BRII inhibitor of p38MAPK [60] (commercially obtained from Axon MedChem, Groningen, The Netherlands or kindly provided by Boehringer Ingelheim Pharmaceuticals, Ridgefield, CT, USA), was used in all in vitro and in vivo experiments described here.

**RNA isolation and cDNA synthesis**

Total RNA from tissues and HL-1 cells was isolated using the Macherey-Nagel NucleoSpin RNA II Kit (Macherey-Nagel, Düeren, Germany) according to the manufacturer’s instructions, which included a DNase-I digest to avoid contamination with genomic DNA. RNA integrity and quality was verified by agarose gel-electrophoresis and spectrophotometrically, respectively. For cDNA synthesis 1-2 μg of total RNA was reverse transcribed in a 30 μl reaction volume using oligo(dT) primer and the RevertAid™ First Strand cDNA Synthesis Kit (Fermentas GmbH, St. Leon-Rot, Germany).

**Quantitative real time (qRT)-PCR**

The following primer pairs specific for murine isoforms of p38MAPK (α, β, γ, δ) and the housekeeping gene RPS29 were designed: p38MAPKα forward: 5′-GGCTGTGCTGCTGACCCCTTATGACC-3′, p38MAPKα reverse: 5′-GGGGTGTTGGAACAAAGCTGAT-3′, p38MAPKβ forward: 5′-AGCCCTATGATGAAAGTGTTGAGGC-3′, p38MAPKβ reverse: 5′-TCAATTTCTATGGGTGCCAGGGAGC-3′, p38MAPKγ forward: 5′-ACAGCCTGAGGCTTTGCGGT-3′, p38MAPKγ reverse: 5′-CCCCAAAGGATTTGCACACGC-3′, p38MAPKδ forward: 5′-CCCAGGAAGATTTGCACACGC-3′, p38MAPKδ reverse: 5′-GTGGTGGTTCATCCTTCGCAGC-3′, RPS29 forward: 5′-GGCTCTACTGGACACCCACG-3′, RPS29 reverse: 5′-ACTGGCACATGTGGTCAGCCCAGTA-3′. The primers were taken from regions with the lowest sequence homology between the isoforms with at least 3 bases at the 3′-end of the primer being absolute (100%) specific for the respective isoform. The optimal annealing temperature for each primer pair was determined experimentally using conventional temperature gradient PCR (Taq DNA Polymerase, Life Technologies, Paisley, UK).
from mouse heart cDNA as template. The annealing temperature gradient was from 54°C to 68°C. PCR products were visualized by ethidium bromide staining under UV-light following separation on 1.4% agarose-gels. The determined annealing temperature yielding only the specific PCR product of the expected size was used for qRT-PCR analysis. Furthermore, melting curve analysis following qRT-PCR revealed one specific peak for each primer pair (data not shown). Specificity of primer pairs was confirmed by BLAST (NCBI), and possible dimer formation was analyzed using FastPCR [62]. All primer pairs were intron-spanning. Quantitative RT-PCR reactions were performed in triplicates in a 25 μl volume containing 5 μl of the 1:5 diluted cDNA, 0.5 μM of each primer (Biomers, Ulm, Germany), and 5 μl five-fold iQ™ SYBR® Green Supermix (Bio-Rad Laboratories GmbH, Munich, Germany) on a Bio-Rad iQ5 Cycler (Bio-Rad Laboratories GmbH, Munich, Germany). After each run a melting curve analysis was carried out to confirm the specificity of the PCR products. Data were normalized to the housekeeping gene RPS29 and the untreated controls using the in-built software (normalized fold expression).

Measurement of ROS levels by fluorescent imaging
40-60 × 10^3 cells were placed in fibronectin/gelatin-coated Lab-Tek chambered cover glass (Nalge Nunc, Rochester, NY), and pretreated with either the carrier DMSO, BIRB796 or N-acetyl cysteine for 1 hour and then subjected to a hypoxia/reperfusion protocol: hypoxia (1 or 6 hours, 0.5% O2, 37°C, 0.05% FCS DMEM or Claycomb medium) and reoxygenation (2 or 15 min, normoxic atmosphere, 37°C, DMEM or Claycomb medium). For the staining procedure, the cells were incubated with MitoTracker Red CM-H2XRos (0.2 μM; Invitrogen Molecular Probes, Eugene, OR, USA) at 37°C for one hour when hypoxia time of one hour was used or for 15 min, when the hypoxia time was 6 hours followed by 15 min of reperfusion (during reperfusion). Digital images were taken using an Olympus IX-70 inverted microscope (Olympus America, Melville, NY, USA) with an Olympus 40 × water immersion objective (numerical aperture 0.8) and an Olympus U-RFL-T mercury-vapor lamp. Images were acquired using a Kappa ACCI camera and Kappa ImageBase software (Kappa Opto-electronics, Gießen, Germany). For MitoTracker Red CM-H2XRos a 568 nm-filter was used. Grey values were measured using Scion Image software for Windows. For every experimental condition grey values from 80-100 cells were averaged.

Rat kidney clamping
Male Lewis rats weighing 220-250 g were obtained from Charles River, Germany and kept with unlimited access to water and standard laboratory chow in agreement with local guidelines and the Austrian Animal Care Law. All experiments were approved by the Austrian Ministry of Education, Science and Culture and were performed in accordance with national animal protection guidelines. Rats were anaesthetized by intramuscular injection of ketamine (100 mg/Kg BW) and xylazine (10 mg/kg BW) (Graeub Veterinary Products, Bern, Switzerland). A middle incision was made to expose the abdominal cavity and after right side nephrectomy the left renal artery was identified and liberated by blunt dissection. Renal artery was clamped (1 hour) using micro suturefine clamps (FST# 18055-01; Fine Scientific Tools, Heidelberg, Germany) to induce ischemia, followed by different times of reperfusion (15 min, 2 days, and 7 days). Renal occlusion was macroscopically verified by the change in color of the kidneys to pale and reperfusion by a blush appearance of the kidney. DMSO/BIRB796 (5 or 20 mg/kg BW) was applied intra-peritoneally one hour prior to vessel clamping. Surgery was performed at room temperature; however, soon after kidney clamping the animal was placed on the heating pad (37°C) and kept there during ischemia/clamping (1 hour) and early reperfusion until the animal recovered from anesthesia. At the given time points of reperfusion the animals were sacrificed and kidney tissues were harvested and stored in neutrally buffered formaldehyde (4.5%) and liquid N2 for tissue histology and biochemical analyses, respectively. The sham-operated animals underwent the surgical procedure that was identical to the ischemic rats except that the clamps were not applied.

Assessment of renal function
Renal function was assessed by serum creatinine, urea, cystatin C and NGAL measurement. Blood samples (0.2 - 0.4 ml) were taken from the tail vein before ischemia as well as at various time points after reperfusion and centrifuged (10800 × g for 4 min) to isolate serum. Serum creatinine and urea were routinely measured at the Central Institute for Medical and Chemical Laboratory Diagnostics (ZIMCL) of the Innsbruck Medical University (IMU). Serum cystatin C and NGAL were measured using ELISA kits (BioVendor, Brno, Czech Republic).

TUNEL staining (terminal deoxynucleotidyl transferase (TdT)-mediated dUTP nick end labeling)
Kidney samples were fixed and collected in 4.5% neutrally buffered formaldehyde at room temperature until further processing. Dehydration, paraffin embedding and preparation of slides were done following standard histology procedures. For the assessment of apoptotic cells tissue sections were stained with the In Situ Cell Death Detection Kit (Roche Inc., Mannheim, Germany). For antigen retrieval the slides were pretreated in citrate buffer (pH 6) in the microwave at 750 watt for 15 min and endogenous peroxidase was blocked by incubation in 5% H2O2 in methanol for 15 min. Afterwards, the TUNEL reaction mixture was prepared freshly and the slides
were incubated for 45 min in a humidified chamber. Slides were counterstained with hematoxylin-eosine (HE) and subsequently analyzed under light microscopy. Each histological section was divided into 3 parts (cortex, corticomedullary junction and medulla). The results were quantified by counting the number of positively stained cells per 5 high-power fields (HPF) at 400 × magnification for each of the 3 areas and given as percentage.

### Statistical analyses
All numerical data are expressed as mean values ± SEM. The experimental groups were compared using one way or two way ANOVA followed by Bonferroni post hoc test. A p value of <0.05 was considered to be statistically significant.

### Abbreviations
IR: Ischemia/reperfusion injury; ROS: Reactive oxygen species; MK2: MAPKAP kinase 2; HR: Hypoxia/reoxygenation; IR: Ischemia/reperfusion; MAPK: Mitogen-activated protein kinase; DAMPs: Damage-associated molecular patterns; NAC: N-acetyl cysteine; B-796: BIRB796 (p38MAPK inhibitor).

### Competing interests
The authors declare no competing interests.

### Authors' contributions
MIA, DD, GB, JT contributed to the design of the study. MIA, ME, CW, MH, HS, MHÉ, SS, KK, ME, SK, AS, CS, SV, RS performed the experiments and analysed the results. MIA compiled the data and prepared a first manuscript draft. MIA, DD, JT contributed to the writing of the manuscript. All authors read and approved the final version of this manuscript.

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### References
1. Eltzschig HK, Ecke T: Ischemia and reperfusion from mechanism to translation. *Nat Med* 2011, 17:1391–1401.
2. Gross O, Thomas CJ, Guarda G, Tschopp J: The inflammasome: an integrated view. *Immunol Rev* 2011, 243:136–151.
3. Tschopp J: Mitochondria: sovereign of inflammation? *Eur J Immunol* 2011, 41:1196–1202.
4. Azadi MB, Chen Y, Gibson SB: Regulation of autophagy by reactive oxygen species (ROS): implications for cancer progression and treatment. *Antioxid Redox Signal* 2009, 11:777–790.
5. Huang J, Lam GT, Brumell JH: Autophagy signaling through reactive oxygen species. *Antioxid Redox Signal* 2011, 14:2215–2231.
6. Carpi A, Menabo R, Kaladennoc N, Pelico P, Di Lisa F, Giorgio M: The cardioprotective effects elicited by p66shc(a) ablation demonstrate the crucial role of mitochondrial ROS formation in ischemia/reperfusion injury. *Biochim Biophys Acta* 2009, 1789:774–780.
7. Chouchani ET, Methner C, Nadtochy SM, Logan A, Pell VR, Ding S, James AM, Cocheme HM, Reinhold J, Illyes KG, et al: Cardioprotection by 5-nitrosation of a cysteine switch on mitochondrial complex I. *Nat Med* 2013, 19:753–759.
8. Matsushima S, Kuroda J, Aigo T, Zhai P, Ikeda Y, Oka S, Feng G, Tan R, Sadoshima J: Broad suppression of NADPH oxidase activity exacerbates ischemia/reperfusion injury through inadvertent downregulation of hypoxia-inducible factor-1alpha and upregulation of peroxisome proliferator-activated receptor-alpha. *Circ Res* 2013, 112:1135–1149.
9. Kukreja RC, Janin Y: Reperfusion injury: basic concepts and protection strategies. *J Thorac Thrombolyso* 1997, 4:5–24.
10. Hummelen M, Lee I, Samavati L, Yu H, Doan JW: Regulation of mitochondrial oxidative phosphorylation through cell signaling. *Biochim Biophys Acta* 2007, 1773:701–712.
11. Pagliarini DJ, Dixon JE: Mitochondrial modulation: reversible phosphorylation takes center stage? *Trends Biochem Sci* 2006, 31:26–34.
12. Acin-Perez R, Salazar E, Kamenetsky M, Buck J, Levin LR, Manfredi G: AMP-activated protein kinase protects against regional myocardial ischemia/reperfusion injury through inadvertent downregulation of hypoxia-inducible factor-1alpha and upregulation of peroxisome proliferator-activated receptor-alpha. *Circ Res* 2013, 112:1135–1149.
13. Ashraf M, Enthammer M, Haller M, Koziel K, Hermann M: Intracellular signaling in ischemia/reperfusion injury (IR): from mechanistic insights to therapeutic options. *J Translant Technol Res* 2012. http://www.omicsonline.org/intracellular-signaling-in-ischemia-reperfusion-injury-(iri)-(from-mechanistic-insights-to-therapeutic-options-2161-0991.S3-002.php?aid=4216.
14. Sucher R, Gehwolf P, Kaier T, Herrmann M, Maglione M, Oberhuber R, Ratschiller T, Kuznetsov AV, Bosch F, Koizlov AV, et al: Intracellular signaling pathways control mitochondrial events associated with the development of ischemia/reperfusion-associated damage. *Transpl Int* 2009, 22:922–930.
15. Chen Z, Gibson TB, Robinson F, Silvestro L, Pearson G, Xu B, Wright A, Vanderbilt C, Cobb MH: MAP kinases. *Chem Rev* 2001, 101:2449–2476.
16. Zebisch A, Czemilofsky AP, Ken G, Smigelskaite J, Sill H, Troppmair J: Signaling through RAS-RAF-MEK-ERK: from basics to bedside. *Curr Med Chem* 2007, 14:601–623.
17. Zebisch A, Troppmair J: Back to the roots: the remarkable RAF oncogene story. *Cell Mol Life Sci* 2006, 63:1314–1330.
18. Meldrum KK, Meldrum DR, Hile KL, Yerkes EB, Ayala A, Cain MP, Rink RC, Casale AJ, Kafer MA: p38 MAPK mediates renal tubular cell TNF-alpha production and TNF-alpha-dependent apoptosis during simulated ischemia. *Am J Physiol Cell Physiol* 2001, 281:C563–C570.
19. Ma XL, Kumar S, Gao F, Louden CS, Lopez BL, Christopher TA, Wang C, Lee JC, Feuerstein GZ, Yue TL: Inhibition of p38 mitogen-activated protein kinase decreases cardiomyocyte apoptosis and improves cardiac function after myocardial ischemia and reperfusion. *Circulation* 1999, 99:1685–1691.
20. Jeong CW, Yoo KY, Lee SH, Jeong HJ, Lee CS, Kim SJ: Curcumin protects against regional myocardial ischemia/reperfusion injury through activation of RISK/GSK-3beta and inhibition of p38 MAPK and JNK. *J Cardiovasc Pharmacol* 2012, 17:387–394.
21. Becatti M, Taddei N, Cecchi C, Nasti N, Nasti PA, Fiorillo C: SIRT1 modulates MAPK pathways in ischemic-reperfusion cardiomyocytes. Cell Mol Life Sci 2012, 69:2245–2260.

22. Cuadrado A, Nebreda A: Mechanisms and functions of p38 MAPK signaling. Biochem J 2010, 429:403–417.

23. Gorga DA, Jabr R, Tanino M, Sarafraz N, Clark JE, Fisher SG, Cao XB, Bellahcene M, Doghe K, Kabir AM, et al: MAPKAPK-2 modulates p38-MAPK localization and small heat shock protein phosphorylation but does not mediate the injury associated with p38-MAPK activation during myocardial ischemia. Cell Stress Chaperones 2009, 14:477–489.

24. Hoff U, Lulchik L, Chaykovska L, Ladwig M, Arnold C, Manthati VL, Fuller TF, Schneider W, Galliis M, Muller DN, et al: Inhibition of 20-HETE synthesis and action protects the kidney from ischemia/reperfusion injury. Kidney Int 2011, 79:57–65.

25. Thadhani R, Pascual M, Bonventre JV: Acute renal failure. N Engl J Med 1996, 334:1488–1490.

26. Devanajan P: Biomarkers for the early detection of acute kidney injury. Curr Opin Pediatr 2011, 23:194–200.

27. Bagshaw SM, Bellomo R, Cystatin C in acute kidney injury. Curr Opin Crit Care 2010, 16:533.

28. Kjeldsen L, Cowland JB, Borregaard N: Neutrophil gelatinase-associated lipocalin and homologous proteins in rat and mouse. Biochim Biophys Acta 2000, 1482:272–283.

29. Barrera-Chimal J, Perez-Villarla R, Cortes-Gonzalez C, Ojeda-Cervantes M, Gamba G, Morales-Buenrostro LE, Bobadilla NA: Hsp72 is an early and sensitive biomarker to detect acute kidney injury. EMBO Mol Med 2011, 3:55–20.

30. Braunersreuther V, Jaquet V: Reactive oxygen species in myocardial reperfusion injury: from physiopathology to therapeutic approaches. Curr Pharm Biotechnol 2012, 13:97–114.

31. Tanaka T, Halicka HD, Huang X, Traganos F, Darzyynkiewicz Z: Constitutive histone H2AX phosphorylation and ATM activation, the reporters of DNA damage by endogenous oxidents. Cell Cycle 2006, 5:1940–1945.

32. Kuznetsov AV, Janakiraman M, Margreiter R, Troppmair J: Regulating cell survival by controlling cellular energy production: novel functions for ancient signaling pathways? FEBS Lett 2004, 577:1–4.

33. Hermann M, Kuznetsov A, Maglione M, Margreiter R, Troppmair J: Preemptive strike: cytoplasmic signaling in the control of mitochondrial apoptosis. Curr Opin Cell Biol 2006, 18:73–80.

34. Droge W: Free radicals in the physiological control of cell function. Physiol Rev 2002, 82:97–155.

35. Bonventre JV, Weinberg JM: Recent advances in the pathophysiology of ischemic acute renal failure. J Am Soc Nephrol 2003, 14:2199–2210.

36. Mikaddem SB, Bens M, Vandewalle A: Differential activation of Toll-like receptor-mediated apoptosis induced by hypoxia. Oncotarget 2010, 1:745–750.

37. Mikaddem SB, Pedruzzi E, Werts C, Coant N, Bens M, Cluzeaud F, Goujon JM, Ogier-Denis E, Vandewalle A: Heat shock protein gp96 and NAD(P)H oxidase 4 play key roles in Toll-like receptor 4-activated apoptosis during renal ischemia/reperfusion injury. Cell Death Differ 2010, 17:1474–1485.

38. Nakano H, Nakajima A, Sakon-Komazawa S, Piao JH, Xue X, Okumura K: Reactive oxygen species mediate crosstalk between NF-kappaB and JNK. Cell Death Differ 2006, 13:730–737.

39. Ichijo H, Nishiida E, Irie K, ten Dijke P, Saitoh M, Moriguchi T, Takagi M, Matsumoto K, Miyazono K, Gotoh Y: Induction of apoptosis by ASK1, a mammalian MAPKKK that activates SAPK/JNK and p38 signaling pathways. Science 1997, 275:90–94.

40. Tsubone K, Matsuzawa A, Takahashi H, Nishitoh H, Morita K, Takeda K, Minowa O, Miyazono K, Noda T, Ichijo H: ASK1 is required for sustained activations of JNK/p38 MAP kinases and apoptosis. EMBO Rep 2001, 2:222–228.

41. Noguchi T, Takeda K, Matsuzawa A, Sagiya S, Nakano H, Gohda J, Inoue J, Ichijo H: Recruitment of tumor necrosis factor receptor-associated family proteins to apoptosis signal-regulating kinase 1 signalosome is essential for oxidative stress-induced cell death. J Biol Chem 2005, 280:37035–37040.

42. Matsuzawa A, Sagiya S, Noguchi T, Takeda K, Matsuzawa A, Sagiya S, Nakano H, Gohda J, Inoue J, Ichijo H: ROS-dependent activation of the TRAF6-ASK1-p38 pathway is selectively required for TLR4-mediated innate immunity. Nat Immunol 2005, 6:587–592.

43. Yong HY, Koh MS, Moan A: The p38 MAPK inhibitors for the treatment of inflammatory diseases and cancer. Expert Opin Investig Drugs 2009, 18:1893–1905.