Major Histocompatibility Complex Class II Expression by Intrinsic Renal Cells Is Required for Crescentic Glomerulonephritis

By Shuo Li,* Christian Kurts‡ Frank Köntgen,*
Stephen R. Holdsworth,* and Peter G. Tipping*

From the *Centre for Inflammatory Diseases, Monash University Department of Medicine, Monash Medical Centre, Clayton, 3168, Victoria, Australia; and the ‡Immunology Division, Walter and Eliza Hall Institute, Parkville, 3050, Victoria, Australia

Summary

The requirement for major histocompatibility complex class II (MHC II) to initiate immune renal injury was studied in a murine model of CD4+ T cell–dependent crescentic glomerulonephritis (GN). C57BL/6 (MHC II+/+) mice developed crescentic GN with glomerular CD4+ T cell infiltration and renal injury, in response to a nephritogenic antigen (sheep globulin) planted on their glomerular basement membrane. MHC II–deficient C57BL/6 mice (MHC II−/−) did not develop crescentic GN, CD4+ T cell infiltration, or injury, indicating that this form of immune glomerular injury is MHC II dependent. The requirement for MHC II expression by intrinsic renal cells was studied in chimeric mice, which expressed MHC II on bone marrow–derived cells and in the thymus, but not in the kidneys. These chimeric mice had normal T and B cell populations and MHC II expression in their spleens and lymph nodes and developed an immune response to systemically and cutaneously administered sheep globulin. However, they did not develop crescentic GN, CD4+ T cell infiltration, or renal injury in response to the sheep globulin planted in their glomeruli. These studies demonstrate that interaction of CD4+ T cells with intrinsic renal cells expressing MHC II is required for development of cell-mediated immune renal injury.

Key words: major histocompatibility complex • glomerulonephritis • T lymphocyte • kidney • mice

T cell responses are normally dependent on recognition of antigen bound to MHC molecules on the surface of APCs. MHC class I molecules are predominantly associated with CD8+ cytotoxic T cell responses. MHC class II (MHC II) molecules present antigens to CD4+ T cells, which stimulate antibody production and isotype switching and act as effector cells for local cell-mediated immune responses.

"Professional" APCs are bone marrow–derived cells that present antigen to naive T cells in secondary lymphoid tissues. After activation, T cells enter nonlymphoid tissues, where they can recognize antigen and initiate local immune responses. It is well accepted that MHC II is required during activation of naive CD4+ T cells in secondary lymphoid tissues. However, the functional contribution of MHC II on resident cells to the effector phase of cell-mediated immune injury targeted at specific tissues in vivo is unknown. MHC II expression can be stimulated on cells in many organs, including mesangial cells (1, 2) and proximal tubular cells in the kidney (3, 4). Thyroid epithelial cells expressing "aberrant" MHC II can present viral antigens to cloned human T cells in vitro (5).

Glomerular antibody deposition and/or accumulation of T cells is observed in the majority of cases of human glomerulonephritis (GN). These immune effectors localize in response to endogenous glomerular antigens or antigens deposited in glomeruli as components of immune complexes or because of their size or charge characteristics. In the most severe forms of human GN, glomerular injury is manifested by a "proliferative" histological pattern, accumulation of T cells and macrophages, proliferation of intrinsic glomerular cells, accumulation of cells and fibrin in Bowman’s space ("crescents"), and rapid deterioration of renal function. Studies of crescentic forms of human (6, 7) and experimental GN (8, 9) suggest an important effector role for CD4+ T cells. Glomerular deposition of Ig is often sparse or absent in crescentic human GN (7), and in an experimental model, crescent formation has been demonstrated to be antibody independent (10). How-
ever, the role of glomerular MHC II expression in the local immune effector response is unknown.

MHC II−/− mice were thymectomized at 4 wk of age, irradiated with 700 rad at 7 wk of age, and transplanted with T cell–depleted bone marrow from B6 (C57BL/6) mice. After an additional 4 wk, mice were subjected to identical transplantation process to generate congenic (900 rad) newborn wild-type (WT) mouse. B6 mice were from B6 (C57BL/6) mice. After an additional 4 wk, mice were thymectomized at 4 wk of age, irradiated with 700 rad at 7 wk of age, and transplanted with T cell–depleted bone marrow from B6 (C57BL/6) mice. After an additional 4 wk, mice were engrafted under the kidney capsule with a thymus from an irradiated (900 rad) newborn wild-type (WT) mouse. B6 mice were subjected to an identical transplantation process to generate control (B6→B6) chimeras.

Assessment of Lymphocyte Populations in Chimeric Mice. Lymphocyte subsets in pooled spleen and LN cell suspensions were assessed by flow cytometry using the following mAbs: FITC-conjugated anti-CD4, PE-conjugated anti-CD8, and FITC-conjugated anti-CD3 (PharMingen, San Diego, CA) as described previously (10). MHC II expression on B cells was assessed using FITC-conjugated anti-MHCII (Phar-Mingen).

Induction of anti-GBM GN and Assessment of Renal Injury. Crescentic GN was initiated in mice by a single intravenous injection of 10 mg of sheep anti-GBM globulin, as described previously (13). Renal injury and other parameters were assessed 21 d later. Histological assessment was performed on 2-μm periodic acid-Schiff–stained kidney sections. Crescent formation was assessed in a minimum of 30 glomeruli, in a blinded protocol, as described previously (13, 14). Proteinuria was determined by the alkaline picric acid method using an autoanalyzer (Cobas Bio; L. Hoffman-La Roche Ltd., Basel, Switzerland).

A assessment of the Systemic Immune Response to Sheep Globulin. Cutaaneous delayed-type hypersensitivity (DTH) to the sheep globulin was assessed by intradermal challenge with 0.5 mg in 20 μl of PBS into the hind foot of mice, 20 d after the systemic administration of sheep anti-mouse GBM globulin, as described previously (14). O valbumin (Sigma-Aldrich Pty. Ltd., Castle Hill, N.S.W., Australia) injected into the opposite foot pad was used as a control. Circulating titers of mouse anti-sheep globulin antibody were measured by ELISA as described previously (10, 14). Optical densities (405 nm) were converted to micrograms per milliliter of antibody by reference to a standard curve generated with known concentrations of bound mouse IgG. Serum from six nonimmunized mice was used as normal control. Isotypes of anti-sheep globulin antibody were also measured by ELISA at a single dilution of mouse serum optimized for each isotype (1:50 for IgG2a, 1:40 for IgG1, IgG2b, and IgG3, and 1:80 for IgM) using horseradish peroxidase–conjugated goat anti-mouse IgG1, IgG2a, IgG2b, IgG3, and IgM (Southern Biotechnology Associates, Inc., Birmingham, AL) at a dilution of 1:4,000.

Experimental Design and Statistical Analysis. The development of GN 21 d after anti-GBM globulin administration was studied in the following groups of mice: B6 (C57BL/6) mice (n = 5), MHCII−/− mice (n = 5), B6→MHCII−/− chimeric mice (MHCII−/− thymus and bone marrow in MHC−/− mice; n = 5), B6→MHCII−/− chimeric mice (MHCII−/− thymus and bone marrow in MHCII−/− mice; n = 5). In addition, measurements of baseline renal function were performed on the following separate groups of nonnephritic mice: B6 (C57BL/6) mice (n = 8), MHCII−/− mice (n = 7), and B6→MHCII−/− chimeric mice (MHCII−/− thymus and bone marrow in MHCII−/− mice; n = 8). In addition, measurements of baseline renal function were performed on the following separate groups of nonnephritic mice: B6 (C57BL/6) mice (n = 8), MHCII−/− mice (n = 7), and B6→MHCII−/− chimeric mice (n = 8).

Results

Development of Crescentic GN is MHC II Dependent. B6 (MHCII−/−) mice developed severe proliferative GN (Fig. 1 A) with crescents in 56.5 ± 5.2% of glomeruli. This resulted in significant proteinuria (15.5 ± 1.5 mg/24 h; base-

| Group                         | Specific serum antibody | μg/ml | SEM |
|-------------------------------|-------------------------|-------|-----|
| B6 with GN                    |                         | 125 ± 29 |     |
| MHCII−/− with GN              |                         | Undetectable |   |
| B6→B6 with GN                 |                         | 121 ± 14 |     |
| B6→MHCII−/− with GN           |                         | 158 ± 34 |     |
line 2.4 \pm 0.3 \text{ mg/24 h, } P <0.0001) \text{ and impairment of renal function (creatinine clearance, } 66.4 \pm 9.0 \text{ \mu l/min; baseline } 112.4 \pm 7.7 \text{ \mu l/min, } P = 0.0397) \text{ (Fig. 2), and was associated with evidence of systemic and local immune responses to sheep globulin. Mouse anti–sheep globulin antibody was present in the serum (125 \pm 29 \text{ \mu g/ml specific mouse anti–sheep globulin antibody}), and prominent linear deposition of mouse Ig was observed in glomeruli. Accumulation of CD4^+ T cells (1.42 \pm 0.37 \text{ /c/gcs normal } 0.21 \pm 0.4 \text{ /c/gcs}) and macrophages (2.21 \pm 0.17 \text{ /c/gcs normal } 0.37 \pm 0.09 \text{ /c/gcs}) in glomeruli was also observed. In contrast, MHCII^{2-/-} mice did not develop proliferative GN (Fig. 2B) or crescent formation (0% of glomeruli). Proteinuria was not increased (2.7 \pm 0.3 \text{ mg/24 h; baseline } 2.2 \pm 0.3 \text{ mg/24 h}), and renal function was preserved (creatinine clearance 125.7 \pm 9.1 \text{ \mu l/min; baseline } 148.6 \pm 22.9 \text{ \mu l/min}) \text{ (Fig. 2). Specific anti–sheep globulin antibody in the serum was undetectable, as was glomerular deposition of mouse Ig. Glomerular CD4^+ T cells (0.08 \pm 0.01 \text{ /c/gcs}) and macrophages (0.40 \pm 0.12 \text{ /c/gcs}) were not increased compared with the numbers observed in normal (nonnephritic) glomeruli. B6\rightarrow M HCII^{2-/-} Chimeric Mice Express MHC II in Spleen and LN Cells and Have Normal Lymphocyte Subsets. Lymphocyte subset populations and immune competence of chimeric mice were assessed 21 d after administration of anti-GBM globulin. Thymic grafts contained similar numbers of cells in both control (B6\rightarrow B6) and B6\rightarrow M HCII^{2-/-} chimeras (B6\rightarrow B6, 3.22 \pm 0.48 \times 10^7 \text{ cells per graft; B6\rightarrow M HCII^{2-/-} mice, } 2.06 \pm 0.14 \times 10^7 \text{ cells per graft). Pooled splenic and LN lymphocyte populations in B6\rightarrow M HCII^{2-/-} mice (CD4^+, 24.5 \pm 5.0%; CD8^+, 12.1 \pm 4.5%; B220^+, 45.4 \pm 8.9% of CD3^+) and B6\rightarrow B6 mice (CD4^+, 22.1 \pm 3.5%; CD8^+, 10.0 \pm 1.9%; B220^+, 56.2 \pm 7.0% of CD3^+) were similar to those in a normal mouse (CD4^+, 18.6%; CD8^+, 11.9%; B220^+, 44% of CD3^+). Their splenic and LN B cells showed similar levels of MHC II expression (Fig. 3). B6\rightarrow M HCII^{2-/-} Chimeric Mice Develop a Systemic Immune Response to Sheep Globulin. The systemic immune response to sheep globulin was similar in chimeric B6\rightarrow M HCII^{2-/-}.
mice and B6→B6 controls. Both groups had similar amounts of specific mouse anti-sheep globulin antibody in their serum (B6→MHCII−/− with GN, 158 ± 43 μg/ml; B6→B6 controls with GN, 121 ± 29 μg/ml) and similar antigen-specific Ig isotype profiles (data not shown). Anti- gen-specific foot pad swelling after intradermal challenge (B6→B6, 0.35 ± 0.03 mm; B6→MHCII−/−, 0.27 ± 0.09 mm; WT, 0.29 ± 0.05 mm) indicated that cutaneous DTH to sheep globulin was equivalent. These data demonstrate that the CD4+ compartment in B6→MHCII−/− mice is functional.

Absence of MHC II Expression by Intrinsic Glomerular Cells Prevents Development of Crescentic GN. Control chimeric mice (B6→B6) developed GN similar to B6 (nontransplanted) mice, with severe proliferative changes (Fig. 1 C) and crescents in 43.2 ± 8.9% of glomeruli. Deposition of mouse IgG (data not shown), accumulation of CD4+ T cells (1.17 ± 0.11 c/gcs) and macrophages (2.24 ± 0.14 c/gcs), and renal injury indicated by significant proteinuria (4.9 ± 1.9 mg/24 h; baseline 0.53 ± 0.10 mg/24 h, P < 0.0001) and reduced creatinine clearance (88.1 ± 25.5 μl/min) were similar to B6 mice with GN. In contrast, chimeric mouse (B6→MHCII−/−) showed no proliferative changes in glomeruli (Fig. 1 D) and did not develop crescents (0% of glomeruli). Glomerular deposition of mouse IgG was unaffected; however, accumulation of CD4+ T cells (0.46 ± 0.08 c/gcs) and macrophages (0.74 ± 0.21 c/gcs) was markedly reduced. These mice did not develop significant proteinuria (2.7 ± 0.3 mg/24 h, P = 0.468 compared with the baseline in B6→B6 mice) or impairment of renal function (creatinine clearance 122.3 ± 30.6 μl/min) (Fig. 4).

**Discussion**

Previous studies have demonstrated that crescentic GN in C57BL/6 mice is T cell dependent, although requiring the development of cell-mediated immune renal injury. MHC II–deficient mice failed to develop a systemic immune response to the nephritogenic antigen (with no detectable circulating antigen-specific antibody or DTH, when challenged cutaneously) and did not develop a local immune response when the antigen was planted in their glomeruli.

Studies of murine lupus have demonstrated that autoantibodies and renal disease do not develop in MHC II–deficient MRL/lpr mice, despite the development of lymphadenopathy and massive expansion of CD4+CD8− (double negative) T cells (16). Renal injury in MRL/lpr mice is associated with glomerular deposition of immune complexes and is B cell dependent (17). Together with our current studies, these provide evidence for a pivotal role for MHC II in the development of both cell-mediated (CD4+ dependent) and antibody-dependent immune glomerular injury.

Chimeric mice were generated to identify the MHC II–expressing cell type recognized by CD4+ T cells in the glomeruli. They lacked MHC II expression on non-bone marrow–derived intrinsic renal cells but had normal levels of MHC II expression on bone marrow–derived cells. Analysis of spleen and LN cells confirmed normal lymphocyte subsets and normal CD4+ to CD8+ T cell ratios in transplanted chimeric mice. Their systemic immune response to the nephritogenic antigen was intact. The circulating antigen-specific antibody levels and isotype profiles and the development of a local DTH reaction after cutaneous challenge demonstrated that these mice develop competent CD4+ T cell–dependent immune responses after antigen presentation by bone marrow–derived professional APCs.
However, chimeric mice lacking MHC II in their kidneys failed to develop local (CD4+ T cell–dependent) immune injury when the same antigen was planted in their glomeruli. This demonstrates that MHC II expression by intrinsic renal cells is required for antigen-specific CD4+ T cell recruitment and initiation of cell-mediated immune renal injury.

Various renal cell types, including mesangial cells (1, 2) and tubular epithelial cells (3, 4), can express MHC II. CD4+ T cell lines and hybridomas can recognize antigen processed and presented by proximal tubular cells (4) and thyroid epithelial cells (5) in vitro, although less efficiently than with antigen processed by bone marrow–derived APCs. Endothelial cells also have the capacity to express MHC II (18, 19). Our current studies were not able to define which of these cell types are recognized by CD4+ T cells in the kidney. Despite the existence of MHC II+ (Ia+) cells in rat glomeruli (20) and MHC II+ dendritic cells in rodent (21, 22) and human kidneys (23), these bone marrow–derived cells are not sufficient to target the immune response to the kidney and initiate crescentic GN.

Upregulation or novel expression of MHC II by renal cells has been demonstrated in many conditions, including allograft rejection (24), GVHD (25), lupus nephritis (26), and IgA disease (27). Tubular epithelial cells can present antigen by cultured syngeneic glomerular mesangial cells (28) and interstitial inflammatory cell infiltrates (29). This indicates expression of MHC II by intrinsic renal cells is not required for development of this antibody-dependent form of GN, in which the immune effector response is targeted to the glomerulus (and other vascular beds) because of local immune complex deposition. In contrast, this study demonstrates that GN, initiated by a planted nephritogenic antigen and directed by CD4+ T cells, requires MHC II expression by intrinsic renal cells. These results provide the first demonstration of the functional importance of local MHC II expression by intrinsic renal cells for targeting an immune injury to the glomerulus.

Because a systemic immune response to the nephritogenic antigen was observed, it is likely that naive CD4+ T cells are activated in secondary lymphoid organs by professional APCs after intravenous antigen challenge. It is unlikely that intrinsic renal cells participate in this initial priming, although we cannot exclude such a role. However, any contribution of this to the subsequent immune response would seem negligible, as chimeric mice without MHC II in their kidneys develop a systemic immune response to the nephritogenic antigen that is indistinguishable from that in normal mice. Expression of MHC II by intrinsic renal cells would appear to be functionally important in the effector phase of this disease, but was not necessary for initiation of the primary immune response.

In conclusion, these studies provide evidence for MHC II–dependent CD4+ T cell–directed injury in crescentic GN. In addition, they demonstrate that in the effector phase of this disease, MHC II expression by intrinsic renal cells is required to direct the CD4+ T cell effector response in the glomerulus, and that MHC II on bone marrow–derived cells alone is not sufficient. This provides the first demonstration of a requirement for MHC II expression by nonprofessional APCs for development of a T cell–dependent injury. The approach of transplanting MHC–intact bone marrow and thymus into MHC–deficient mice may be used to explore the role of local MHC II expression in a variety of CD4+ T cell–dependent organ-specific immune diseases.
presentation and tumor necrosis factor in renal tubular epithelial cells. Kidney Int. 37:783–792.
4. Hagerty, D.T., and P.M. Allen. 1992. Processing and presentation of self and foreign antigens by the renal proximal tubule. J. Immunol. 148:2324–2330.
5. Londel, M., J.R. Lamb, G.F. Bottazzo, and M. Feldmann. 1984. Epithelial cells expressing aberrant MHC class II determinants can present antigen to cloned human T cells. Nature 312:639–641.
6. Neal, T.J., P.G. Tipping, S.D. Carson, and S.R. Holdsworth. 1988. Participation of cell-mediated immunity in deposition of fibrin in glomerulonephritis. Lancet. 2:421–424.
7. Stilmant, M.M., W.K. Bolton, B.C. Sturgill, and W.G. Couser. 1979. Crescentic glomerulonephritis without immune deposits clinicopathologic features. Kidney Int. 15:184–195.
8. Huang, X.R., S.R. Holdsworth, and P.G. Tipping. 1994. Evidence for delayed-type hypersensitivity mechanisms in glomerular crescent formation. Kidney Int. 46:69–78.
9. Tipping, P.G., T.J. Neal, and S.R. Holdsworth. 1985. T lymphocyte participation in antibody-induced experimental glomerulonephritis. Kidney Int. 27:530–537.
10. Li, S., S.R. Holdsworth, and P.G. Tipping. 1997. Antibody independent crescentic glomerulonephritis in mu chain deficient mice. Kidney Int. 51:672–678.
11. Kontgen, F., G. Suss, C. Steward, M. Steinmetz, and H. Bluethmann. 1993. Targeted disruption of the MHC class II Aa gene in C57BL/6 mice. Int. Immunol. 5:957–964.
12. Kurts, C., H. Kosaka, F.R. Carbone, J.F. Miller, and W.R. Heath. 1997. Class I-restricted cross-presentation of exogenous self-antigens leads to deletion of autoreactive CD8+ T cells. J. Exp. Med. 186:239–245.
13. Tipping, P.G., X.R. Huang, M. Qi, G.Y. Van, and W.W. Tang. 1998. Crescentic glomerulonephritis in CD4 and CD8 deficient mice: requirement for CD4 but not CD8 cells. Am. J. Pathol. 152:1541–1548.
14. Huang, X.R., P.G. Tipping, S. Li, and S.R. Holdsworth. 1997. Th1 responsiveness to nephritogenic antigens determines susceptibility to crescentic glomerulonephritis in mice. Kidney Int. 51:94–103.
15. Bradford, M.M. 1976. A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Anal. Biochem. 72:248–254.
16. Jevnikar, A.M., M.J. Grusdy, and L.H. Glimcher. 1994. Prevention of nephritis in major histocompatibility complex class II-deficient MRL/lpr mice. J. Exp. Med. 179:1137–1143.
17. Shlomchik, M.J., M.P. Madalo, D. Nii, M. Trounstein, and D. Huszar. 1994. The role of B cells in lpr/lpr-induced autoimmunity. J. Exp. Med. 180:1295–1306.
18. Pober, J.S., M.A. Gimbrone, Jr., R.S. Cotran, C.S. Reiss, S.J. Burakoff, W. Fiers, and K.A. Ault. 1983. Ia expression by vascular endothelium is inducible by activated T cells and by human gamma interferon. J. Exp. Med. 157:1339–1353.
19. Collins, T., A.J. Korman, C.T. Wake, J.M. Boss, D.J. Kappes, W. Fiers, K.A. Ault, M.A. Gimbrone, Jr., J.L. Strominger, and J.S. Pober. 1984. Immune interferon activates multiple class II major histocompatibility complex genes and the associated invariant chain gene in human endothelial cells and dermal fibroblasts. Proc. Natl. Acad. Sci. USA. 81:4917–4921.
20. Schreiner, G.F., J.M. Kiely, R.S. Cotran, and E.R. Unanue. 1981. Characterization of resident glomerular cells in the rat expressing Ia determinants and manifesting genetically restricted interactions with lymphocytes. J. Clin. Invest. 68:920–931.
21. M ayrhofer, G., and M.A. Schon-Hegrad. 1983. Ia antigens in rat kidney, with special reference to their expression in tubular epithelium. J. Exp. Med. 157:2097–2109.
22. Austyn, J.M., D.F. Hankins, C.P. Larsen, P.J. Morris, A.S. Rao, and J.A. Roake. 1994. Isolation and characterization of dendritic cells from mouse heart and kidney. J. Immunol. 152:2401–2410.
23. Bishop, G.A., and B.M. Hall. 1989. Expression of leucocyte and lymphocyte adhesion molecules in the human kidney. Kidney Int. 36:1058–1085.
24. Benson, E.M., R.B. Colvin, and P.S. Russet. 1985. Induction of IA antigens in murine renal transplants. J. Immunol. 134:7–9.
25. Sinclair, G.D., A. Wadgymar, P.F. Halloran, and T.L. Delovitch. 1984. Graft-vs.-host reactions induce H-2 class II gene transcription in host kidney cells. Immunogenetics. 20:503–511.
26. Wuthrich, R.P., M.A. Yui, G. Mazoujian, N. Nabavi, L.H. Glimcher, and V.E. Kelley. 1989. Enhanced MHC class II expression in renal proximal tubules precedes loss of renal function in MRL/lpr mice with lupus nephritis. Am. J. Pathol. 134:45–51.
27. Yoko yama, H., M. Takaeda, T. Wada, M. Ogi, N. Tomosugi, T. Takabatake, T. Abe, M. Yoshimura, H. Kida, and K. Kobayashi. 1992. Intraglomerular expression of MHC class II and Ki-67 antigens and serum gamma-interferon levels in IgA nephropathy. Nephron. 62:169–175.
28. Kelley, V.R., C. Diaz-Gallo, A.M. Jevnikar, and G.G. Singer. 1993. Renal tubular epithelial and T cell interactions in autoimmune renal disease. Kidney Int. Suppl. 39:5108–S115.
29. Mukherjee, R., Z. Zhang, R. Zhong, Z.Q. Yin, D.C. Ropenian, and A.M. Jevnikar. 1996. Lupus nephritis in the absence of renal major histocompatibility complex class I and class II molecules. J. Am. Soc. Nephrol. 7:2445–2452.