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Complement Activation Contributes to Both Glomerular and Tubulointerstitial Damage in Adriamycin Nephropathy in Mice

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Adriamycin nephropathy is a model of focal segmental glomerulosclerosis, characterized by proteinuria and progressive glomerulosclerosis and tubulointerstitial damage. In this study, we examined the role of complement in the etiology of adriamycin nephropathy in mice. We used mice deficient in C1q, factor D, C3, and CD59, and compared them with strain-matched controls. C3 deposition occurred in the glomeruli of wild-type mice as early as 48 h following a single i.v. injection of adriamycin. C3-deficient mice developed significantly less proteinuria and less podocyte injury at day 3 postadriamycin than controls, suggesting that complement is important in mediating the early podocyte injury. At later time points, C3-deficient mice were protected from glomerulosclerosis, tubulointerstitial injury, and renal dysfunction. Factor D-deficient mice were also protected from renal disease, confirming the importance of alternative pathway activation in this model. In contrast, C1q-deficient mice developed similar disease to controls, indicating that the complement cascade was not activated via the classical pathway. CD59-deficient mice, which lack adequate control of C5b-9 formation, developed significantly worse histological and functional markers of renal disease than controls. Interestingly, although more C9 deposited in glomeruli of CD59-deficient mice than controls, in neither group was tubulointerstitial C9 staining apparent. We have demonstrated for the first time that alternative pathway activation of complement plays an important role in mediating the initial glomerular damage in this in vivo model of focal segmental glomerulosclerosis. Lack of CD59, which regulates the membrane attack complex, led to greater glomerular and tubulointerstitial injury. The Journal of Immunology, 2006, 177: 4094–4102.

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2Abbreviations used in this paper: MAC, membrane attack complex; HPF, high-powered field.

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nephropathy. We have also shown that complement-mediated injury occurs via activation of the alternative, but not the classical pathway in this model. In addition, inhibition of the membrane attack pathway by its regulatory protein CD59 is important in controlling this type of complement-dependent glomerular injury and subsequent tubulointerstitial injury.

Materials and Methods

**Animals**

CD59-deficient (mCd59a−/−), C1q-deficient (Clqa−/−), and C3-deficient (C3−/−), and factor D (Cfd−/−) mice were generated, as described previously (10–13). All gene-targeted animals were then backcrossed for six generations onto a BALB/c genetic background and compared with strain and age-matched controls. To ensure that C3−/− BALB/c (N6) mice were of the same H2 haplotype as wild-type BALB/c mice, H2 haplotype was checked for by PCR. Only female mice were used. Mice were kept in a specific pathogen-free environment, and experiments were performed according to institutional guidelines.

**Experimental protocol**

To induce adriamycin nephropathy, a single i.v. injection of doxorubicin (adriamycin; Pharmacia & Upjohn) diluted 1/2 with 0.9% saline was administered into the tail vein. For experiments with C3−/−, Cfd−/− and Clqa−/− mice, a dose of 10 mg/kg adriamycin was used. A lower dose of 9 mg/kg was administered in experiments using mCd59a−/− mice, as preliminary experiments demonstrated that mCd59a−/− mice became rapidly unwell with large doses. Mice were killed at 8 wk postadriamycin injection unless they became ill at earlier time points. In addition, to ascertain the time course of renal complement deposition, some wild-type BALB/c mice were killed at earlier time points.

**Histological analysis**

Kidneys were fixed for 24 h in 4% buffered formal saline, transferred to 70% ethanol, and embedded in paraffin. Sections were then stained with periodic acid-Schif. All analyses were performed blinded to the sample identity. Tubulointerstitial damage was assessed by ranking of sections taking into account tubular necrosis, tubular dilatation, and cast formation in randomized sections. Glomerulosclerosis was assessed by grading the area of periodic acid-Schiff-positive sclerosis for each glomerulus, as follows: grade 0 = no sclerosis; grade 1 = 0–25%; grade 2 = 25–50%; grade 3 = 50–75%; and grade 4 = 75–100%. The mean glomerulosclerosis score for 50 glomeruli was then calculated. Paraffin-fixed sections were also stained with picrosirius red for assessment of collagen deposition. The mean area of positive staining was quantified using Image-Pro Plus software (Media Cybernetics) of images captured from a Photonic Science Color Coolview digital camera (Photonic Science).

**Immunofluorescence**

Kidneys were snap frozen in isopentane and stored at −70°C. Frozen sections were cut at a thickness of 5 μm. An observer without knowledge of the sample identity performed all the quantitative immunofluorescence analyses. For C3 staining, a goat anti-mouse C3 FITC-conjugated Ab (Valeant Pharmaceuticals) was used. For C9 staining, a rabbit anti-rat C9 primary Ab (1:100) (J办法silical) was used. For the type IV collagen staining, a polyclonal rabbit anti-human type IV collagen Ab (1:100) (Research Diagnostics) and a FITC-labeled mouse anti-rabbit IgG secondary (1:50) (Sigma-Aldrich; F-4151) were used. All incubations were performed for 1 h at room temperature, and all Abs were diluted in PBS. A negative control (PBS) was used in each experiment to ensure there was no binding of the secondary Ab to the kidney section. In quantitative immunofluorescence studies, to exclude artifacts due to variable decay of the fluorochrome, all sections from one experiment were stained and analyzed at the same time. Sections were examined at ×400 magnification using an Olympus BX4 fluorescence microscope (Olympus Optical). A Photonic Science Color Coolview digital camera (Photonic Science) was attached to the microscope and, using Image-Pro Plus software (Media Cybernetics), images were captured for analysis. For glomerular analysis 20 glomeruli were examined in each section, and for the tubulointerstitium 10 high-powered field (HPF) of the cortico-medullary area were assessed for each section. In each case, the mean fluorescence intensity was recorded, with results expressed in arbitrary fluorescence units.

**Immunohistochemistry**

For α smooth muscle actin staining, paraffin-embedded, formalin-fixed sections were used. These were rehydrated and deparaffinized through graded alcohols. An Ag retrieval step was then performed by heating slides in 0.01 M citrate buffer (pH 6) in a microwave oven at 600 W for 20 min. Sections were blocked with 5% normal rabbit serum, and a primary monoclonal mouse anti-human smooth muscle actin monoclonal Ab (clone 1A4; Sigma-Aldrich) (1/50 dilution) was then applied. The sections were then processed with the DAKO Envision AP kit (DakoCytomation), following the manufacturer’s instructions. The kit uses Fast Red as the chromogenic substrate. The quantity of smooth muscle actin on renal sections was assessed by ranking sections according to the degree of Fast Red staining. Apoptosis was assessed by TUNEL staining using the In Situ Cell Death Detection Kit, POD (Roche Applied Science), following the manufacturer’s instructions, and quantified by counting the number of apoptotic nuclei per HPF averaged over 20 HPF per section.

**Electron microscopy**

Specimens (1 mm³) of renal cortex were fixed in 3% glutaraldehyde in 0.1 M cacodylate buffer for 4 h at 4°C. The samples were then postfixed in 2% aqueous osmium tetroxide, block stained in 2% aqueous uranyl acetate, dehydrated through ascending grades of ethanol, and embedded in Spur’s resin at 70°C overnight. Ultrathin sections were collected on 400 mesh copper grids and stained with 1% aqueous uranyl acetate and Reynolds’s lead citrate.

**Renal function assessment**

Serum urea was measured using an Olympus AU600 analyzer (Olympus Diagnostics). Proteinuria was measured by dipstick of urine (Hema-Com-bistix; Bayer) daily for the first week and then weekly. In addition, mice were placed in metabolic cages for 24-h collection of urine to allow more accurate assessment of urine albumin concentration. The albumin concentration was measured by radial immunodiffusion. Samples and standards (mouse albumin) (Sigma-Aldrich) were placed in wells (4 μl/well) in 1.2% agarose in PBS containing rabbit anti-mouse albumin (Biogenesis). Gels were dried and stained with Coomassie blue. Albumin concentration was calculated with reference to a standard curve.
Statistical analysis

All values described in the text and figures are expressed as median and range for n observations. Statistical analysis was conducted using GraphPad Prism 3.02 (GraphPad). Data were analyzed using a Mann-Whitney U test for all comparisons, and a p value of <0.05 was considered to be significant. For survival analysis, a Kaplan-Meier statistic was used and a p value of <0.05 was also considered significant.

Results

Initial dose-ranging experiments using between 7 and 11 mg/kg adriamycin in wild-type BALB/c female mice suggested that a dose of 9–10 mg/kg adriamycin produced significant irreversible injury characterized by glomerulosclerosis and tubular injury at 2 wk postinjection, followed by interstitial inflammation and fibrosis at later time points (4–6 wk; data not shown). Higher doses produced much more severe injury that developed more rapidly, while lower doses produced only mild reversible histological abnormalities. However, in all experiments, independently of the dose administered, significant proteinuria was observed (+ + + + on dipstick) from weeks 1 to 6.

Glomerular C3 deposition occurs by 48 h after adriamycin administration

To investigate the role of the complement system in mediating the initial glomerular injury following adriamycin injection, we killed BALB/c mice at various time points to study glomerular complement deposition. Immunofluorescence microscopy revealed that in unmanipulated BALB/c mice kidneys, C3 was present around tubules and along Bowman’s capsule, but no C3 was detected in glomeruli (Fig. 1A). However, as early as 48 h postadriamycin administration, there was sparse glomerular C3 staining (Fig. 1B). This increased in intensity by day 5 (Fig. 1C). At 10 days, by which point significant glomerulosclerosis and tubulointerstitial injury had occurred, intense glomerular C3 staining was present, particularly within more severely diseased glomeruli (Fig. 1D). In addition, there was increased C3 deposition in areas of most severe tubulointerstitial damage.

C3-deficient mice were protected from early glomerular injury

Guided by these findings, we decided to investigate the role of complement activation in the pathogenesis of adriamycin nephropathy by studying the effect of injecting 9 mg/kg adriamycin in...
C3−/− animals compared with BALB/c controls. Small amounts of albumin could be detected in the urine of wild-type animals as early as day 2 postadriamycin injection and reached a maximum level by day 6. In contrast, the onset of albuminuria was markedly delayed in C3−/− mice, but achieved a similar upper limit to the wild-type mice by day 10 after the administration of adriamycin (Fig. 4A). Consistent with these findings, electron microscopy of glomeruli at day 3 after adriamycin showed that there was better preservation of podocyte foot processes in C3−/− mice than wild-type animals (Fig. 2, B and C).

Absence of C3 reduced progressive renal injury
Four weeks postadriamycin injection, C3−/− mice were significantly protected from chronic glomerular damage (median sclerosis score 0.8; range 0.3–1.1; n = 8 for C3−/− vs 2.0; 0.8–3.6; n = 8 for wild type, p = 0.007; Fig. 3A) and tubulointerstitial injury (median rank of tubular injury 6; range 3–9; n = 8 for wild type vs 2; 1–5; n = 8 for C3−/−, p = 0.004; Fig. 3B). Consistent with these structural differences, C3−/− animals were protected from renal impairment when compared with wild-type controls (median urea 7.2 mmol/L; 5.7–9.1; n = 8 for C3−/− vs 12.8; 10.3–60.0; n = 8 for controls, p = 0.0002; Fig. 3C). Histological changes showed severe, often global sclerosis in wild-type animals (Fig. 4A) with only relatively minor, segmental abnormalities in C3−/− animals (Fig. 4B). Concomitantly, wild-type animals displayed severe tubular damage typified by loss of the epithelial brush border, flattening of tubular cells, and tubular cast formation (Fig. 4C). In contrast, tubular injury was mild in C3−/− mice (Fig. 4D). In wild-type animals, C3 was deposited especially in areas of most severe renal damage, but also in a peritubular distribution (Fig. 4E). No C3 staining was seen in C3-deficient mice (Fig. 4F).

Complement activation by the alternative pathway caused renal injury
C3 activation can occur by the classical, alternative, or lectin pathways. To dissect out the role of alternative pathway activation, we used mice deficient in the alternative pathway component factor D. Cfd−/− mice were protected from early proteinuria in a similar fashion to C3−/− mice (Fig. 5A), suggesting that alternative pathway activation mediated the early complement-induced podocyte damage. Three weeks after adriamycin administration, Cfd−/− mice were significantly protected from both glomerular injury (median injury score 3.2; range 0.8–3.5; n = 6 for controls vs 0.0–0.8; n = 5 for Cfd−/− mice, p = 0.02; Fig. 5B) and tubulointerstitial damage (median injury rank 9; range 6–11; for controls vs 3.5; 1–7; for Cfd−/− mice, p = 0.009; Fig. 5C). In addition, renal function was preserved in Cfd−/− mice as compared with matched controls (median urea 9.4 mmol/L; 8.6–12.9; for controls 0.0009).
vs 4.8; 4.2–5.6; for Cfd−/− mice, p = 0.036; Fig. 5D). To confirm that the absence of factor D protected Cfd−/− mice from renal injury by preventing C3 activation, we stained renal sections for C3. No C3 immunofluorescence staining was apparent in either glomerular or tubulointerstitial compartments in the Cfd−/− mice (Fig. 5F).

Classical pathway activation of complement was not involved in the pathogenesis of adriamycin nephropathy

To explore possible classical pathway involvement, we examined adriamycin-induced nephropathy in C1q-deficient mice. The levels of proteinuria were similar in C1qa−/− and wild-type animals during the entire period of observation (Fig. 6A). Structural injury 4 wk postadriamycin administration was not significantly different between C1qa−/− mice and BALB/c controls in terms of either glomerulosclerosis (median injury score 2.8; range 0.4–3.2; n = 6 for C1qa−/− vs 1.9; 1.1–2.7; n = 7 for controls, p = 0.48; Fig. 6B) or tubulointerstitial injury (median rank of tubular injury 7; range 2–12; n = 6 for C1qa−/− vs 6; 1–11; n = 7 for controls, p = 0.76; Fig. 6C). In addition, there were no functional differences in terms of serum urea between the two groups of mice (median urea 12.5 mmol/L; 6.6–32.2; n = 6 for C1qa−/− vs 8.4; 7.4–23.1; n = 7 for controls, p = 0.6; Fig. 6D).

The terminal complement pathway played an important role in mediating renal damage

To determine the role of the membrane attack pathway in the pathogenesis of adriamycin-induced renal damage, we used mCd59a−/− mice that lack the major regulator of MAC formation. Despite a similar degree of proteinuria (Fig. 7A), mCd59a−/− mice

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**FIGURE 5.** Markers of renal injury after adriamycin injection in Cfd−/− and control mice. Cfd−/− mice developed less proteinuria measured by dipstick than wild-type animals after adriamycin administration (A). Renal sections from Cfd−/− animals displayed significantly less glomerulosclerosis (B) and tubulointerstitial injury (C) compared with matched controls. In addition, Cfd−/− mice were protected from renal dysfunction (measured by serum urea) compared with controls (D). Wild-type mouse kidneys showed significant glomerular C3 staining (E). In contrast, C3 staining was notably absent from Cfd−/− mouse kidneys (F). The error bars denote SEM.
FIGURE 6. Markers of renal injury after adriamycin injection in C1qa−/− and control mice. At 3 wk after adriamycin administration, there were no differences in proteinuria measured by dipstick between C1qa−/− and wild-type mice (A). Additionally, no significant differences in either glomerular (B) or tubulointerstitial injury (C) or in serum urea (D) were demonstrated between C1qa−/− animals and controls.

Discussion

The model of adriamycin nephropathy in rodents has been studied as a model of proteinuric renal disease in which there are progressive glomerulosclerosis and tubulointerstitial injury. In particular, it has been used to elucidate the role of proteinuria in leading to progressive tubulointerstitial scarring. In this study, we examined the role of the complement system in this model in mice. We confirmed previous descriptions on the time course of the renal disease in this model in BALB/c mice (15) and found that after a single i.v. dose of adriamycin there was rapid onset of albuminuria, which was first detectable by day 2. Renal sections demonstrated focal and segmental glomerulosclerosis and subsequent, progressive tubulointerstitial scarring. These changes were accompanied by increased deposition of C3 in glomeruli. We therefore studied the course of the model in C3-deficient mice.

Mice lacking C3 showed a reduction in severity of the disease. The earliest manifestation of this was a delay in the onset of detectable albuminuria accompanied by a reduction in podocyte damage as assessed by effacement of foot processes. Subsequently, mice without C3 showed less glomerulosclerosis and less tubulointerstitial scarring and, functionally, this was reflected by better renal function with a lower serum urea. The classical pathway of complement activation was not involved in initiating this complement-dependent injury, as the absence of C1q did not alter disease severity. To investigate whether complement-mediated damage ensued from alternative pathway activation, we studied mice deficient in the alternative pathway component factor D. We demonstrated that Cfd−/− mice were protected from early proteinuria, and from later glomerular and tubulointerstitial injury. This was also manifested functionally as an improvement in renal function as assessed by serum urea. It would have been interesting to study mice deficient in factor B. However, the factor B gene lies on chromosome 17 in the same region as the MHC, and therefore, backcrossing factor B-deficient mice (that are H2b) onto a BALB/c background (H2d) would have meant comparing mice with different H2 haplotypes, which could have confounded the results thereby obtained.

We hypothesize that adriamycin causes initial toxic injury to the podocyte, and then the damaged cells are able to activate the alternative pathway possibly because of reduced surface expression of complement-inhibitory molecules. The deposition of C3 then...
exacerbates podocyte injury, leading to earlier onset of proteinuria and subsequently more severe glomerular injury and sclerosis. Once activated, the complement system may mediate renal damage through either the leukocyte chemoattractant effect of C5a or via MAC. To investigate further the role of the membrane attack pathway, we used \textit{mCd59a}^{-/-} mice and demonstrated that the lack of CD59, and therefore unregulated MAC deposition, significantly exacerbated renal disease in terms of glomerulosclerosis, tubulointerstitial injury, and serum urea. We have shown previously exacerbation of glomerular injury in nephrotoxic nephritis in mice lacking CD59 (16), and the present results emphasize further the important role that CD59 plays in controlling glomerular injury due to complement activation.

In parallel with the effects on glomerular injury, we found that tubulointerstitial injury was reduced in mice lacking C3 and exacerbated in mice without CD59, implying an important role for the MAC. Mice lacking CD59 showed increased tubulointerstitial apoptosis, as demonstrated by TUNEL staining, increased interstitial collagen deposition, and increased interstitial myofibroblasts identified by \textit{α} smooth muscle actin staining. The pathogenic mechanisms that link proteinuric renal disease and progressive tubulointerstitial fibrosis are of considerable interest and have been reviewed recently (17). There is a clear relationship between the degree of proteinuria and the severity of interstitial disease in rodent models, such as protein-overload proteinuria and puromycin aminonucleoside nephritis. Studies using these models have suggested that the proteinuria itself could induce the progressive interstitial injury, and several hypotheses have been proposed as potential mechanisms of proteinuria-induced tubulointerstitial injury. These include direct tubulotoxicity of high protein concentrations (18) or that specific proteins such as growth factors, lipoproteins (19, 20), transferrin (21), or activated complement components (22, 23) may be damaging. Recent studies have emphasized the role of the MAC. Rangan et al. (3) examined adriamycin nephropathy in C6-deficient rats that were unable to form MAC. They found that MAC deposition occurred predominantly on the luminal surface of proximal tubules in wild-type C6-sufficient rats. Despite a similar level of proteinuria and glomerular injury, C6-deficient rats had fewer peritubular myofibroblasts than controls. These data suggest that proteinuria-induced intraluminal formation of C5b-9 is responsible for myofibroblast formation, and thereby contributes to progressive interstitial damage and renal failure in proteinuric glomerular disease. An alternative hypothesis for the tubulointerstitial injury in focal and segmental glomerulosclerosis is that podocyte injury causes adhesion of the glomerular tuft to Bowman’s capsule, followed by accumulation of misdirected filtrate around the origin of the proximal tubules with subsequent occlusion and tubular atrophy (24). These two hypotheses of tubular

\textbf{FIGURE 7.} Markers of renal injury after adriamycin injection in \textit{mCd59a}^{-/-} and control mice. At 3 wk after adriamycin administration, there were no differences in proteinuria between \textit{mCd59a}^{-/-} and wild-type mice (A). Renal sections from \textit{mCd59a}^{-/-} animals displayed significantly greater glomerulosclerosis (B) and tubulointerstitial injury (C) compared with matched controls. In addition, \textit{mCd59a}^{-/-} mice developed greater renal dysfunction (measured by serum urea) than controls (D). The wild-type mouse kidneys showed minor tubular injury (E). In contrast, \textit{mCd59a}^{-/-} mouse kidneys displayed severe tubular damage and cast formation (F). The error bars denote SEM.
damage due to proteinuria and misdirected filtration with subsequent nephron loss are not mutually exclusive.

Our study does not allow us to determine which mechanism leads to tubulointerstitial scarring in adriamycin nephropathy in mice. However, it is notable that, although we found markedly increased staining for C9 in the glomeruli of mice lacking CD59, we found very little C9 staining associated with tubules in wild-type or CD59-deficient mice, which argues against a major role of tubular MAC deposition in causing direct tubular injury, but rather suggests that in the absence of CD59 there is increased glomerular MAC leading to increased glomerular scarring, and this then leads to tubulointerstitial scarring by a process not dependent on tubular complement activation.

Clearly, there are significant differences between our model and the model of adriamycin nephropathy in the rat described by Rangan et al. (3), in which tubular MAC was detected. In their model, no C3 was found in glomeruli, whereas we observed clear C3 deposition that increased with time. The reason for these differences is not clear and may reflect either a species difference or differences in the dose of adriamycin and severity of the model. They found only a mild glomerulosclerosis, but no difference in the progression of glomerulosclerosis in rats lacking C6, suggesting that MAC did not play a role in the glomerular lesions, whereas our results in CD59-deficient mice clearly show that if MAC activity is uncontrolled, then this leads to increased glomerulosclerosis.

In conclusion, we have demonstrated an important functional role of the complement system in mediating injury in adriamycin nephropathy. We have shown that lack of C3 reduces early glomerular injury and proteinuria and ameliorates subsequent glomerular and tubulointerstitial scarring with preservation of renal function. We have demonstrated for the first time that lack of a functional alternative pathway markedly reduces both histological and functional markers of renal injury in this model. We have also shown that CD59, by limiting deposition of the MAC, protects the glomerulus from scarring. CD59 also limits tubulointerstitial scarring, although whether this is indirect via the effect on glomerular scarring or a specific role for tubular CD59 is unclear.

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