The Journal of Immunology

Complement Factor C5a Mediates Renal Ischemia-Reperfusion Injury Independent from Neutrophils

Bart de Vries, Jörg Köhl, Wouter K. G. Leclercq, Tim G. A. M. Wolfs, Annemarie A. J. H. M. van Bijnen, Peter Heeringa and Wim A. Buurman

J Immunol 2003; 170:3883-3889; ;
doi: 10.4049/jimmunol.170.7.3883
http://www.jimmunol.org/content/170/7/3883

The Journal of Immunology is published twice each month by
The American Association of Immunologists, Inc.,
1451 Rockville Pike, Suite 650, Rockville, MD 20852

Print ISSN: 0022-1767 Online ISSN: 1550-6606.

Complement Factor C5a Mediates Renal Ischemia-Reperfusion Injury Independent from Neutrophils[1]

Bart de Vries,* Jörg Köhl,‡ Wouter K. G. Leclercq,* Tim G. A. M. Wolfs,* Annemarie A. J. H. M. van Bijnen,* Peter Heeringa,† and Wim A. Buurman[2]*

The complement system has been shown to mediate renal ischemia-reperfusion (I/R) injury. However, the contribution of complement factor C5a to I/R injury, in particular in the kidney, remains to be established. In this study, we investigated the impact of blocking the C5aR pathway on the inflammatory response and on the renal function in a murine model of I/R injury. First, we analyzed C5aR expression in kidneys of healthy mice. Intriguingly, we found expression on mesangial, as well as on tubular epithelial, cells. After I/R injury, C5aR expression was up-regulated in tubular epithelial cells. In addition, mRNA levels of CXC chemokines and TNF-α increased significantly and kidneys were heavily infiltrated by neutrophils. Blocking the C5aR pathway by a specific C5a receptor antagonist (C5aRA) abrogated up-regulation of CXC chemokines but not of TNF-α and reduced neutrophil infiltration by >50%. Moreover, application of the C5aRA significantly reduced loss of renal function. This improvement of function was independent of the presence of neutrophils because neutrophil depletion by mAb NIMP-R14 did not affect the protective effect of C5aRA treatment. Furthermore, blocking of the C5aR pathway had no influence on renal apoptosis. These data provide evidence that C5a is crucially involved in the pathogenesis of renal I/R injury by modulation of neutrophil-dependent as well as neutrophil-independent pathways, which include the regulation of CXC chemokines but not TNF-α or apoptotic pathways. ***The Journal of Immunology,*** **2003, 170: 3883–3889.**

Organ injury as a consequence of ischemia followed by reperfusion is a major clinical problem. Renal ischemia-reperfusion (I/R)[3] injury is the most common cause of acute renal failure as seen after renal transplantation, major abdominal and vascular surgery, coronary bypass surgery, and in trauma and sepsis (1). I/R injury is characterized by the massive influx of neutrophils, which are believed to play a crucial role in the pathophysiology of postischemic renal failure (2, 3). The infiltration of neutrophils into tissue sites of inflammation is regulated by CXC chemokines such as IL-8, Groα, of which cytokine-induced neutrophil chemoattractant (KC) is the murine homolog, and macrophage inflammatory protein-2 (MIP-2) (4).

The complement system has also been shown to be an important mediator of I/R injury (5–7). Both the formation of membrane attack complex (MAC) as well as the generation of the anaphylatoxin C5a can potentially mediate I/R injury. The MAC has been reported to mediate neutrophil influx, synthesis of proinflammatory cytokines and may cause direct cell injury, apoptosis, and necrosis (8–10). Responses to C5a are mediated by the C5aR, a member of the rhodopsin family of seven transmembrane-spanning G-protein-linked receptors (11). Activation of C5aR induces recruitment of neutrophils and macrophages, and activates these and other cells to produce cytokines, chemokines, and adhesion molecules (12, 13). Recent work has also attributed a role to C5a in the regulation of apoptosis (14, 15).

Recently, we showed that inhibition of the complement system by inhibition of C5 activation, preventing C5a generation as well as MAC formation, strongly protects against renal I/R injury (16). Inhibition of C5 abrogated the induction of chemokines and influx of neutrophils and abolished I/R-induced late apoptosis. Renal I/R injury has in particular been attributed to the formation of MAC, whereas C5a has been demonstrated to be involved in I/R injury of the heart and the intestine (5, 17–20). No specific data currently exist concerning the role of C5a in renal I/R.

Therefore, we analyzed the role of C5a in I/R injury using a specific C5aR antagonist. Our findings give evidence that the C5aR pathway becomes activated in I/R injury and mediates renal dysfunction as a consequence of a strong C5a induced inflammatory response and tissue damage, which involves neutrophil-dependent, as well as neutrophil-independent, pathways.

Materials and Methods

Abs and reagents

For in vivo studies, a C5a receptor antagonist (C5aRA) was used. This C5aRA has been shown to neutralize C5a function in vitro and in vivo (20). NIMP-R14 (rat anti-mouse neutrophil mAb) was kindly provided by Dr. M. Strath (National Institute for Medical Research, London, U.K.). This mAb has an in vivo neutrophil-depleting capacity (21). Rabbit anti-mouse C5aR polyclonal Ab (C5aR) was a kind gift from Dr. J. van Beek (College of Medicine, University of Wales, Cardiff, U.K.). Secondary peroxidase-conjugated goat anti-rabbit and goat anti-rat IgG Abs were purchased from Jackson ImmunoResearch Laboratories (West Grove, PA). FITC-conjugated and Texas Red-conjugated secondary Abs were purchased from

*Department of General Surgery, Nutrition and Toxicology Research Institute Maastricht, and †Department of Clinical and Experimental Immunology, Cardiovascular Research Institute Maastricht, Maastricht University, Maastricht, The Netherlands; and ‡Institute of Medical Microbiology, Medical School Hannover, Hannover, Germany

Received for publication October 18, 2002. Accepted for publication January 28, 2003.

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked *advertisement* in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

[1] This study was supported by Dutch Kidney Foundation Grant C99.1840.

[2] Address correspondence and reprint requests to Dr. Wim A. Buurman, Department of General Surgery, Maastricht University, P.O. Box 616, Universiteitssingel 50, 6200 MD Maastricht, the Netherlands. E-mail address: W.Buurman@ah.unimaas.nl

[3] Abbreviations used in this paper: I/R, ischemia-reperfusion; MIP-2, macrophage inflammatory protein-2; MAC, membrane attack complex; C5aRA, C5a receptor antagonist; LM, ligase-mediated; BUN, blood urea nitrogen; PMN, polymorphonuclear cell.

0022-1767/03/$02.00

PickCell Laboratories (Amsterdam, The Netherlands) and Southern Biotechnology Associates (ITK Diagnostics, Uithoorn, The Netherlands), respectively. All other reagents were purchased from Sigma-Aldrich (St. Louis, MO).

Experimental protocol

Male Swiss mice weighing 20–25 g were obtained from Charles River Breeding Laboratories (Heidelberg, Germany). Animals were housed individually in standard laboratory cages and were allowed free access to food and water throughout the experiments. The studies were conducted under a protocol approved by the Institutional Animal Care Committee of the University of Maastricht (Maastricht, The Netherlands). At the start of the experiments, mice were anesthetized with sodium pentobarbital (100 mg/kg i.p.). Body temperature was maintained at 39°C by a heating pad until animals recovered from anesthesia. Under aseptic conditions a 1.0-cm long midline abdominal incision was made and ischemia was induced by applying a nontraumatic vascular clamp to the left renal pedicle for 45 min. Subsequently, the wound was covered with cotton soaked in sterile PBS. After removal of the clamp, the left kidney was inspected for restoration of blood flow and the contralateral kidney was removed. The wound was closed in two layers and 0.25% bupivacaine was applied topically for postoperative pain management. The animals were sacrificed at indicated time points after reperfusion. At the time of sacrifice, blood was collected and the left kidney was harvested for analysis. Renal tissue was divided into representative pieces for the different assays. For immunohistochemistry, total cross-sections were embedded in OCT compound and immediately frozen in isopentane/dry ice. For apoptosis and mRNA assays, kidney pieces were snap-frozen in liquid nitrogen. Tissue samples were divided in four equal parts in a standardized fashion resulting in similar cortex-medulla ratios in each sample.

Mice ($n = 6$ per group) were subjected to ischemia and treated with C5aRA or PBS. Pharmacological interventions were given i.p., based on pilot experiments, 15 min before removal of the clamps, 1 and 2 h after reperfusion (3×100 μl of 1.8×10^{-5} M C5aRA dissolved in PBS, or 3×100 μl of PBS). In separate experiments, neutrophils were depleted using mAb NIMP-R14 (1 ml of 1 mg/ml in PBS), i.p. 6 h before induction of ischemia, which has been shown to deplete neutrophils for several days (21).

Renal histology

Cryostat sections (5 μm) of frozen tissue were fixed with acetone and stained for C5aR, using a rabbit anti-mouse C5aR polyclonal Ab, and for neutrophils, using mAb NIMP-R14. Staining was either visualized by 3-amino-9-ethylcarbazole followed by hematoxylin counterstain or immunofluorescence. No significant staining was detected in slides incubated with control rabbit serum (for C5aR) and rat IgG (for NIMP-R14) instead of the primary Ab indicating the absence of significant background staining. Neutrophils were quantified in complete cross-sections by examining 20 fields of vision per kidney section (three to four sections per kidney) at ×200 magnification in a blinded fashion.

Apoptosis assay

Presence of internucleosomal DNA cleavage in kidneys was investigated with a commercial ligase-mediated (LM)-PCR assay kit (Apoalert; Clontech Laboratories, Palo Alto, CA) enabling semiquantitative measurement of the extent of apoptosis. In brief, DNA was isolated from renal tissue samples using a commercially available DNA purification kit (Promega, Madison, WI). DNA purity and concentration were determined by electrophoresis through a 0.8% agarose gel containing ethidium bromide followed by visualization under UV illumination as well as by measuring absorbance at 260/280 nm. Dephosphorylated adaptors were ligated to 5′-phosphorylated blunt ends with T4 DNA ligase (during 16 h at 16°C) and served as primers in a LM-PCR. Amplified DNA was subjected to gel electrophoresis on a 1.2% agarose gel containing ethidium bromide.

Measurement of renal C5aR, MIP-2, KC, and TNF-α mRNA levels by RT-PCR

For RT-PCR, total RNA was extracted from kidneys using the SV Total RNA isolation system (Promega) and treated with RQ1 RNase-Free DNase (Promega). Total RNA was reverse-transcribed using an oligo(dT) primer and Moloney murine leukemia virus reverse transcriptase (Life Technologies, Paisley, U.K.).

For semiquantitative PCR analysis, cDNA samples were standardized based on the content of β-actin cDNA as housekeeping gene. β-Actin cDNA was evaluated by performance of a β-actin PCR on multiple dilutions of each cDNA sample. The amount of amplified product was estimated by densitometry of ethidium bromide-stained 1.2% agarose gels using a CCD camera and Imagemaster VDS software (Pharmacia, Uppsala, Sweden). Primers used for the amplification of murine β-actin were: 5′-TAA AAC GCA GCT CAG TAA CAG TCG G-3′ (sense primer) and 5′-TGC AAT CCT GTG GCA TCC ATG AAA C-3′ (antisense primer). To determine renal C5aR, MIP-2 and KC mRNA expression, PCR with specific primers were performed using appropriate dilutions of the cDNA. The sequences of these specific primers were as follows: C5aR, 5′-ATT GCT CCT CAC CAT TCC ATC-3′ (sense) and 5′-TGA TAG GGC AGC CAG AAG ATA-3′ (antisense); MIP-2, 5′-TGC CGG CTC CTC AGT GCT G-3′ (sense) and 5′-AAA CTT TTT GAC CGC CCT TGA-3′ (antisense); KC, 5′-CGC TCG CTT CTC TGT GCA-3′ (sense) and 5′-ATT TTC TGA ACC AAG GGA GCT-3′ (antisense); TNF-α, 5′-GGC AGG TCT ACT TTG GAG TCA TTG C-3′ (sense) and 5′-ACA TTC GAG GCT CCA GTG AAT TCG G-3′ (antisense). For each primer couple, the following PCR conditions were used: C5aR, 95°C for 30 s, 60°C for 30 s, 72°C for 30 s during 40 cycles; MIP-2, 95°C for 30 s, 55°C for 30 s, 72°C for 30 s during 34 cycles; KC, 95°C for 30 s, 55°C for 30 s, 72°C for 30 s during 35 cycles; TNF-α, 95°C for 30 s, 63°C for 30 s, 72°C for 30 s during 38 cycles. PCR were performed in a total volume of 25 μl in PCR buffer (PerkinElmer, Boston, MA), in the presence of 0.2 mM dNTP (Pharmacia), 1.0 μM of each primer, 0.3 mM $MgCl_2$, and 0.5 U *Taq* polymerase (PerkinElmer). Levels of MIP-2 and KC expression were evaluated by densitometric image analysis, as described above. Relative MIP-2 and KC levels were calculated by comparison of band intensities of the PCR products with standard curves prepared by PCR amplifications on dilution series of a highly concentrated murine renal cDNA.

Real-time quantitative RT-PCR for TNF-α was performed on a Taqman ABI 7700 Sequence Detection System (Applied Biosystems, Foster City, CA). β-actin was used as reference gene. The following oligonucleotide primers and probes were used: β-actin, 5′-GAC AGG ATG CAG AAG GAG ATT ACT G-3′ (sense) and 5′-CCA CCG ATC CAC ACA GAG TAC TT-3′ (antisense) both at a concentration of 300 nM, and internal fluorescence-labeled probe (JOE) 5′-ATC AAG ATC ATT GCT CCT CCT GAG CGC-3′ at a concentration of 200 nM; TNF-α, 5′-CAT CTT CTC AAA ATT CGA GTG ACA A-3′ (sense) and 5′-TGG GAG TAG ACA AGG TAC AAC CC-3′ (antisense) both at a concentration of 200 nM, and internal fluorescence-labeled probe (FAM) 5′-CAC GTC GTA GCA AAC CAC CAA GTG GA-3′ at a concentration of 100 nM. All primers and probes were obtained from Applied Biosystems.

Renal function

Blood urea nitrogen (BUN) and serum creatinine were measured in serum obtained at the time of sacrifice using a Urea 25 Kit (ABX Diagnostics, Eindhoven, Holland) and a CREA MPR3 Kit (Boehringer Mannheim, Mannheim, Germany), respectively, in a Cobas Fara autoanalyzer (Roche, Basel, Switzerland).

Statistical analysis

Data are expressed as medians with interquartile ranges, and statistical analysis was performed by Mann-Whitney *U* test. Values of $p < 0.05$ were taken to denote statistical significance.

Results

The C5aR is widely expressed in the kidney

First, the renal C5aR mRNA expression was examined by RT-PCR. In kidneys of healthy male Swiss mice we found clear expression of C5aR. After renal I/R, C5aR mRNA levels increased evidently (Fig. 1*A*). Immunohistochemical staining for C5aR in healthy kidney revealed a faint expression on tubular epithelial cells and more intense staining of mesangial cells (Fig. 1*B*). After a 24-h reperfusion, C5aR expression in ischemic kidneys was upregulated on tubular cells. In addition, infiltrating neutrophils stained positive for the C5aR (Fig. 1*C*).

To verify the hypothesis that during renal I/R tubular epithelial cells, in addition to infiltrating inflammatory cells, express the C5aR, we performed a double-staining using immunofluorescence on tissue sections of kidneys subjected to ischemia followed by a 24-h reperfusion. Fig. 2*A* shows that renal tissue is infiltrated by neutrophils. The tubular epithelial cells show a strong positive staining for the C5aR (Fig. 2*B*). The overlay picture (Fig. 2*C*) shows that not only do all infiltrating neutrophils express the C5aR but that tubular epithelial cells also express C5aR.

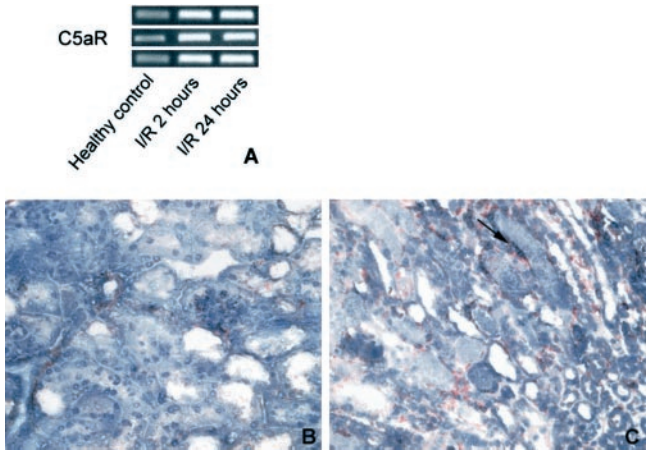

FIGURE 1. Expression of the C5aR in murine kidney tissue. C5aR mRNA is present in healthy kidney tissue and is up-regulated in tissue from mice subjected to renal I/R (*A*). Immunohistochemical staining shows the localization of the C5aR in healthy kidney tissue and 24 h after I/R (*B* and *C*, respectively). In healthy kidney, C5aR tubular, as well as mesangial, cells express the C5aR (*B*). After renal I/R, C5aR is up-regulated on tubular epithelium; additionally infiltrating neutrophils (arrow) also stain positive for the C5aR. Data shown are representative for experiments performed in four animals per group.

Blocking the C5aR pathway attenuates I/R-induced renal dysfunction

Next, the functional role of C5a in the pathophysiology of renal I/R injury was studied. BUN and serum creatinine, as a measure for renal dysfunction, increased significantly from median values of 9.5 mmol/L (BUN) and 80.4 μmol/L (creatinine) in healthy controls to 58.3 mmol/L (BUN) and 245.3 μmol/L (creatinine) in animals subjected to renal ischemia followed by 24 h reperfusion. Treatment with the C5aRA significantly reduced median BUN concentrations from 58.3 to 27.3 mmol/L as well as serum creatinine values from 245.3 to 150.2 μmol/L ($p < 0.05$) 24 h after I/R injury (Fig. 3, *A* and *B*, respectively).

Neutrophil-influx in renal I/R injury depends mainly on the C5aR pathway

A key feature of I/R injury is the influx of neutrophils. In fact, renal I/R induced a significant influx of neutrophils (median of 5.1 polymorphonuclear cells (PMNs) per field of vision) 24 h after reperfusion. Treatment with the C5aRA significantly reduced the influx of neutrophils, to a median value of 2.3 PMNs per field of vision, compared with control-treated animals ($p < 0.05$; Fig. 4). Infiltrating neutrophils mainly localized to the corticomedullary region after renal I/R, the inhibitory effect of C5aRA was most pronounced in these regions (data not shown). To further analyze the mechanism of C5a-mediated I/R injury, the role of neutrophils in the course of renal I/R injury was investigated. For this purpose, neutrophils were depleted before the induction of ischemia by administration of mAb NIMP-R14, 6 h before renal ischemia. Neutrophil-depleted mice received either the C5aRA or control (PBS) treatment. To our surprise, neutrophil depletion did not protect against I/R-induced renal dysfunction (Fig. 3). Renal function did not differ between neutrophil-depleted animals and control-treated animals (median BUN values of 56.4 vs 58.3 mmol/L and serum creatinine 245.3 vs 247.5 μmol/L; both $p > 0.5$). These data suggest that neutrophils are not essential for renal dysfunction in the course of renal I/R injury. However, application of the C5aRA significantly protected neutrophil-depleted mice from renal failure.

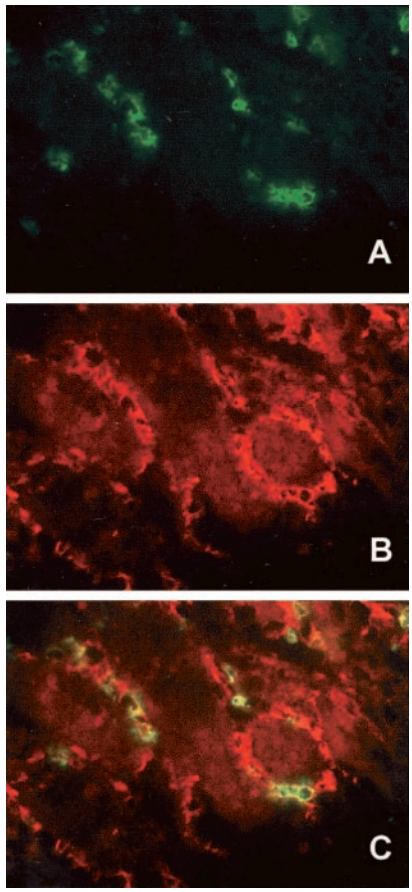

FIGURE 2. Immunofluorescence double-staining for infiltrating neutrophils and the C5aR on kidney tissue sections after renal I/R. Infiltrating neutrophils are present at 24 h I/R (*A*); additionally the C5aR is widely expressed in the same tissue section (*B*). The overlay picture (*C*) shows that infiltrating neutrophils as well as tubular cells widely express the C5aR. Green staining, neutrophils (FITC), red staining, C5aR (Texas Red). These data are representative for experiments performed in four different animals.

BUN and serum creatinine values decreased significantly from 56.4 (BUN) and 245.3 (serum creatinine) in PMN-depleted mice to 24.7 mmol/L and 125.2 μmol/L in C5aRA-treated mice ($p < 0.05$; Fig. 3, *A* and *B*, respectively). These data indicate that infiltration of neutrophils alone is not sufficient to mediate renal I/R injury. Moreover, our results give evidence that activation of the complement system and, in particular, triggering of the C5aR pathway is a crucial mechanism inducing renal dysfunction in I/R injury.

Induction of the CXC chemokines KC and MIP-2 and TNF-α in the course of renal I/R

C5a is a powerful chemoattractant and can induce neutrophil influx. C5a is also known to be involved in the induction of chemokine and cytokine production. In this context, we investigated the renal expression of the murine chemokines KC and MIP-2 in the absence or the presence of the C5aRA by semiquantitative PCR techniques. Renal I/R induces a 2- and 5-fold up-regulation of renal mRNA levels of the respective murine CXC chemokines KC and MIP-2 at a 24-h reperfusion as compared with healthy controls (Figs. 5, *A* and *B*, respectively). Treatment with the C5aRA completely prevented the up-regulation of KC and MIP-2 mRNA (Fig. 5, *A* and *B*, respectively). These data give evidence that C5a plays an important role in the regulation of chemokine induction in the course of renal I/R injury.

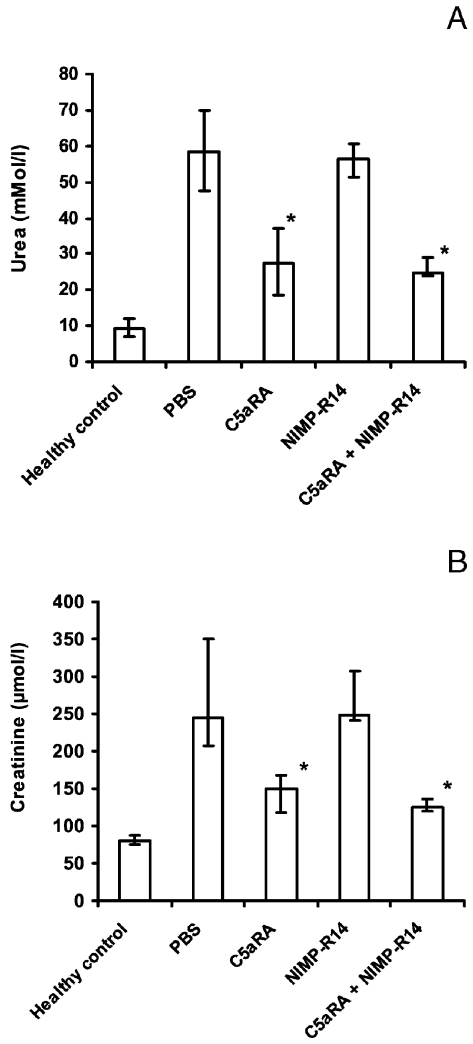

FIGURE 3. The C5aRA significantly reduces renal function loss after renal I/R. Renal function was measured by BUN (*A*) and serum creatinine (*B*) 24 h after renal I/R ($n = 6$ per group). Renal I/R induces loss of renal function which is significantly reduced by treatment with the C5aRA. Neutrophil depletion has no effect on the loss of renal function, whereas treatment with C5aRA significantly reduces BUN and creatinine values in neutrophil-depleted mice. BUN and creatinine values are expressed as medians with interquartile ranges. Statistical significance as compared with control-treated animals was denoted at $p < 0.05$ (∗).

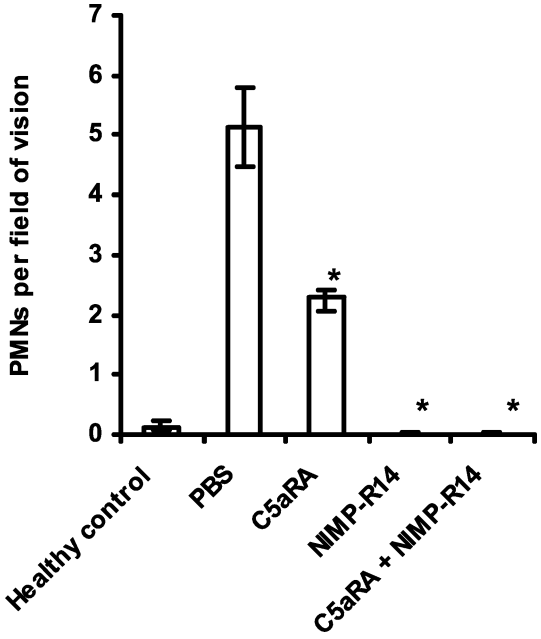

FIGURE 4. The C5aRA reduces neutrophil infiltration after renal I/R. Neutrophils were counted in three to four sections per kidney, four kidneys per group after immunohistochemical staining with mAb NIMP-R14. Data are expressed as the median number of neutrophils per field of vision with interquartile ranges. Statistical significance as compared with PBS-treated animals was denoted at $p < 0.05$ (∗).

Another important mediator of renal I/R injury is TNF-α. TNF-α mediates the induction of chemokines and subsequent neutrophil influx, but is also involved in the induction of apoptosis. Therefore, we assessed the renal expression of TNF-α upon renal I/R by real-time and semiquantitative PCR. Data did not differ between real-time and semiquantitative PCR, thus only real-time PCR data are shown. Renal I/R induced a significant 2.5-fold increase of TNF-α mRNA ($p < 0.05$). Interestingly, treatment with C5aRA did not effect this local up-regulation of TNF-α in the course of renal I/R injury (Fig. 5*C*) suggesting that the C5a-mediated up-regulation of KC and MIP-2 mRNA is independent of TNF-α.

C5aRA does not effect I/R-induced apoptosis

Renal apoptosis is an important feature in renal I/R injury. In this study, we show that renal apoptosis occurred as early as 2 h after reperfusion which was still ongoing at 24 h (Fig. 6). Treatment with the C5aRA has no influence on the induction of renal apoptosis, neither after 2 h nor after 24 h of reperfusion. Thus, C5a appears to be not involved in renal apoptosis in the course of renal I/R injury.

Discussion

The complement system has been implicated in several models of I/R injury (5–7). In myocardial I/R models, recent work indicates that the mannose-binding lectin, as well as the classical activation pathway, plays a role in complement activation and subsequent organ damage (22, 23). Regarding the precise pathway of complement activation upon renal I/R injury much remains to be resolved, however evidence is growing that activation of the complement system plays a crucial role in the pathogenesis of renal I/R injury (5). Recently, we showed that inhibition of the activation of complement factor C5 is strongly protective against the development of tissue injury upon renal I/R, indicating that the complement system indeed plays a crucial role in the development of renal I/R injury (16). To further unravel the role of the complement system, the involvement of C5a and its receptor in the pathophysiology of renal I/R injury was investigated. This study shows that C5aRA significantly attenuates renal I/R injury. This appears to be in contrast to studies by Zhou et al. (5) who provided evidence for a crucial involvement of the MAC in renal I/R injury using transgenic mice. They showed that C3, C5, but also C6-deficient mice are protected against tissue damage upon renal I/R. Moreover, inhibition of C5, preventing C5a generation, in C6-deficient mice did not have additional protective effects. On the basis of these data, Zhou et al. (5) concluded that renal I/R injury is solely dependent on formation of MAC. However, the lack of additional effects of anti-C5 in these C6-deficient mice could well be explained by codominant effects of C5a and MAC as previously reported for C5a and IgG FcγRs (24). Furthermore, the model used by Zhou et al. (5) cannot be directly compared with the one used in this study because the experimental setting was different. These authors per-

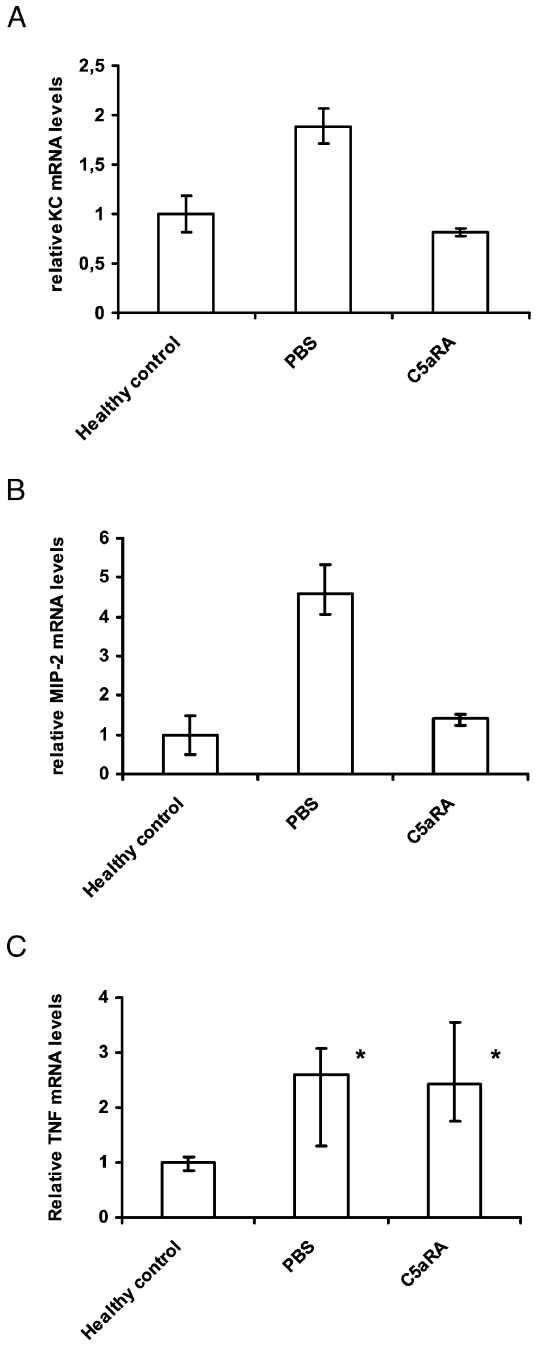

FIGURE 5. The C5aRA inhibits I/R-induced up-regulation of KC and MIP-2 mRNA levels (*A* and *B*, respectively) as measured by semiquantitative PCR. Renal I/R induces an evident up-regulation of KC and MIP-2 at 24 h reperfusion (*A* and *B*, respectively). Treatment with C5aRA abrogates the up-regulation of KC and MIP-2 mRNA. Data shown are medians with interquartile ranges ($n = 4$ per group) calibrated against equal amounts of β-actin mRNA. For TNF-α mRNA levels, real-time PCR was used (*C*). Renal I/R induces a significant up-regulation of TNF-α which is unaffected by C5aRA treatment (*C*). Data shown are medians with interquartile ranges ($n = 6$ per group) calibrated against β-actin mRNA levels. Statistical significance as compared with healthy controls was denoted at $p < 0.05$ (*).

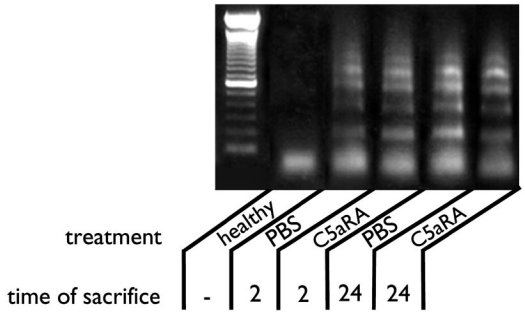

FIGURE 6. The C5aRA does not effect I/R-induced apoptosis. The extent of renal apoptosis is reflected by fragmented DNA amplified by LM-PCR and visualized on ethidium bromide-stained gel. In PBS-treated animals, internucleosomal DNA cleavage was evident after 2 and 24 h of reperfusion. Treatment with C5aRA did not effect internucleosomal DNA cleavage. Data shown are representative for three independent assays on different renal samples ($n = 3$ per group). On the *left*, a 100-bp m.w. marker is shown.

formed bilateral warm ischemia with a duration of up to 1 h, in complement-deficient mice with different backgrounds, among others C57BL/6 mice, a mouse strain known to be sensitive for renal I/R injury (5, 25). Recently, Park et al. (26) showed that complement inhibition, using the rodent C3-convertase inhibitor Crry-Ig, does not protect against renal I/R in the mouse, suggesting that the complement system is not essentially involved in renal I/R injury. The model used in this elegant study is characterized by a very short duration of renal ischemia (20–30 min) and heparin pretreatment. In contrast, studies of Zhou et al. (5) and ours, using longer ischemia times, showed that the complement system is crucially involved in renal I/R injury. Taken together, these studies indicate that the experimental models used, and especially ischemia times, play an important role in the involvement of the complement system and the effect of complement inhibition on I/R injury. This is in line with recent work of Iwata et al. (27) who showed that duration of ischemia crucially determines the mechanisms involved in I/R injury. Whereas I/R injury due to short ischemic insults is mainly mediated by neutrophils, after longer ischemic insults, apoptosis plays a crucial role in the development of I/R injury. Previously, we also showed the important pathogenic role of apoptosis in our 45-min renal I/R model (28). These data suggest that the complement system is most crucially involved in I/R injury due to more severe, clinically relevant, ischemic insults. In this study, we indeed show that the application of a specific C5aRA strongly reduces renal I/R injury implicating an important pathophysiological role of this complement cleavage product.

Our data are in line with findings obtained in intestinal and cardiac I/R models (17–20). Intravenous, as well as oral, administration of C5aRA was capable to reduce local and remote tissue injury in intestinal models of I/R injury (19, 20). In cardiac I/R models, inhibition of C5a has been shown to reduce infarct size and improve cardiac function upon ischemia (17, 29).

C5a functions via the specific C5aR, a member of the rhodopsin family of seven transmembrane-spanning G-protein-linked receptors (11). The C5aR was originally shown to be present on myeloid cells, among others neutrophils and macrophages (11). Binding of C5a to the C5aR induces chemoattraction and degranulation of leukocytes. It also functions as an anaphylatoxin, inducing smooth muscle cell contraction, histamine release from mast cells, vasodilatation, and increased vascular permeability. More recent work has shown that C5aR is also present on nonmyeloid cells, in particular bronchial and alveolar epithelial cells, hepatocytes, endothelial cells, and also in renal tissue on mesangial and (proximal) tubular epithelial cells (30). In this study, we report the presence of the C5aR on mesangial cells and tubular epithelium of the murine

kidney, on mRNA as well as on the protein level. Moreover, we show that C5aR is locally up-regulated in the course of renal I/R injury. These findings are in line with the reported expression of C5aR in the human kidney (31, 32).

Administration of C5aRA strongly reduced the influx of neutrophils in the course of renal I/R injury, which is in line with the effects of C5aRA in other inflammatory models in vivo (17, 19, 20, 33). Neutrophils are considered to be crucially involved in the pathophysiology of I/R injury, nevertheless, the role of neutrophils in renal I/R injury remains controversial (2, 34). Amsterdam et al. (18) previously showed that inhibition of C5a, using a mAb against C5a, reduced infarct size in the course of cardiac I/R, without reduction of the influx of neutrophils, indicating that some of the effects of C5a inhibition are independent of infiltrating neutrophils (17, 29). In our study, neutrophil depletion did not effect the course of renal I/R injury, as was previously reported (35, 36) but rebutted by others (3). Interestingly, the protective effects of C5aRA were independent of the influx of neutrophils, as neutrophil depletion in addition to C5aRA did not influence its protective effects. These data suggest that C5a has other receptor-mediated functions in the course of renal I/R injury, potentially mediated by C5aR expressed on nonmyeloid cells such as tubular epithelial cells, leading to renal function loss.

The induction of chemokines KC and MIP-2 in the course of I/R injury has been described previously and is reported to play a crucial role in neutrophil recruitment and subsequent I/R injury (3, 37, 38). In this study, we show for the first time that C5a is crucially involved in the regulation of these chemokines in the course of I/R. The importance of C5a in the induction of chemokines has been reported in a rat lung injury model induced by IgG immune complex deposition, however in this model, C5a-mediated chemokine induction depends on the presence of a costimulus (IgG immune complex) (12, 39). Interestingly, in these studies, C5a did not mediate local TNF-α production (39). This is in line with our data showing that C5a is not involved in TNF-α production in the course of renal I/R injury.

Activation of the complement system has been implicated in the induction of apoptosis, a process which has been shown to be crucially involved in the pathophysiology of I/R injury (28). In particular, the MAC is regarded to induce apoptosis in several inflammatory models (40, 41). Recently, we showed that inhibition of C5, which prevents both MAC formation and C5a generation, abrogated I/R-induced apoptosis (16). The present study shows that C5a does not play a role in the induction of apoptosis in the course of renal I/R, indicating that, with respect to the involvement of the complement system, the MAC is responsible for I/R-induced apoptosis. Furthermore, our data show that loss of renal function is not directly coupled with renal apoptosis. It appears that loss of function is a result of other phenomena, in which C5a plays an important role and which remain to be investigated. Taken together, our data suggest that the C5a-C5aR interaction on tubular epithelial cells induces a local inflammatory response resulting in cellular dysfunction rather than cell death which plays an important role in the pathophysiology of renal I/R injury.

In conclusion, the data presented in this study demonstrate a crucial role for C5a in the pathophysiology of renal I/R injury. C5aRA significantly attenuates I/R-induced renal failure; C5aRA strongly reduces the influx of neutrophils and induction of chemokines. Interestingly, the protective effects of C5aRA are not dependent on the presence of neutrophils but rather on direct abrogation of renal functional loss possibly mediated by direct activation of renal epithelial cells.

References

1. Thadhani, R., M. Pascual, and J. V. Bonventre. 1996. Acute renal failure. *N. Engl. J. Med. 334:1448.*
2. Heinzelmann, M., J. M. Mercer, and J. C. Passmore. 1999. Neutrophils and renal failure. *Am. J. Kidney Dis. 34:384.*
3. Miura, M., X. Fu, Q. W. Zhang, D. G. Remick, and R. L. Fairchild. 2001. Neutralization of groalpha and macrophage inflammatory protein-2 attenuates renal ischemia/reperfusion injury. *Am. J. Pathol. 159:2137.*
4. Lukacs, N. W., C. Hogaboam, E. Campbell, and S. L. Kunkel. 1999. Chemokines: function, regulation and alteration of inflammatory responses. *Chem. Immunol. 72:102.*
5. Zhou, W., C. A. Farrar, K. Abe, J. R. Pratt, J. E. Marsh, Y. Wang, G. L. Stahl, and S. H. Sacks. 2000. Predominant role for C5b-9 in renal ischemia/reperfusion injury. *J. Clin. Invest. 105:1363.*
6. Vakeva, A. P., A. Agah, S. A. Rollins, L. A. Matis, L. Li, and G. L. Stahl. 1998. Myocardial infarction and apoptosis after myocardial ischemia and reperfusion: role of the terminal complement components and inhibition by anti-C5 therapy. *Circulation 97:2259.*
7. Weisman, H. F., T. Bartow, M. K. Leppo, H. C. Marsh Jr., G. R. Carson, M. F. Concino, M. P. Boyle, K. H. Roux, M. L. Weisfeldt, and D. T. Fearon. 1990. Soluble human complement receptor type 1: in vivo inhibitor of complement suppressing post-ischemic myocardial inflammation and necrosis. *Science 249:146.*
8. Kilgore, K. S., P. A. Ward, and J. S. Warren. 1998. Neutrophil adhesion to human endothelial cells is induced by the membrane attack complex: the roles of P-selectin and platelet activating factor. *Inflammation 22:583.*
9. Kilgore, K. S., C. M. Flory, B. F. Miller, V. M. Evans, and J. S. Warren. 1996. The membrane attack complex of complement induces interleukin-8 and monocyte chemoattractant protein-1 secretion from human umbilical vein endothelial cells. *Am. J. Pathol. 149:953.*
10. Cragg, M. S., W. J. Howatt, L. Bloodworth, V. A. Anderson, B. P. Morgan, and M. J. Glennie. 2000. Complement mediated cell death is associated with DNA fragmentation. *Cell Death Differ. 7:48.*
11. Gerard, C., and N. P. Gerard. 1994. C5A anaphylatoxin and its seven transmembrane-segment receptor. *Annu. Rev. Immunol. 12:775.*
12. Czermak, B. J., V. Sarma, N. M. Bless, H. Schmal, H. P. Friedl, and P. A. Ward. 1999. In vitro and in vivo dependency of chemokine generation on C5a and TNF-α. *J. Immunol. 162:2321.*
13. Schieferdecker, H. L., G. Schlaf, K. Jungermann, and O. Gotze. 2001. Functions of anaphylatoxin C5a in rat liver: direct and indirect actions on nonparenchymal and parenchymal cells. *Int. Immunopharmacol. 1:469.*
14. Guo, R. F., M. Huber-Lang, X. Wang, V. Sarma, V. A. Padgaonkar, R. A. Craig, N. C. Riedemann, S. D. McClintock, T. Hlaing, M. M. Shi, and P. A. Ward. 2000. Protective effects of anti-C5a in sepsis-induced thymocyte apoptosis. *J. Clin. Invest. 106:1271.*
15. Mukherjee, P., and G. M. Pasinetti. 2001. Complement anaphylatoxin C5a neuroprotects through mitogen-activated protein kinase-dependent inhibition of caspase 3. *J. Neurochem. 77:43.*
16. De Vries, B., R. A. Matthijsen, T. G. Wolfs, A. A. Van Bijnen, P. Heeringa, and W. Buurman. 2003. Inhibition of complement factor C5 protects against renal ischemia-reperfusion injury: inhibition of late apoptosis and inflammation. *Transplantation 75:375.*
17. Riley, R. D., H. Sato, Z. Q. Zhao, V. H. Thourani, J. E. Jordan, A. X. Fernandez, X. L. Ma, D. R. Hite, D. F. Rigel, T. C. Pellas, et al. 2000. Recombinant human complement C5a receptor antagonist reduces infarct size after surgical revascularization. *J. Thorac. Cardiovasc. Surg. 120:350.*
18. Amsterdam, E. A., G. L. Stahl, H. L. Pan, S. V. Rendig, M. P. Fletcher, and J. C. Longhurst. 1995. Limitation of reperfusion injury by a monoclonal antibody to C5a during myocardial infarction in pigs. *Am. J. Physiol. 268:H448.*
19. Arumugam, T. V., I. A. Shiels, T. M. Woodruff, R. C. Reid, D. P. Fairlie, and S. M. Taylor. 2002. Protective effect of a new C5a receptor antagonist against ischemia-reperfusion injury in the rat small intestine. *J. Surg. Res. 103:260.*
20. Heller, T., M. Hennecke, U. Baumann, J. E. Gessner, A. M. zu Vilsendorf, M. Baensch, F. Boulay, A. Kola, A. Klos, W. Bautsch, and J. Kohl. 1999. Selection of a C5a receptor antagonist from phage libraries attenuating the inflammatory response in immune complex disease and ischemia/reperfusion injury. *J. Immunol. 163:985.*
21. Tacchini-Cottier, F., C. Zweifel, Y. Belkaid, C. Mukankundiye, M. Vasei, P. Launois, G. Milon, and J. A. Louis. 2000. An immunomodulatory function for neutrophils during the induction of a $CD4^+$ Th2 response in BALB/c mice infected with *Leishmania major*. *J. Immunol. 165:2628.*
22. Jordan, J. E., M. C. Montalto, and G. L. Stahl. 2001. Inhibition of mannose-binding lectin reduces postischemic myocardial reperfusion injury. *Circulation 104:1413.*
23. Buerke, M., H. Schwertz, W. Seitz, J. Meyer, and H. Darius. 2001. Novel small molecule inhibitor of c1s exerts cardioprotective effects in ischemia-reperfusion injury in rabbits. *J. Immunol. 167:5375.*
24. Baumann, U., J. Kohl, T. Tschernig, K. Schwerter-Strumpf, J. S. Verbeek, R. E. Schmidt, and J. E. Gessner. 2000. A codominant role of FcγRI/III and C5aR in the reverse Arthus reaction. *J. Immunol. 164:1065.*
25. Burne, M. J., M. Haq, H. Matsuse, S. Mohapatra, and H. Rabb. 2000. Genetic susceptibility to renal ischemia reperfusion injury revealed in a murine model. *Transplantation 69:1023.*
26. Park, P., M. Haas, P. N. Cunningham, J. J. Alexander, L. Bao, J. M. Guthridge, D. M. Kraus, V. M. Holers, and R. J. Quigg. 2001. Inhibiting the complement system does not reduce injury in renal ischemia reperfusion. *J. Am. Soc. Nephrol. 12:1383.*

27. Iwata, A., J. M. Harlan, N. B. Vedder, and R. K. Winn. 2002. The caspase inhibitor z-VAD is more effective than CD18 adhesion blockade in reducing muscle ischemia-reperfusion injury: implication for clinical trials. *Blood 100: 2077.*
28. Daemen, M. A., C. van't Veer, G. Denecker, V. H. Heemskerk, T. G. Wolfs, M. Clauss, P. Vandenabeele, and W. A. Buurman. 1999. Inhibition of apoptosis induced by ischemia-reperfusion prevents inflammation. *J. Clin. Invest. 104:541.*
29. Amsterdam, E. A., S. V. Rendig, and J. C. Longhurst. 1992. Contractile actions of C5a on isolated porcine myocardium. *Am. J. Physiol. 263:H740.*
30. Zwirner, J., A. Fayyazi, and O. Gotze. 1999. Expression of the anaphylatoxin C5a receptor in non-myeloid cells. *Mol. Immunol. 36:877.*
31. Zahedi, R., M. Braun, R. A. Wetsel, B. H. Ault, A. Khan, T. R. Welch, M. Frenzke, and A. E. Davis. 2000. The C5a receptor is expressed by human renal proximal tubular epithelial cells. *Clin. Exp. Immunol. 121:226.*
32. Abe, K., M. Miyazaki, T. Koji, A. Furusu, T. Nakamura-Kurashige, T. Nishino, Y. Ozono, T. Harada, H. Sakai, and S. Kohno. 2001. Enhanced expression of complement C5a receptor mRNA in human diseased kidney assessed by in situ hybridization. *Kidney Int. 60:137.*
33. Pellas, T. C., W. Boyar, J. van Oostrum, J. Wasvary, L. R. Fryer, G. Pastor, M. Sills, A. Braunwalder, D. R. Yarwood, R. Kramer, et al. 1998. Novel C5a receptor antagonists regulate neutrophil functions in vitro and in vivo. *J. Immunol. 160:5616.*
34. Jordan, J. E., Z. Q. Zhao, and J. Vinten-Johansen. 1999. The role of neutrophils in myocardial ischemia-reperfusion injury. *Cardiovasc. Res. 43:860.*
35. Paller, M. S. 1989. Effect of neutrophil depletion on ischemic renal injury in the rat. *J. Lab. Clin. Med. 113:379.*
36. Thornton, M. A., R. Winn, C. E. Alpers, and R. A. Zager. 1989. An evaluation of the neutrophil as a mediator of in vivo renal ischemic-reperfusion injury. *Am. J. Pathol. 135:509.*
37. Daemen, M. A., B. de Vries, C. van't Veer, T. G. Wolfs, and W. A. Buurman. 2001. Apoptosis and chemokine induction after renal ischemia-reperfusion. *Transplantation 71:1007.*
38. Lentsch, A. B., H. Yoshidome, W. G. Cheadle, F. N. Miller, and M. J. Edwards. 1998. Chemokine involvement in hepatic ischemia/reperfusion injury in mice: roles for macrophage inflammatory protein-2 and KC. *Hepatology 27:1172.*
39. Czermak, B. J., A. B. Lentsch, N. M. Bless, H. Schmal, H. P. Friedl, and P. A. Ward. 1999. Synergistic enhancement of chemokine generation and lung injury by C5a or the membrane attack complex of complement. *Am. J. Pathol. 154:1513.*
40. Sato, T., M. G. Van Dixhoorn, F. A. Prins, A. Mooney, N. Verhagen, Y. Muizert, J. Savill, L. A. Van Es, and M. R. Daha. 1999. The terminal sequence of complement plays an essential role in antibody-mediated renal cell apoptosis. *J. Am. Soc. Nephrol. 10:1242.*
41. Hughes, J., M. Nangaku, C. E. Alpers, S. J. Shankland, W. G. Couser, and R. J. Johnson. 2000. C5b-9 membrane attack complex mediates endothelial cell apoptosis in experimental glomerulonephritis. *Am. J. Physiol. 278:F747.*