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Alport Alloantibodies but Not Goodpasture Autoantibodies Induce Murine Glomerulonephritis: Protection by Quinary Crosslinks Locking Cryptic α3(IV) Collagen Autoepitopes In Vivo

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The noncollagenous (NC1) domains of α3α4α5(IV) collagen in the glomerular basement membrane (GBM) are targets of Goodpasture autoantibodies or Alport posttransplant nephritis alloantibodies mediating rapidly progressive glomerulonephritis. Because the autoepitopes but not the alloepitopes become cryptic upon assembly of α3α4α5NC1 hexamers, we investigated how the accessibility of B cell epitopes in vivo influences the development of glomerulonephritis in mice passively immunized with human anti-GBM Abs. Alport alloantibodies, which bound to native murine α3α4α5NC1 hexamers in vitro, deposited linearly along the mouse GBM in vivo, eliciting crescentic glomerulonephritis in Fgr2b<sup>−/−</sup> mice susceptible to Ab-mediated inflammation. Goodpasture autoantibodies, which bound to murine α3NC1 monomer and dimer subunits but not to native α3α4α5NC1 hexamers in vitro, neither bound to the mouse GBM in vivo nor induced experimental glomerulonephritis. This was due to quinary NC1 crosslinks, recently identified as sulfilline bonds, which comprehensively locked the cryptic Goodpasture autoepitopes in the mouse GBM. In contrast, non-crosslinked α3NC1 subunits were identified as a native target of Goodpasture autoantibodies in the GBM of squirrel monkeys, a species susceptible to Goodpasture autoantibody–mediated nephritis. Thus, crypticity of B cell autoepitopes in tissues uncouples potentially pathogenic autoantibodies from autoimmune disease. Crosslinking of α3α4α5NC1 hexamers represents a novel mechanism averting autoantibody binding and subsequent tissue injury by posttranslational modifications of an autoantigen. The Journal of Immunology, 2010, 185: 000–000.

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The α3ε4α5ε5NC1 hexamers are also the target of anti-GBM alloantibodies mediating Alport posttransplant nephritis (APTN), a serious complication affecting ~3–5% of Alport patients receiving a kidney transplant (15–18). APTN is the result of an alloimmun reaction to “foreign” α3ε4α5ε5(IV) collagen present in the allograft GBM but absent from the Alport patient’s tissues. APTN is most prevalent in patients with X-linked Alport syndrome, who develop alloantibodies against several alloepitopes within the αSNC1 domain (17). Upon binding to the allograft GBM, APTN alloantibodies cause aggressive glomerulonephritis with similar consequences in alloantibodies cause aggressive glomerulonephritis with similar clinical presentation and pathology findings as in autoimmune anti-GBM disease (19). However, the APTN alloepitopes are accessible in α3ε4α5ε5NC1 hexamers of the human GBM, unlike the GP alloepitopes (4, 17).

Whether differences in the epitope specificity between GP alloantibodies and APTN alloantibodies are pathogenetically relevant is not known. We postulated that APTN alloantibodies are more nephrigenic than GP alloantibodies because they bind to all isoforms of α3ε4α5ε5NC1 hexamers from the GBM. Testing this hypothesis requires a suitable animal model. A landmark study has demonstrated that GP alloantibodies injected into squirrel monkey kidneys bind to the GBM of the recipient host, causing severe glomerulonephritis (20). However, the nephrigenicity of APTN alloantibodies has not been evaluated by passive transfer into animal models.

The purpose of the present study was to determine whether the relative inaccessibility of B cell alloepitopes in the GBM limits the severity of autoantibody-mediated glomerulonephritis. Because rodent models are preferable to nonhuman primates on humane grounds, we developed a mouse model of anti-GBM glomerulonephritis by passive immunization with human anti-GBM Abs. We show that APTN alloantibodies but not GP alloantibodies bind to mouse GBM in vivo, causing crescentic glomerulonephritis in susceptible mouse strains. Although cross-reactive with murine αSNC1 subunits in vitro, GP alloantibodies did not bind to native α3ε4α5ε5NC1 hexamers of the mouse GBM in vivo, nor did they induce disease. Resistance against GP autoantibody-mediated nephritis was due to quinary2 (intermolecular) NC1 crosslinks locking the cryptic GP alloepitopes in the mouse GBM. In contrast, the GBM of squirrel monkeys contained non-crosslinked αSNC1 subunits reactive with GP alloantibodies under native conditions. These findings indicate that quinary crosslinks of α3ε4α5ε5NC1 hexamers, recently identified as sulfilimine bonds (22), lock the cryptic GP alloepitopes, conferring protection against nephritis mediated by GP alloantibodies, but not against APTN alloantibody-mediated disease. Thus, potentially pathogenic alloantibodies can be uncoupled from autoimmune disease by posttranslational modifications of an autoantigen that render B cell alloepitopes structurally inaccessible in tissues.

Materials and Methods

**Anti-GBM Abs**

Previously characterized serum or kidney-eluted anti-GBM alloantibodies from four X-linked Alport syndrome patients who developed APTN (17), as well as sera or plasma exchange fluid from six patients with GP disease (18), were used for in vitro binding studies. Only kidney-eluted alloantibodies from one patient with APTN were available in sufficient amounts for in vivo studies. Purified GP IgG alloantibodies used for in vivo experiments were isolated from the plasma exchange fluid of two patients by affinity chromatography on immobilized human αSNC1 (4). Normal human IgG (hIgG) was purchased from Sigma-Aldrich (St. Louis, MO) or purified from healthy donor sera by affinity chromatography on immobilized protein A. Nephrotoxic nephritis serum from sheep immunized with mouse GBM was a gift from Dr. A. Richard Kitching (Monash University, Clayton, Victoria, Australia).

**Preparation of NC1 hexamers**

Mouse kidneys were purchased from Pel-Freez Biologicals (Rogers, AR). Frozen kidneys from adult squirrel monkeys (Saimiri sp.) were obtained from the Squirrel Monkey Breeding and Research Resource (University of Texas MD Anderson Cancer Center, Houston, TX). Renal basement membranes including the GBM were isolated from homogenized kidney cortex and digested with bacterial collagenase (Worthington, Lakewood, NJ). The NC1 hexamers thus solubilized were purified by passage through a DE-52 ion-exchange column and gel-filtration chromatography (23).

**Immunoassays**

Indirect ELISA was performed as described (17). To assay the binding of human anti-GBM Abs to mouse Arts, Nunc MaxiSorp 96-well plates were coated overnight with NC1 hexamers from mouse GBM (300 ng/well) in PBS (pH 7.4). Prior to coating, some NC1 hexamers were treated with 6 M guanidine hydrochloride for 15 min at 60°C for dissociation into subunits. Sera diluted 1:100 or purified hIgG Abs (100 ng/ml) were used as primary Abs. The hIgG bound to the immobilized Arts was detected with alkaline phosphatase-conjugated goat anti-human IgG (Rockland Immunochemicai, Gilbertsville, PA). To assay the circulating mouse anti-human IgG Abs, wells coated with normal human IgG (300 ng/well) were incubated with mouse sera diluted 1:200, followed by detection with HRP-conjugated goat Abs specific for mouse IgG1, IgG2b, or IgG2c subclasses (Bethyl Laboratories, Montgomery, TX). The levels of human IgG in mouse sera were assayed by capture ELISA in plates coated with goat anti-human IgG, Fc-specific (300 ng/well).

**Western blots and immunoprecipitation**

Western blots were performed as described (17). NC1 hexamers from the mouse or human GBM (1 μg/well) were separated by SDS-PAGE and transferred onto Immobilon-P (Millipore, Bedford, MA). The membrane was blocked with 5% of blotting grade non-fat dry milk and cut into strips. Strips were incubated with purified hIgG Abs (1 μg/ml) or anti-αSNC1 mAb 8D1, which were detected with alkaline phosphatase-conjugated secondary Abs. For immunoprecipitation, NC1 hexamers (20 μg) isolated from mouse or squirrel monkey kidneys were incubated overnight at 4°C with preimmune hIgG Abs (20 μg), Ag–Ab complexes bound to protein G–Sepharose 4 Fast Flow (GE Healthcare Bio-Sciences, Piscataway, NJ) were solubilized in sample buffer, separated by SDS-PAGE, and transferred onto Immobilon-P for blotting with Abs specific for NC1 domains (24).

**Indirect immunofluorescence staining**

Cryostat sections (5 μm) of snap-frozen mouse kidneys embedded in OCT were fixed in acetone at −20°C for 10 min. Some sections were treated for 5 min on ice with 6 M urea in 0.1 M glycine (pH 2.2) to unmask cryptic epitopes. After blocking with 3% normal goat serum and 3% bovine albumin in PBS for 45 min, appropriately diluted primary Abs were added for 1 h, and then the sections were stained with Alexa Fluor 488 goat anti-human Ig (H+L) (Invitrogen, Eugene, OR), polyclonal anti-rat Ig (BD Pharmingen, San Jose, CA), or FITC-conjugated donkey anti-sheep IgG (Jackson ImmunoResearch Laboratories, West Grove, PA). Stained sections were observed with an Axioskop 2 Fluorescence microscope (Carl Zeiss MicroImaging, Thornwood, NY) and images were captured with the AxioVision 4.8 software.

**Mouse studies**

C57BL/6J (B6) and B6.CbItm57−−/− mice were purchased from The Jackson Laboratory (Bar Harbor, ME), and B6.FcγRIIB−−/− mice were from Taconic Farms (Germantown, NY). The mice were maintained in a specific pathogen-free facility with access to water and food. All mouse studies were performed in accordance with the principles for humane treatment of laboratory animals and were approved by the Institutional Animal Care and Use Committee at Vanderbilt University. Each mouse was injected once in the tail vein with 0.1 mg of purified hIgG in 100 μl of PBS, divided in four...
groups: kidney-eluted APTN alloantibodies, affinity-purified GP-1 or GP-2 autoantibodies, and normal human serum IgG. Blood was collected at the indicated time points by saphenous vein puncture, along with spot urine samples. Blood urea nitrogen was measured by a kinetic urease and glutamate dehydrogenase assay, and urinary creatinine was measured by alkaline picrate (Jaffe reaction), using kits from Thermo Electron (Louisville, CO). Urinary albumin excretion was assayed using a mouse albumin ELISA quantitation kit (Bethyl Laboratory, Montgomery, TX). Portions of kidneys and lungs collected from mice sacrificed at the end of experiments were embedded in paraffin or OCT for further evaluation. For light microscopic assessment of the kidney histopathology, 5-μm paraffin sections stained with H&E or with periodic acid–Schiff reagent were observed with an Axioskop 40 microscope. Images were captured with MRGrab software (Carl Zeiss MicroImaging). For direct immunofluorescence, frozen sections of OCT-embedded kidneys were fixed in acetone and stained with FITC-conjugated goat anti-mouse Ig (BD Pharmingen), Alexa Fluor 488 goat anti-human IgG (H+L), or FITC-conjugated goat anti-mouse C3c (Nordic Immunological Laboratory, Tilburg, The Netherlands).

Statistical analyses
Data were analyzed using GraphPad Prism (GraphPad Software, San Diego, CA), by two-tailed r test for two groups or ANOVA followed by Dunnett’s post hoc test for three or more groups. Statistical significance was inferred for p values <0.05.

Results
Patient GP autoantibodies and APTN alloantibodies bind to the NC1 domains of α3α4α5(IV) collagen from the mouse GBM
The lack of cross-reactivity between human autoantibodies and homologous Abs from other species is a potential roadblock preventing the transfer of autoimmune disease to animal models by passive immunization with patient autoantibodies (25). To determine whether mice are a suitable model for this study, we first verified that human anti-GBM Abs cross-react with mouse collagen IV. By Western blot, NC1 domains from mouse GBM bound hlG from patients with GP disease or APTN, but not normal hlG (Fig. 1A). Next, we assessed the accessibility of the epitopes in the mouse GBM. By indirect ELISA (Fig. 1B), only APTN alloantibodies exhibited significant reactivity toward native NC1 hexamers from the mouse GBM, whereas GP autoantibodies bound preferentially to dissociated hexamers, revealing the crypticity of GP autoepitopes. This finding was corroborated by indirect immunofluorescence staining (Fig. 1C). Under native conditions, only APTN alloantibodies stained the GBM and tubular basement membranes of normal mouse kidneys. GP autoantibodies produced the same staining pattern on kidney sections treated with acid urea for epitope unmasking, but did not bind to mouse basement membranes under native conditions. The same results were found using kidneys from C57BL/6, 129/Sv, DBA/1, and SJL/J mice (Supplemental Fig. 1). Additionally, the alveolar basement membranes of mouse lungs were stained by APTN alloantibodies under native conditions, but by GP autoantibodies only after acid urea treatment (Supplemental Fig. 2). Finally, we verified that both APTN alloantibodies and GP autoantibodies bind specifically to mouse α3α4α5(IV) collagen because neither stained kidney basement membranes from Col4a5-null Alport mice (Fig. 1D), in contrast to sheep anti-mouse GBM Abs used to elicit murine nephrotoxic serum nephritis, which appear to target other Ags in the mouse GBM. We have thus shown that NC1 hexamers of mouse α3α4α5(IV) collagen harbor cryptic autoepitopes recognized by GP autoantibodies and accessible alloepitopes targeted by APTN alloantibodies.

APTN alloantibodies but not GP autoantibodies bind in vivo to mouse GBM
In vivo binding of human anti-GBM Abs to target Ags was investigated in C57BL/6J mice injected with APTN alloantibodies, GP autoantibodies from two patients, and hlG from normal human sera. Renal function was monitored for 8 wk postinjection to assess the development of kidney injury. At all time points, urinary albumin excretion (Fig. 2A) and blood urea nitrogen levels (Fig. 2B) were found to be normal in all mice. Light microscopic examination of the kidneys revealed no histological abnormalities in any group (Fig. 2Cir-f). Direct immunofluorescence revealed bright linear staining for hlG along the GBM in all mice injected with APTN alloantibodies (Fig. 2Cg), but no hlG deposition was detected in the kidneys of mice injected with either GP autoantibodies (Fig. 2Ch) or normal hlG (Fig. 2Ci). Linear GBM deposition of mouse IgG (mlG) (Fig. 2Cj) but not of mC3 (Fig. 2Cm) was also observed in APTN-injected mice, indicating that these mice produced Abs to the foreign globulin. APTN alloantibodies stained in vitro but did

![FIGURE 1. APTN alloantibodies and GP autoantibodies cross-react with the NC1 domains of mouse α3α4α5(IV) collagen. A, Western blots show the binding of hlG to NC1 dimer and monomer subunits of hexamers from the mouse or human GBM, after incubation with GP autoantibodies, APTN alloantibodies, or normal human serum IgG. Staining with mAb 8D1 identifies the position and relative abundance of α3NC1 monomers and dimers. B, The binding of APTN alloantibodies (n = 4), GP autoantibodies (n = 4), and normal human sera IgG (n = 3) to NC1 hexamers from mouse GBM (300 ng/well), native (●) or dissociated (○), was measured by indirect ELISA (left). After subtracting the nonspecific binding to BSA (x), the relative hlG binding to native versus dissociated mouse hexamers was calculated for each sample (right). Unlike APTN alloantibodies, GP autoantibodies reacted very weakly with normal mouse GBM hexamers (***p < 0.0001). C, Binding of APTN alloantibodies and GP autoantibodies to mouse kidney basement membranes under native conditions or after acid urea treatment was evaluated by indirect immunofluorescence staining. D, Indirect immunofluorescence staining of kidneys from B6Col4a5−/−Y (wild type) and B6Col4a5−/−Y (Alport) mice with APTN alloantibodies, GP autoantibodies, a mAb specific for mouse α3α4α5(IV) collagen, and nephrotoxic serum from sheep immunized with mouse GBM. Staining with GP autoantibodies was performed on acid urea-treated kidney sections. Original magnification ×400. D, dimer; M, monomer; NHS, normal human serum; NTS, nephrotoxic serum.](http://www.jimmunol.org/)

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not bind in vivo to other murine basement membranes containing \( \alpha_3 \alpha_4 \alpha_5(IV) \) collagen, such as renal tubular basement membranes or lung alveolar basement membranes (Supplemental Fig. 2). These results show that APTN alloantibodies, unlike GP autoantibodies, bind specifically to the mouse GBM in vivo, but do not induce glomerulonephritis in C57BL/6J mice.

Binding of APTN alloantibodies to the mouse GBM induces severe glomerulonephritis in B6.Fcgr2b\(^{-/-}\) mice

The development of experimental glomerulonephritis after passive immunization with human anti-GBM IgG Abs was next investigated using B6.Fcgr2b\(^{-/-}\) mice, because the absence of the inhibitory IgG Fc receptor FcγRIIB exacerbates susceptibility to Ab-mediated inflammation and autoimmune disease (26, 27). Injection of APTN alloantibodies (but not of GP-1 and GP-2 autoantibodies, nor normal hIgG) into Fcgr2b\(^{-/-}\) mice caused increased albuminuria after 2 wk (Fig. 3A) and abnormally high blood urea nitrogen levels after 4 wk (Fig. 3B). By 8 wk, 80% (four out of five) of mice injected with APTN alloantibodies died or were sacrificed because of end-stage glomerulonephritis.

![Figure 2](image2.png)

**FIGURE 2.** APTN alloantibodies but not GP autoantibodies bind in vivo to the mouse GBM. C57BL/6J mice (n = 4/group) were injected with 0.1 mg of APTN alloantibodies, GP-1 or GP-2 autoantibodies, or normal human serum IgG. A and B, Kidney function was evaluated by measuring urinary albumin-to-creatinine ratios (A) and blood urea nitrogen levels (B) at the times indicated. The graphs depict the means and SEM. Differences among groups of mice injected with different human IgG Abs were not statistically significant. C, Kidney histopathology in mice sacrificed at 8 wk after the injection of APTN alloantibodies (a, d, g, j, m), GP autoantibodies (b, e, h, k, n), or normal hIgG (c, f, i, l, o) was evaluated by light microscopy on paraffin sections stained by H&E (a–c) or periodic acid–Schiff (d–f). Deposition of hIgG (g–i), mIgG (j–l), and mC3 (m–o) in the mouse glomeruli was evaluated by direct immunofluorescence staining. Original magnification ×400. G, glomeruli; NHS, normal human serum.

![Figure 3](image3.png)

**FIGURE 3.** APTN alloantibodies but not GP autoantibodies induce crescentic glomerulonephritis in Fcgr2b\(^{-/-}\) mice. B6.Fcgr2b\(^{-/-}\) mice were injected with 0.1 mg of APTN alloantibodies (n = 5 mice), GP-1 or GP-2 autoantibodies (n = 4 mice each), or normal human serum IgG (n = 4 mice). A and B, Kidney function was evaluated by measuring urinary albumin-to-creatinine ratios (A) and blood urea nitrogen levels (B) at the times indicated. The graphs depict the means and SEM. Mice injected with APTN alloantibodies, but not those injected with GP-1 or GP-2 autoantibodies, developed significantly higher albuminuria and blood urea nitrogen levels than did control mice injected with normal hIgG (p < 0.05 by ANOVA followed by Dunnett’s multiple comparison test). C, Kidney histopathology in Fcgr2b\(^{-/-}\) mice sacrificed at 8 wk after the injection of APTN alloantibodies (a, d, g, j, m, p), GP autoantibodies (b, e, h, k, n, q), or normal human IgG (c, f, i, l, o, r) was evaluated by light microscopy on paraffin sections stained by H&E (a–c) or periodic acid–Schiff (d–f). Glomerular deposition of hIgG (g–i), mIgG (j–l), and mC3 (m–o) was evaluated by direct immunofluorescence staining of frozen kidney sections. Original magnification ×400. Double staining of frozen kidney sections (p–r) assessing the colocalization of hIgG (green) with mouse \( \alpha_3 \alpha_4 \alpha_5(IV) \) collagen (red) is shown. NHS, normal human serum.
renal disease, compared with zero of eight mice injected with GP-1 or GP-2 autoantibodies. Light microscopic examination of the kidneys revealed crescentic necrotizing glomerulonephritis in APTN-treated mice, but not in those receiving GP autoantibodies or normal hlgG (Fig. 3Ca–f). Direct immunofluorescence staining of kidneys from Fcgr2b<sup>−/−</sup> mice injected with APTN autoantibodies revealed linear GBM binding of hlgG, along with mlgG and mC3 deposition along the capillary loops (Fig. 3Cg, j, m). However, APTN autoantibodies did not bind in vivo to mouse renal tubular or alveolar basement membranes containing α3α4α5(IV) collagen (Supplemental Fig. 2). Weak staining for hlgG, mlgG, and mC3 in kidneys from mice without APTN autoantibodies was also occasionally observed in wild-type mice (Fig. 3Ci, l, o). This pattern of hlgG deposition, judged to be nonspecific because it did not colocalize with mouse α3α4α5(IV) collagen (Fig. 3Cp, q, r), may be caused by immune complexes between hlgG and mouse anti-human IgG Abs (MAHA). MAHA were detected in mouse sera at 3 d after injection of APTN alloantibodies, GP autoantibodies and normal hlgG (Fig. 3Ca, j, m). At this time point, before production of MAHA, kidney histology appeared normal by light microscopy (not shown), and nonspecific glomerular deposits of hlgG were not observed. Original magnification ×400.

**Susceptibility of B6.Fcgr2b<sup>−/−</sup> mice to APTN Ab-induced glomerulonephritis is due to enhanced production of mlgG2b and mlgG2c against hlgG**

We next inquired why APTN autoantibodies elicit severe glomerulonephritis in Fcgr2b<sup>−/−</sup> but not in wild-type mice. Because the injection of APTN autoantibodies led to C3 deposition along the capillary loops in Fcgr2b<sup>−/−</sup> but not in wild-type mice, we hypothesized that the absence of the inhibitory IgG Fc receptor may augment production of complement-fixing mlgG subclasses, linking the GBM-bound hlgG to inflammatory effectors. For all mlgG subclasses, the titers of MAHA were consistently higher in Fcgr2b<sup>−/−</sup> mice than in wild-type mice, but they were less influenced by the nature of hlgG injected into mice (Fig. 5). In wild-type mice, MAHA were almost exclusively mlgG1, whereas Fcgr2b<sup>−/−</sup> mice also produced significant amounts of mlgG2b and mlgG2c MAHA. These results suggest that mlgG2b and/or mlgG2c Abs to hlgG may exacerbate glomerulonephritis in Fcgr2b<sup>−/−</sup> mice injected with APTN autoantibodies.

**NC1 crosslinks lock cryptic α3NC1 autoepitopes in the mouse GBM**

We finally addressed the molecular basis of the inaccessibility of GP autoantibodies in the mouse GBM. Because GP autoantibodies mediate anti-GBM disease in human patients and squirrel monkeys (20) but not in mice, we hypothesized that species-specific structural features of GBM collagen IV may affect its immunoreactivity toward GP autoantibodies, thus determining the host’s susceptibility to GP autoantibody-mediated glomerulonephritis. We therefore analyzed how human anti-GBM Abs bind to NC1 domains from the GBM of mice and squirrel monkeys using immunoprecipitation (Fig. 6A). As reference, Fig. 6B depicts the reactivity of NC1 hexamer isoforms from human GBM toward GP autoantibodies (14) and APTN autoantibodies (17). In both monkeys and mice, APTN autoantibodies coprecipitated α3NC1, α4NC1, and α5NC1 monomers and dimers (Fig. 6A, lanes c, g). This pattern of reactivity, also seen with human GBM NC1 domains (17), indicates that APTN autoantibodies bind to native α3α4α5NC1 hexamers from all species (Fig. 7A, 7C, 7D). Under native conditions, GP autoantibodies mainly targeted α3NC1 and α4NC1 monomers from the monkey GBM (Fig. 6A, lane b). This pattern of reactivity, previously found for human GBM NC1 domains (14), suggests that the GBM of squirrel monkeys also contains non-crosslinked hexamers (Fig. 6B). In contrast,

**FIGURE 4.** Time course for hlgG clearance from mouse sera, MAHA production, and glomerular IgG deposition at 3 d after passive immunization. A, Serum levels of MAHA in the Fcgr2b<sup>−/−</sup> mice injected with hlgG were measured by indirect ELISA. B, The levels of hlgG in mouse sera were measured by capture ELISA. C, Indirect immunofluorescence analysis of hlgG or mlgG deposition in kidneys from Fcgr2b<sup>−/−</sup> mice at 3 d after injection of APTN autoantibodies, GP autoantibodies, or normal hlgG. At this time point, before production of MAHA, kidney histology appeared normal by light microscopy (not shown), and nonspecific glomerular deposits of hlgG were not observed. Original magnification ×400.

**FIGURE 5.** Fcgr2b<sup>−/−</sup> mice have enhanced production of mlgG2b and mlgG2c anti-hlgG Abs (MAHA). Titers of circulating MAHA of mlgG (A), mlgG1 (B), mlgG2b (C), and mlgG2c (D) subclasses were measured by indirect ELISA. Sera collected from wild-type (filled bars) and Fcgr2b<sup>−/−</sup> mice (open bars) at 4 wk after the injection of patient alloantibodies (APTN), autoantibodies (GP-1, GP-2), or normal hlgG were diluted 1/500. Binding of mlgG to plates coated with normal hlgG was assayed using subclass-specific secondary Abs. The graphs depict the means and statistical significance of differences in MAHA titers between wild-type and Fcgr2b<sup>−/−</sup> mice was analyzed by two-way ANOVA followed by Bonferroni posttests (∗p < 0.05; ∗∗p < 0.01; ∗∗∗p < 0.0001). NHS, normal human serum.
Reduced by in vitro dissociation of mouse GBM NC1 hexamers mediated nephritis (Fig. 6). Consequently, mice are resistant to GP autoantibodies within isoforms of autoantigen impenetrable by GP autoantibodies. Anti-GBM Abs binding to the NC1 domains of native NC1 hexamers from squirrel monkeys (a–c) or mouse (d–g) kidneys, or with mouse NC1 subunits produced by dissociating the hexamers with 6 M guanidinium hydrochloride (h–j). After immunoprecipitating the immune complexes with protein G beads, the NC1 domains bound to human anti-GBM Abs were resolved into dimer and monomer bands (Fig. 6B). The number of component NC1 dimer subunits produced by quinary NC1 cross-links (indicated by horizontal bars), directly engaging effectors of Ab-mediated inflammation (complement and/or activating IgG Fc receptors) and causing glomerulonephritis. GP autoantibodies injected into mice also bind to crosslinked α3α4α5NC1 hexamers in the murine GBM (C, D), where they fix MAHA. GBM fixation of mIgG2a/c and IgG2b in Fcgr2b−/− mice (D) but not of mIgG1 in wild-type mice (C) then leads to crescentic glomerulonephritis. Passively transferred GP autoantibodies do not bind to crosslinked α3α4α5NC1 hexamers in the mouse GBM (E), and hence they do not induce glomerulonephritis, but elicit MAHA, likely forming circulating immune complexes. In murine glomerulonephritis induced by immunization with heterologous α3NC1 Ags (F), nephrotoxic mIgG Abs probably target epitopes of α3α4α5NC1 hexamers accessible in the GBM. In Fcgr2b−/− mice immunized with Cellmatrix-IV (G), some mIgG autoantibodies may bind to the collagenous domain of murine α1α2(IV) collagen. In murine models of nephrotrophic nephritis (H), heterologous globulin bound to unknown GBM Ags acts as a planted Ag to fix mIgG subclasses mediating glomerulonephritis. C.I.C., circulating immune complexes; GN, glomerulonephritis.

we investigated the role of the accessibility of B cell epitopes in vivo in the pathogenesis of these diseases. Crypticity of GP autoepitopes led us to conjecture that APTN autoantibodies would cause more severe experimental nephritis than would GP autoantibodies in a passive transfer model of anti-GBM disease. We found that only APTN autoantibodies bound in vivo to the mouse GBM, inducing crescentic glomerulonephritis in Fcgr2b−/− mice susceptible to Ab-mediated inflammation (Fig. 7C, 7D). We have thus demonstrated the nephritogenic potential of APTN autoantibodies and established the first murine model of glomerulonephritis induced by a patient’s anti-GBM Abs that reproduces the severity of human disease. In contrast, GP autoantibodies neither bound to mouse α3α4α5 (IV) collagen in vivo nor induced experimental nephritis (Fig. 7E), owing to quinary NC1 crosslinks locking the GP autoepitopes in the mouse GBM. These results show that the crypticity of B cell epitopes in tissues is sufficient to uncouple potentially pathogenic autoantibodies from autoimmune disease.

The significance of differences in the epitope specificity of GP autoantibodies and APTN autoantibodies

Our study illustrates how seemingly small differences in the location of epitopes targeted by anti-GBM Abs impact the development of glomerulonephritis. The different accessibility of the collagen IV autoepitopes and alloepitopes in the GBM is thought to reflect the
distinct immune mechanisms triggering GP disease and APTN (28–30). The crypticity of GP autoepitopes in α3α4α5NC1 hexamers implies that a perturbation of the native structure of the autoantigen may be instrumental in breaching immune self-tolerance toward α3 (IV) collagen in GP disease. In contrast, APTN alloantibodies target accessible alloepitopes in the α3α4α5NC1 hexamers—antigenic determinants encountered in the normal renal allograft but not in the basement membranes of the affected patients, who presumably lack immune tolerance toward missing collagen IV chains. In this study, both GP autoantibodies and APTN alloantibodies were shown to cross-react with NC1 subunits of murine α3α4α5(IV) collagen in vitro, yet only the GP autoepitopes were completely inaccessible within the collagen IV network of mouse GBM in vivo. As a result, mice were protected against anti-GBM glomerulonephritis induced by GP autoantibodies, but not by APTN alloantibodies.

Because relatively large amounts of Ag-specific hlGg were used for passive transfer experiments, only anti-GBM Abs from a small number of patients could be tested in vivo. Nevertheless, these samples were judged to be representative based on their in vitro binding to mouse GBM Ags, which are essentially identical to additional samples of GP autoantibodies and APTN alloantibodies tested only in vitro. We also note that APTN alloantibodies injected in mice were eluted from an allograft kidney, and hence they were highly enriched in the nephrotoxic hlGg species. In all in vitro immunoprecipitations, kidney-eluted and serum APTN alloantibodies bound to mouse GBM Ags similar to each other but different from GP autoantibodies (Fig. 1 and Supplemental Fig. 1). However, kidney-eluted APTN alloantibodies have higher affinity for α3α4α5NC1 hexamers than do serum APTN alloantibodies (17), which may translate into greater nephritogenic potential. To emulate the enrichment in autoantigen-specific hlGg species upon kidney binding and the subsequent elution, GP autoantibodies used for passive immunizations were affinity-purified from plasma exchange fluid using immobilized α3NC1 monomers.

In vivo binding of APTN alloantibodies to basement membranes containing α3α4α5(IV) collagen

The proximal step initiating crescentic glomerulonephritis in mice injected with APTN alloantibodies is the GBM deposition of hlGg. Prerequisites for this binding are the ability of human APTN alloantibodies to cross-react with mouse α3α4α5(IV) collagen, as well as the structural accessibility of the alloepitopes within the α3α4α5NC1 hexamers (Fig. 1). However, other murine basement membranes containing α3α4α5(IV) collagen, such as those in renal tubules and lung alveoli, bind APTN alloantibodies in vitro (by indirect immunofluorescence staining) but not in vivo. APTN alloantibodies readily bind to the GBM because fenestrations in glomerular endothelial cells allow the passage of large macromolecules, which is an adaptation to the blood filtration function. In most capillary beds, endothelial cells have tight junctions impermeable to molecules of IgG size, which prevent the access of circulating Abs to the underlying basement membranes under normal physiological conditions. Thus, cellular and anatomic barriers can modulate the accessibility of (auto)antigens in vivo, influencing which tissues become targets of Ab-mediated inflammation.

Murine anti-GBM Ab-mediated glomerulonephritis is exacerbated by the absence of the inhibitory IgG Fc receptor FcγRIIB

In vivo binding of APTN alloantibodies to the mouse GBM was necessary but not sufficient for induction of glomerulonephritis, because only Fcγ2b−/− mice were susceptible to disease. This echoes the finding that hlGg autoantibodies from patients with rheumatoid arthritis are arthritogenic in Fcγ2b−/− but not in wild-type mice (27). Several mechanisms may contribute to the susceptibility of Fcγ2b−/− mice to Ab-mediated glomerulonephritis. Because the expression of the inhibitory receptor FcγRIIB on myeloid cells counterbalances signaling through activating IgG Fc receptors (FcγRI, -III, and -IV), neutrophils and macrophages from Fcγ2b−/− mice would have a lower threshold of activation by immune complexes (3). FcγRIIB is also a negative regulator of B cells, implicated in the feedback inhibition of Ab production or apoptosis of plasma cells (31). Consequently, Fcγ2b−/− mice produce larger amounts of Abs following antigenic stimulation, as observed for MAHA titers in our study. Finally, it has not escaped our attention that significant amounts of mlgG2bc MAHA are elicited by injection with hlGg only in Fcγ2b−/− but not in wild-type mice. Unlike mlgG1, mlgG2b and mlgG2c, an allotype of mlgG2a in mice with the Igk-1b allele (32), are proinflammatory because they can activate complement and have higher affinity for activating IgG Fc receptors (33). Fixation of mlgG2a and mlgG2b (but not mlgG1) to the mouse GBM induces acute glomerular injury due to an FcγRIII- and FcγRIV-dependent influx of neutrophils (34). In contrast, even long-term persistence of mlgG1 in the GBM of mice injected with an anti-α3NC1 mAb does not induce any glomerular pathology (35). Autoimmune pathology in Fcγ2b−/− mice immunized with bovine collagen type IV is associated with enhanced production of mlgG2a/b autoantibodies (36), suggesting that a propensity toward production of proinflammatory mlgG subclasses may contribute to the susceptibility of Fcγ2b−/− mice to Ab-mediated glomerulonephritis.

The cryptic GP autoepitopes are locked by quinary NC1 crosslinks, characteristic posttranslational modification of collagen IV

In contrast to APTN alloantibodies, affinity-purified GP IgG autoantibodies did not induce crescentic glomerulonephritis into Fcγ2b−/− mice. Even very large amounts of affinity-purified GP autoantibodies (5 mg/mouse, 50 times more than in this study) injected in XenoMouse II only cause mild nephritis with patchy mesangial expansion and glomerular hlGg deposition in a punctate rather than a linear pattern (37). The inability of GP autoantibodies to bind in vivo to the mouse GBM in significant amounts explains the inconspicuous glomerular pathology after passive immunization. In this study, we showed that quinary NC1 crosslinks of α3α4α5(IV) collagen prevent the binding of GP autoantibodies to mouse GBM both in vitro and in vivo. Previous studies of α3α4α5NC1 hexamers from human GBM have shown that crosslinks yield α3−α5NC1 heterodimers and α4−α4NC1 homodimers (9), which reinforce the hexamers and prevent their dissociation by GP autoantibodies in vitro (14), as also demonstrated for α3α4α5NC1 hexamers isolated from bovine testes (12). In this study, GP autoantibodies likewise bound to murine α3−α5NC1 dimers and α3NC1 monomers, after the NC1 hexamers from the mouse GBM had been dissociated (Fig. 6A, lane i). Because NC1 crosslinks do not prevent the binding of GP autoantibodies to α3−α5NC1 dimer subunits, the impenetrability of native murine α3α4α5NC1 hexamers by GP autoantibodies must be the combined result of the crypticity of GP autoepitopes together with the structural stabilization of NC1 hexamers by quinary crosslinks. Collectively, these findings imply that the NC1 crosslinks “lock” the cryptic GP autoepitopes within the α3α4α5 (IV) collagen superstructure.

The chemical nature of the collagen IV bonds crosslinking NC1 dimers has been elusive. Long presumed to be crosslinked by disulfide bonds (38), NC1 dimers have been shown to contain intermolecular covalent bonds between conserved Met39 and Lys211 residues, initially assigned as thioether bonds (12, 39, 40). Most recently, this unusual posttranslational modification has been identified.
as a sulfilimine bond, uniquely found within collagen IV networks in tissues (22). Sulfilimine bonds have been proposed to occur in most metazoa, based on the evolutionary conservation of the Met\(^{31}\) and Lys\(^{311}\) in the NC1 domains of collagen IV from vertebrates and most invertebrate phyla, except in hydra, flatworms, sponges, and Placozoa (22). This implies that the cryptic GP autoepitopes are locked in the mouse GBM by sulfilimine bonds crosslinking the NC1 domains of adjoining α3ε4ε5(IV) collagen molecules. Thus, posttranslational modifications of autoantigens, often implicated in autoimmune etiology (41–43), can also autoantibody disease, as showcased by NC1 crosslinks of α3ε4ε5(IV) collagen.

**Species differences in the susceptibility to GP autoantibodies**

Unlike mice in this study or XenoMouse II (37), human patients or squirrel monkeys are susceptible to anti-GBM nephritis mediated by GP autoantibodies (20). However, biochemical analyses of NC1 domains from the GBM of mice (24), humans (9), and monkeys (44) have revealed a similar architecture, with α3ε4ε5(IV) collagen molecules forming supramolecular networks. We found that the reactivity toward GP autoantibodies is inversely correlated with the extent to which the NC1 hexamers of the GBM undergo posttranslational modifications forming quinary crosslinks. In the murine GBM, α3ε4ε5NC1 hexamers undergo comprehensive crosslinking, thereby locking all GP autoepitopes. In contrast, a small proportion of α3ε4ε5NC1 hexamers without NC1 crosslinks that react with GP autoantibodies under native conditions has been found to occur in the GBM of humans (14) and squirrel monkeys (this study). Why the crosslinking of GP autoantigen varies among species is unknown. As mouse kidneys contained a smaller proportion of NC1 monomers than did human or monkey kidneys (Figs. 1A, 6A), we speculate that a putative enzyme producing the NC1 crosslink may be more active and/or expressed at higher levels in rodent kidneys. It is perhaps not coincidental that NC1 hexamers from rat kidneys have the smallest proportion of NC1 monomers and the lowest reactivity with GP autoantibodies among six species of mammals (45). Because susceptibility to GP Ab-mediated nephritis is associated with GBM isoforms of α3(IV) collagen not stabilized by NC1 crosslinks, these isoforms are likely implicated in the pathogenesis of GP disease as targets for GP autoantibodies directed against cryptic epitopes.

Since the α3NC1 autoepitopes targeted by GP autoantibodies are inaccessibile in the mouse GBM, what are the targets of nephritogenic mIgG Abs in mouse models of anti-GBM glomerulonephritis? In mice immunized with α3NC1 from bovine GBM (46–48) or recombinant human α3NC1 (37, 49), which develop glomerulonephritis associated with serum anti-GM Abs and linear GBM deposition of mIgG, it is likely that some mIgG may be produced against non-cryptic mouse α3NC1 epitopes (Fig. 7F). Supporting this view, mIgG mAb 8D1, raised against human α3ε4ε5NC1 hexamers in vitro (23) and in vivo (35). More intriguing is the nature of autoantibodies mediating crescentic glomerulonephritis and hemorrhagic pneumonitis (GP syndrome) (35) in Fcγr2b\(^{−/−}\) mice immunized with Cellmatrix-IV (36). Cellmatrix-IV consists of collagen IV fragments solubilized from bovine lens capsule basement membranes by limited pepsin digestion, a treatment that destroys the NC1 domains (50). Sera from mice immunized with Cellmatrix-IV contain mIgG Abs binding to pepsin-extracted murine collagen IV from Engelbreth–Holm–Swarm tumors, suggesting that their epitopes reside in the collagenous domain of α1ε2 (IV) collagen (Fig. 7G), a rare target of human anti-GM autoantibodies (51). Mouse GBM Ags other than α3ε4ε5(IV) collagen are also targeted by anti-GM Abs from sheep nephrotoxic sera (Fig. 7H). The new mouse model of glomerulonephritis described herein is suitable for investigating the pathogenic role of alloantibodies in APTN and for testing new experimental therapies, such as using decoy Ag to prevent the binding of pathogenic Abs to target tissues (25). For these purposes, the widely used murine model of nephrotoxic serum nephritis induced by heterologous anti-mouse GBM Abs—although useful for studies of the effector mechanisms of Ab-mediated glomerulonephritis—is inadequate, since anti-GM Abs from nephrotoxic sera do not reproduce the restricted Ag and epitope specificity of hIgG Abs mediating anti-GM disease in patients. Whereas our model resembles murine nephrotoxic nephritis models with regard to the development of mIgG against the foreign globulin, which amplify glomerular injury in the autologous phase, much smaller amounts of GBM-specific patient Abs (0.1 mg of hIgG per mouse) were sufficient to induce severe experimental nephritogeny in susceptible mice, thus mitigating against the limited availability of human anti-GM Abs. Although the nephritogenicity of autoantibodies from GP patients cannot currently be evaluated by passive transfer into mice, this may become possible when mice unable to crosslink α3ε4ε5(IV) collagen are genetically engineered. Until then, primate models remain available for this purpose (20).

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**Disclosures**

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