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Bullous Pemphigoid Autoantibodies Directly Induce Blister Formation without Complement Activation

Hideyuki Ujiie,* Tetsumasa Sasaoka,† Kentaro Izumi,* Wataru Nishie,* Satoru Shinkuma,* Ken Natsuga,* Hideki Nakamura,* Akihiko Shibaki,* and Hiroshi Shimizu*

Complement activation and subsequent recruitment of inflammatory cells at the dermal/epidermal junction are thought to be essential for blister formation in bullous pemphigoid (BP), an autoimmune blistering disease induced by autoantibodies against type XVII collagen (COL17); however, this theory does not fully explain the pathological features of BP. Recently, the involvement of complement-independent pathways has been proposed. To directly address the question of the necessity of the complement activation in blister formation, we generated C3-deficient COL17-humanized mice. First, we show that passive transfer of autoantibodies from BP patients induced blister formation in neonatal C3-deficient COL17-humanized mice without complement activation. By using newly generated human and murine mAbs against the pathogenic noncollagenous 16A domain of COL17 with high (human IgG1, murine IgG2), low (murine IgG1), or no (human IgG4) complement activation abilities, we demonstrate that the deposition of Abs, and not complements, is relevant to the induction of blister formation in neonatal and adult mice. Notably, passive transfer of BP autoantibodies reduced the amount of COL17 in lesional mice skin, as observed in cultured normal human keratinocytes treated with the same Abs. Moreover, the COL17 depletion was associated with a ubiquitin/proteasome pathway. In conclusion, the COL17 depletion induced by BP autoantibodies, and not complement activation, is essential for the blister formation under our experimental system. The Journal of Immunology, 2014, 193: 4415–4428.

Bullous pemphigoid (BP), the most common autoimmune blistering disorder, is characterized by tense blisters with itchy urticarial erythema and plaques that develop on the entire body. Histologically, subepidermal blisters associated with inflammatory cell infiltration in the dermis are observed. BP is induced by autoantibodies against type XVII collagen (COL17, also called BP180 and BPAG2), a hemidesmosomal type II transmembrane protein that spans the lamina lucida and projects into the lamina densa of the dermal/epidermal junction (DEJ) (1–4). Studies to map the epitopes on COL17 have revealed that the juxtamembranous extracellular noncollagenous 16A domain (NC16A) is preferentially recognized by autoantibodies in the sera of BP patients (5, 6). The pathogenicity of IgG Ab from BP patients (BP-IgG) had been unclear because BP-IgG fails to recognize murine COL17 and to reproduce the skin detachment in wild-type mice owing to differences in the amino acid sequence between humans and mice. Our recent studies using COL17-humanized (COL17m/−/−,h+) mice, which lack murine COL17 but express human COL17, have directly demonstrated the pathogenicity of Abs against the NC16A of human COL17 (hNC16A), including BP-IgG, in vivo (7–13).

C3 is detected at the DEJ of the lesional/perilesional skin in most BP cases by direct immunofluorescence (IF) (14, 15). Findings from an IgG passive transfer neonatal mouse model have demonstrated that the binding of Abs to murine COL17 triggers immune reactions, including complement activation (16), mast cell degranulation (17), and neutrophil infiltration (18). The infiltrating neutrophils were shown to be activated via FcyRIII (19) and to release neutrophil elastase and matrix metalloproteinase-9, which are responsible for the dermal/epidermal separation (20). Thus, the binding of Abs to COL17 as well as subsequent immune reactions are thought to be essential for BP blister formation. However, this theory does not fully explain why Abs against a distinctive portion of NC16A are specifically pathogenic (13) or why separation occurs specifically within the lamina lucida (21). Recently, BP-IgG has been shown to be able to deplete the amount of COL17 in cultured normal human keratinocytes (NHKs) (22, 23) and to diminish their adhesive strength to the culture dish in vitro (22). More recently, we demonstrated that polyclonal F(ab′)2 Abs against NC16A induced dermal/epidermal separation in injected neonatal mice and reduced the amount of COL17 in cultured NHKs (13).

An accurate understanding of a disease’s pathomechanism is essential for the development of disease-specific therapeutic strategies. To determine the necessity of the complement in BP blister formation clearly, we newly generated C3-deficient COL17-humanized mice and plural human and murine mAbs against hNC16A that have various degrees of complement activation ability. First, we demonstrate that BP-IgG induced blister...
formation in neonatal C3-deficient COL17-humanized mice. Next, we used mAbs to show that the deposition of Abs at NC16A was more relevant to the induction of blister formation than was complement activation in neonatal and adult mice. BP-IgG reduced the amount of COL17 in vivo and in vitro, and the COL17 depletion was mediated by a ubiquitin/proteasome pathway. These findings provide new insights into the blister formation and approaches to the treatment of BP.

Materials and Methods

Mice

The COL17-humanized mice were generated as previously described (7). Briefly, human COL17-transgenic mice (C57BL/6 background) expressing the squamous epithelium-specific K14 promoter and human COL17A1 cDNA (COL17+/+;h+) (24) were crossed with heterozygous murine Col17a1−/− mice (the F1 mouse had a 129S/Ev × C57BL/6 background, backcrossed with C57BL/6 for 10 generations) to produce COL17-humanized mice (COL17−/−;h+). C3−/−COL17-humanized mice were generated by crossing COL17-humanized mice with B6;129S4-C3−/− mice (B6;129S4-C3−/−, h+). Upstream, COL17A1−/− (Central Institute for Experimental Animals, Kawasaki, Japan) were reported previously (9). All animal procedures were conducted according to guidelines of the Hokkaido University Institutional Animal Care and Use Committee.

Preparation and purification of BP-IgG

Sera from four BP patients were used. These patients met three criteria: 1) subepidermal blistering lesions present clinically on skin, 2) in vivo deposition of IgG at the DEJ in skin samples from the patients, and 3) circulating anti-DEJ IgG Abs that react with the epidermal side of 1 M NaCl–split normal human skin (NHS). Total IgG was purified from the patients’ sera by protein G–Sepharose column chromatography (GE Healthcare, Uppsala, Sweden) and concentrated by Amicon ultrafiltration 30K (Millipore, Billerica, MA) (see Fig. 2A). The purity of BP-IgGs was confirmed by SDS-PAGE. The collection of samples was approved by the local ethics committee and the Institutional Review Board of Hokkaido University. Full, written informed consent was obtained from all individuals. This study was performed according to the Declaration of Helsinki.

Passive transfer studies

We performed passive transfer of Abs into mice as described previously (7, 9). Briefly, each neonatal COL17-humanized mouse or C3−/−COL17-humanized mouse (1 d old) received a single i.p. injection of BP-IgG1 and BP-IgG2 (1000 μg/mouse), BP-IgG3 and BP-IgG4 (1500 μg/mouse), normal human IgG (hIgG; Nilon Pharmaceutical, Tokyo, Japan) (1500 μg/mouse), recombinant hIgG1 (rhIgG1; 4.5–30 μg/mouse), control hIgG (Sigma-Aldrich, St. Louis, MO) (30 μg/mouse), rhIgG4 (7.5–50 μg/mouse), control hIgG (Sigma-Aldrich) (50 μg/mouse), monoclonal murine IgG1 (mlgG1; TS9-3, TS21-1, and T66-1) (25–50 μg/mouse), monoclonal mlgG2c (TS2-4) (50–100 μg/mouse), or control mlgG (100–300 μg/mouse) without marking. To inhibit FcγR in vivo, neonatal COL17-humanized mice were injected i.p. with 20 μg rat anti-mouse mAb 2.4G (specific for FcγRIII and FcγRIII, BD Biocis) or control rat IgG2b (BD Biosciences) and 2 h later were injected i.p. with 50 μg rhlgG4 according to the reported method (19). To obtain a sufficient effect, higher doses of 2.4G were administered than in a previous study (19). For proteasome inhibition, neonatal mice were injected i.p. with 1.5 μg proteasome-inhibitor MG-132 (Calbiochem, San Diego, CA) and 3 h later were injected i.p. with 50 μg rhlgG4. The same dose of MG-132 was also injected at 24 h after the injection of rhlgG4. The dose of MG-132 was determined based on previous studies (25, 26). At 48 h after Ab injection, back skins of the injected mice were evaluated for detachment with gentle rubbing performed up to four times. In some experiments, skin fragility was evaluated at 6 and 12 h after Ab injection. For histological investigations, back or ear skin was obtained from the mice after removal of skin detachment and was processed for light microscopy (H&E) and for direct IF using FITC-conjugated Abs against hlgG, mlgG, and mc3.

Construction of rhlgG1 and rhlgG4 expression vector

rhlgG1 and rhlgG4 mAbs to hNC16A were generated using the previously described Fab-B4 fragment (10). Conversion of Fab-B4 to rhlgG1 or rhlgG4 was performed as previously described (27), with some modifications. The V region and C region L chain (Vλ Cδ4) and the V region H chain (VH) of the Fab-B4 fragment were amplified by PCR with primers containing a restriction site as follows: VH Cδ4, forward primer, 5′-CTACTCTGTGCTC- CCGGGTGCAACAGTCTGTGTTGACGGCGGCG-3′, reverse primer, 5′-TCGACTCGGCGCGCCCTATCGACTCTGGAGGGCGCTACTGTC- TC-3′; VH Cδ4, reverse primer, 5′-TTCCTCCTACTTGACGACGTCCCA- GATGGGTCTCTGTCGCCGTCACGTGTCGTCGG-3′; reverse primer, 5′-GGTGAGGAGGCCACTGGACGCGGTGACGCGTGCC-3′. After digestion with SacII and AsclII for the VH region, the PCR products were subcloned into an hlgG1 construction vector (Medical and Biological Laboratories, Nagoya, Japan). To generate the rhlgG4 construction vector, C region H chains of hlgG1 were converted to those of rhlgG4. The constructed hlgG1 and hlgG4 cassettes were further cloned into the pCMV-Script expression vector (Stratagene, Santa Clara, CA) (see Fig. 2A).

Production and purification of rhlgG1 and rhlgG4

Expression of rhlgG1 and rhlgG4 was performed by transfection of the expression vectors into CHO-K1 cells. Stably expressing cells were selected under 700 μg/ml Geneticin (Life Technologies). For large-scale production of rhlgGs, CHO-K1 cells were stationary-cultured in CHO-S-SEMI II (Invitrogen, Carlsbad, CA) for 3 d at 37°C in 5% CO2 and the culture supernatant was harvested. Purification of rhlgGs was performed using protein A–Sepharose (GE Healthcare, Uppsala, Sweden) according to the manufacturer’s instructions. The purified rhlgGs were dialyzed against PBS and concentrated by Amicon ultrafiltration 30K (Millipore) and were then characterized by SDS-PAGE, hNC16A ELISA, and indirect IF on NHS obtained from healthy volunteers.

Establishment of HEK293 human COL17 cells and human COL17ΔNC16A cells

The HEK293 human COL17 cells used in this study were previously established (11). Briefly, the constructed plasmid pcDNA5/FRT (Invitrogen, Carlsbad, CA) for 3 d at 37°C in 5% CO2 and the culture supernatant was harvested. Purification of rhlgGs was performed using protein A–Sepharose (GE Healthcare, Uppsala, Sweden) according to the manufacturer’s instructions. The purified rhlgGs were dialyzed against PBS and concentrated by Amicon ultrafiltration 30K (Millipore) and were then characterized by SDS-PAGE, hNC16A ELISA, and indirect IF on NHS obtained from healthy volunteers.

IF studies

Direct IF was performed on the skin samples from neonatal mice that were passively transferred with IgG using standard protocols (7). Briefly, mouse skins were mounted and snap frozen into optimal cutting temperature compound, and 5-μm cryosections were prepared. The sections were blocked with 10% BSA for 1 h at 37°C and incubated with Abs, including FITC-conjugated Abs against hlgG (Jackson Immunoresearch Laboratories), mlgG (Jackson Immunoresearch Laboratories), or murine C3 (mc3; MP Biomedicals, Solon, OH) in a 1:100 dilution. Indirect IF study was performed on skin samples from human or COL17-humanized mice prepared as above. The sections were blocked with BSA and incubated with rhlgGs or monomeric mlgG for 1 h at 37°C and detected by secondary Ab, including FITC-conjugated Abs against hlgG (Jackson Immunoresearch Laboratories), hlgG1, hlgG4 (Beckman Coulter, Brea, CA), mlgG (Jackson Immunoresearch Laboratories), mlgG1, mlgG2a, mlgG2b, and mlgG3 (BD Biosciences) in a 1:100 dilution, or mlgG2c (Bethyl Laboratories, Montgomery, TX) in a 1:500 dilution.

HEK293 human COL17, HEK293 human COL17ΔNC16A, and HEK293 cells cultured in a collagen I-coated eight-well chambers (BD Biosciences) were fixed with 100% methanol for 5 min at −20°C. Chambers were washed once with PBS and incubated with primary Abs for 30 min at 37°C. After two washings with PBS, they were incubated with FITC-conjugated Abs to hlgG and propidium iodide (Dojindo Laboratories, Kumamoto, Japan) in a 1:100 dilution for 30 min at 37°C.

ELISA assay

Serum mc3 levels were examined by ELISA (Kamiya Biomedical Company, Seattle, WA) according to the manufacturer’s instructions. The titters of mlgG1 and rhlgG4Abs against hNC16A were determined by using a BPI80 ELISA kit (Medical and Biological Laboratories) according to the manufacturer’s instructions. To measure the titters of mlgGs against hNC16A in hybridoma-transferred mice, serum diluted to 1:300 was used.
as the primary Ab, and HRP-conjugated anti-mlgG Ab (Jackson ImmunoResearch Laboratories) diluted to 1:40,000 was used as the secondary Ab. Bound Abs were read at the OD of 450 nm using an ELISA plate reader (Mithras, Berthold Technologies). The ELISA index value was defined by the following formula: index = [(OD450 of tested serum – OD450 of negative control)/OD450 of positive control – OD450 of negative control] × 100. Titers of mlgGs were simply shown by the OD450 value.

Dot blot analysis
To detect the epitope of rhlgG1 and rhlgG4 in hNC16A (Glu400 to Arg566), dot blotting was performed using four chemically synthesized peptides conjugated with BSA: R4 (Glu400 to Be660), R5 (Arg660 to Gin663), R7 (Asp661 to Gin666), and R8 (Ser662 to Arg666) (Greiner Bio-One) (13). The amino acid numbering system is based on the human COL17 sequence (NP_004855.3). Synthesized peptides were diluted to 0.1 mg/ml in distilled water, and 10 μl of this was spotted on nitrocellulose membrane. The membrane was blocked for 30 min at room temperature with 2% skimmed milk in TBS and then incubated with rhlgGs, Fab-B4, normal hlgG, monoclonal mlgGs, or normal mlgG. Bound Abs were visualized enzymatically using HRP-conjugated anti-hlgG Ab (DakoCytomation, Glostrup, Denmark), anti-human λ chain Ab (Bethyl Laboratories), or anti-mlgG Ab (Jackson ImmunoResearch Laboratories). The blots were detected using the ECL Prime detection kit (GE Healthcare, Fairfield, CT).

Complement fixation study
Complement activation induced by rhlgG1, rhlgG4, or Fab-B4 in human skin samples was investigated by IF study as previously described, with minor modifications (9, 10). Cryosections of human skin were incubated with Abs in a 1:100 dilution for 1 h at 37°C. BP-IgG1 in a 1:100 dilution was used as a positive control. The sections were washed three times with PBS and incubated with mouse serum complement (Innovative Research, Novi, MI) in a 1:50 dilution for 1 h at 37°C. Then, in situ deposition of mC3 was detected with FITC-conjugated Ab specific to mC3 in a 1:100 dilution.

C1q-binding assay
The human C1q-binding activity of rhlgGs and Fab-B4 was determined by C1q-binding assay by ELISA as previously described, with minor modifications (11). The rhlgGs and Fab-B4 with 2-fold serial dilution (starting concentration, 20 μg/ml) in 0.1 M sodium carbonate buffer (pH 9.5) were coated in a Microtest 96-well ELISA plate (BD Biosciences) and left overnight at 4°C. The plate was washed three times with PBS containing 0.05% Tween 20 and blocked for 1 h at room temperature with ELISA assay diluent (BD Biosciences), then incubated for 2 h with 100 μl of 4 μg/ml human complement component C1q (Sigma-Aldrich) in assay diluent. The plate was washed four times and incubated with 100 μl of a 1:400 dilution of sheep polyclonal Ab to human C1q (HRP) (Abcam, Japan) for 1 h at room temperature. After five washings, the plate was displayed in 100 μl of 3% hydrogen peroxide and 0.1% 3,3′-diaminobenzidine. After the skin graft, spleen cells were removed from the immunized mice (7) and the skin samples were lysed in Laemmli sample buffer. Immunoblotting was performed as described previously, with modifications (13). The samples were heated at 95°C for 5 min, applied to 4–12% gradient Bis-Tris gels (Invitrogen), transferred to a polyvinylidene difluoride membrane. The membrane was blocked for 1 h at room temperature in 5% skimmed milk dissolved in TBS with 0.05% Tween 20. Blots were incubated with 1:1000 dilution of 09040 IgG for 1 h at room temperature, followed by incubation with 1:2000 diluted HRP-conjugated anti-rabbit IgG for 30 min at room temperature. As controls, membranes were incubated with 1:2000 diluted anti-β-tubulin Ab (Abcam, Cambridge, U.K.) for 1 h at room temperature followed by incubation with 1:2000 diluted HRP-conjugated anti-rabbit IgG Ab for 30 min at room temperature. Bound Abs were detected using the ECL Prime detection kit.

Depletion of COL17 in cultured NHKs by Abs
Ab stimulation of NHKs was performed as previously described (13, 22). NHKs were purchased from Life Technologies (human epidermal keratinocytes, neonatal). The NHKs were cultured in serum-free keratinocyte growth medium (Clonetics, San Diego, CA) containing 0.03 mM calcium, epidermal growth factor (10 ng/ml), bovine pituitary extract (0.1 mg/ml), insulin (0.5 mg/ml), and hydrocortisone (0.5 mg/ml) at 37°C under 5% CO2. The NHKs used in this study had been cultivated for no more than four passages. Abs (150 μg/ml BP-IgG1, 300 μg/ml BP-IgG2, 690 μg/ml BP-IgG3, 900 μg/ml of BP-IgG4, 40 μg/ml rhlgG1 or control hlgG1, 60 μg/ml rhlgG4 or control hlgG4, 150 μg/ml mlgGs) were added to the culture medium of the NHKs. Bases of BP-IgGs and rhlgGs were determined by the results of hNC16A ELISA. After 6 h of incubation, the cells were lysed in Laemmli sample buffer. To evaluate the effect of proteasome inhibitor on the COL17 depletion in cultured NHKs, several doses of MG-132 were added with rhlgG1 (40 μg/ml), rhlgG4 (60 μg/ml) or BP-IgG1 (150 μg/ml). Immunoblotting of cell lysates was performed as described above. To detect COL17, blots were incubated with 1:2000 diluted murine anti-COL17/3 (31) for 1 h at room temperature followed by incubation with 1:5000 diluted HRP-conjugated anti-mouse IgG Ab for 1 h at room temperature.

Detection of ubiquitinated COL17
To detect the ubiquitinated COL17, immunoprecipitation was done with mAb TS39-3. Cell lysates from NHKs, which were treated with rhlgG4 (60 μg/ml) and/or MG-132 (6.25 μM), were incubated with TS39-3 conjugated with Dynabeads protein G (Invitrogen) overnight at 4°C, or downstream incubated with Dynabeads protein G (1 μg/ml) for 2 h at 4°C. The beads were denatured and applied to 4–12% gradient Bis-Tris gels. Blots were incubated with 1:2000 diluted mAb NC16A-3 or 1:5000 diluted anti-ubiquitin mAb P4D1 (Santa Cruz Biotechnology, Heidelberg, Germany)

Transfer of hybridomas
For each mouse, 8 × 10⁵ hybridoma cells were washed twice, suspended in 0.2 ml PBS, and then injected s.c. into the lower back of the Rag-2⁻/⁻/COL17-humanized mice. Tumors were visible at the injection site after ~7 d. Tumor size for all of the mice selected in the study ranged from 2.5 to 6 mm in diameter when the observation term was terminated. The mice were observed until day 21 because they died before day 28. At day 28, tail skins were evaluated for detachment with gentle rubbing performed up to five times. Biopsies of lesional or perilesional skin were obtained between 21 and 28 d after the transfer for light microscopy (H&E) and for direct IF using FITC-conjugated Abs against mlgG and mC3.
for 1 h at room temperature, followed by incubation with 1:5000 diluted HRP-conjugated anti-mouse IgG for 1 h at room temperature. Bound Abs were detected using the ECL Prime detection kit.

Statistical analysis

Data are expressed as means ± SEM. A Dunnett multiple comparison test was used to identify differences between the COL17/β-tubulin ratios from skin mice treated with versus without BP-IgGs, those from NHKs treated with versus without BP-IgGs, or those from NHKs treated with versus without monoclonal mlgGs. A Tukey all-pairwise comparison test was applied to identify differences between the COL17/β-tubulin ratios from NHKs treated with rhlgGs versus control hlgGs, those from NHKs treated with versus without MG-132, or to identify differences between the affected body surface areas of hybridoma-transferred mice. The p values < 0.05 were considered significant.

Results

BP-IgG induces blister formation in complement-deficient COL17-humanized mice

To evaluate the pathogenicity of Abs against human COL17 in the absence of complements, we established in this study C3-deficient COL17-humanized (C3−/−/COL17-humanized) mice. Serum mC3 levels examined by ELISA were below the detection limit in neonatal C3−/−/COL17-humanized neonatal mice and were 380 ± 35.2 μg/ml in neonatal COL17-humanized mice (n = 7 for both). We prepared BP-IgG from four patients and measured the titer of IgG specific to hNC16A by ELISA (index values: BP-IgG1, 5794.9; BP-IgG2, 2734.5; BP-IgG3, 1192.4; BP-IgG4, 842.6). The high purity of the BP-IgGs was confirmed by Coomassie blue staining (Fig. 1A). We i.p. injected these Abs (BP-IgG1 and BP-IgG2, 1000 μg/mouse; BP-IgG3 and BP-IgG4, 1500 μg/mouse) or normal hlgG (1500 μg/mouse) into neonatal COL17-humanized mice and C3−/−/COL17-humanized mice. As previously reported (7), BP-IgGs induced dermal/epidermal separation in COL17-humanized mice (Fig. 1B, 1C). Direct IF revealed linear deposition of hlgG and mC3 at the DEJ of the injected mice skin (Fig. 1D, 1E). Interestingly, BP-IgGs also produced blisters in the C3−/−/COL17-humanized mice (Fig. 1F). Subepidermal separation and slight inflammatory cell infiltration were observed in the skin samples of the IgG-injected C3−/−/COL17-humanized mice (Fig. 1G). Direct IF revealed linear deposition of hlgG but not mC3 at the DEJ (Fig. 1H, 1I). Normal hlgG did not produce skin detachment. Neither hlgG nor mC3 was detected in skin samples from the control hlgG-injected mice (data not shown). The skin detachment results are summarized in Table I. Next, we evaluated the BP-IgG1 transferred mice at 6 and 12 h after transfer. As shown in Table II, there is no significant difference in time span between COL17-humanized mice and C3−/−/COL17-humanized mice, suggesting that the presence of complement does not affect the time span of blister induction in neonatal mice. Thus, BP-IgGs were proven to induce blister formation in neonatal mice in a complement-independent manner.

Monoclonal hlgG Abs against hNC16A induce blister formation in mice in complement- and FcγRII/III-independent manners

Because the BP-IgGs were polyclonal, each might recognize different epitopes and have different pathogenicity. Therefore, we sought to compare the pathogenicity of Abs that recognize an identical epitope in hNC16A and have different abilities to produce complement activation. For this, we generated rhlgG1 and rhlgG4 mAbs against hNC16A by combining a Fab-B4 fragment that reacts to hNC16A (10) with Fc portions of hlgG1 or hlgG4 (Fig. 2A). It is acknowledged that the IgG1 subclass can activate all types of Fc receptors and the complement C1 component, whereas the IgG4 subclass has restricted Fc receptor-activating abilities and does not activate C1q (32–34). High purity of the rhlgGs was confirmed by Coomassie blue staining (Fig. 2B). The reactivity of the rhlgGs against hNC16A was confirmed by IF study using skin samples and human COL17-expressing mammalian cells (HEK293) (Fig. 2C, 2D) and ELISA. The ELISA index values for 0.6 μg/ml purified rhlgG1 and rhlgG4 were 3013 and 1794, respectively. Epitope mapping of the rhlgGs and Fab-B4 by using four small synthesized peptides of hNC16A (13) revealed both rhlgGs bound to the R5 (Arg196 to Gln255) peptide that was also recognized by Fab-B4 (Fig. 2E). Complement fixation analysis by indirect IF demonstrated that rhlgG1 as well as BP-IgG1 were able to fix mC3 to the DEJ of NHS, whereas rhlgG4 and Fab-B4 were not (Fig. 3A). C1q-binding assay by ELISA showed that rhlgG4 and Fab-B4 demonstrated much lower binding activity to C1q than that of rhlgG1 (Fig. 3B).

To examine the pathogenicity of the rhlgGs in vivo, Abs (30 μg rhlgG1 or control-hlgG1, 30 μg rhlgG4 or control-hlgG4) were i.p. injected into neonatal COL17-humanized mice. Doses were determined by the results of hNC16A ELISA. As expected, rhlgG1 produced dermal/epidermal separation (Fig. 3C, 3D), al-

**FIGURE 1.** BP-IgGs induce blister formation in C3-deficient COL17-humanized mice. (A) Coomassie blue staining of affinity-purified BP-IgGs separated by SDS-PAGE on 12.5% polyacrylamide gel. M, marker. Lane 1, 1 μg BP-IgG1; lane 2, 1 μg BP-IgG2; lane 3, 1 μg BP-IgG3; lane 4, 1 μg BP-IgG4. (B–I) Representative clinical presentations, H&E staining, and hlgG and mC3 deposition 48 h after the passive transfer of BP-IgG1 into COL17-humanized mice (B–E) and into C3-deficient COL17-humanized mice (F–I). Skin detachment is indicated by an arrow. Linear deposition of hlgG and mC3 at the DEJ in direct IF is indicated by arrows. H&E, original magnification ×20; direct IF, original magnification ×20.
though control-hlgG1 or control-hlgG4 did not induce blister formation (Fig. 3G, 3H, 3O, 3P). Direct IF revealed linear deposition of hlgG and mC3 at the DEJ of the rhlgG1-injected mice skin (Fig. 3E, 3F). Neither hlgG nor mC3 was detected in skin samples from the control hlgG-injected mice (Fig. 3I, 3J, 3Q, 3R). Notably, all the mice injected with rhlgG4 developed dermal/epidermal separation, which is associated with linear deposition of hlgG but is not associated with a deposition of mC3 (Fig. 3K–N). Little inflammatory cell infiltration was observed in the skin samples of the rhlgG1- or rhlgG4-injected mice (Fig. 3D, 3L). At lower doses of rhlgGs, blister formation was more frequently induced by rhlgG1 (18 μg, 87.5%; 9 μg, 75%) than by rhlgG4 (30 μg, 50%; 15 μg, 62.5%) (Table III). The lowest doses of rhlgGs (4.5 μg rhlgG1, 7.5 μg rhlgG4) induced no skin detachment. Next, we injected 50 μg rhlgG4 into human and murine COL17-expressing (COL17humanized) mice. Despite the deposition of hlgG4 at the DEJ, no blister formation was induced (Fig. 2S). This suggests that IgG binding to hNC16A does not affect the function of murine COL17 in vivo. We also transferred rhlgGs into neonatal C3-deficient COL17-humanized mice. Both rhlgG1 (30 μg) and rhlgG4 (50 μg) induced blister formation in all C3−/−/COL17-humanized mice associated with linear deposition of hlgG but not mC3 at the DEJ of the skin (Table III). These results demonstrate that monoclonal hlgGs against hNC16A induce blister formation in mice regardless of complement activation.

We considered that the pathogenicity of mouse-derived Abs should also be examined, because the in vivo experiments in this study used mice. Moreover, we wanted to investigate the pathogenicity of Abs that act to the different epitope of hNC16A from that recognized by rhlgGs. We therefore generated hybridomas that produce murine mAbs against hNC16A. Using splenocytes from wild-type mice (C57BL/6) immunized by grafting their backs with human COL17-expressing mouse skin (9, 24), we obtained three mlgG1 clones (TS39-3, TS21-1, and TS66-1) and one mlgG2c clone (TS4-2) against hNC16A that strongly reacted to NHS (Fig. 4A). The hybridomas were derived from C57BL/6 mice; therefore, TS4-2 should be regarded as IgGc instead of as IgG2a (35). The reactivity of TS4-2 to COL17-humanized mouse skin was quite weak (Fig. 4B). Epitope mapping of those monoclonal mlgGs using the four small synthesized peptides of hNC16A revealed that all the Abs bound to R7 (Asp522 to Gln545) peptide (Fig. 5A). It is commonly known that the mlgG2 and mlgG3 subclasses are potent activators of complements, whereas mlgG1 is a weak activator (36–38). As we expected, C1q-binding activities were high in IgGc (TS4-2) and low in IgG1 (TS39-3, TS21-1, and TS66-1) (Fig. 5B). We i.p. injected the Abs into neonatal COL17-humanized mice. As shown in Fig. 5C, a low dose of monoclonal IgG1 Abs (TS39-3, TS21-1, and TS66-1, 25 μg) induced blisters in all the injected mice that were associated with weak deposition of mC3 at the DEJ (three of three), whereas a high dose of IgGc (TS4-2, 500 μg) caused weak deposition of IgG and distinct deposition of mC3 at the DEJ but showed a low potential to induce blister formation in the injected mouse (positive: two of six) (Table IV). Low doses of monoclonal mlgG1 Abs (TS39-3, TS21-1, and TS66-1, 25 μg) induced blisters in all of the neonatal C3-deficient COL17-humanized mice (Table IV), showing that monoclonal mlgG against the R7 region of hNC16A also induces blister formation in mice in a complement-independent manner. This is in line with the results that little inflammatory cell infiltration had been observed in the dermis of the rhlgG-injected mice.

The deposition of monoclonal murine IgG Abs at hNC16A was more relevant to the induction of blister formation than was in situ complement activation

We considered that the pathogenicity of mouse-derived Abs should also be examined, because the in vivo experiments in this study used mice. Moreover, we wanted to investigate the pathogenicity of Abs that act to the different epitope of hNC16A from that recognized by rhlgGs. We therefore generated hybridomas that produce murine mAbs against hNC16A. Using splenocytes from wild-type mice (C57BL/6) immunized by grafting their backs with human COL17-expressing mouse skin (9, 24), we obtained three mlgG1 clones (TS39-3, TS21-1, and TS66-1) and one mlgG2c clone (TS4-2) against hNC16A that strongly reacted to NHS (Fig. 4A). The hybridomas were derived from C57BL/6 mice; therefore, TS4-2 should be regarded as IgGc instead of as IgG2a (35). The reactivity of TS4-2 to COL17-humanized mouse skin was quite weak (Fig. 4B). Epitope mapping of those monoclonal mlgGs using the four small synthesized peptides of hNC16A revealed that all the Abs bound to R7 (Asp522 to Gln545) peptide (Fig. 5A). It is commonly known that the mlgG2 and mlgG3 subclasses are potent activators of complements, whereas mlgG1 is a weak activator (36–38). As we expected, C1q-binding activities were high in IgGc (TS4-2) and low in IgG1 (TS39-3, TS21-1, and TS66-1) (Fig. 5B). We i.p. injected the Abs into neonatal COL17-humanized mice. As shown in Fig. 5C, a low dose of monoclonal IgG1 Abs (TS39-3, TS21-1, and TS66-1, 25 μg) induced blisters in all the injected mice that were associated with weak deposition of mC3 at the DEJ (three of three), whereas a high dose of IgGc (TS4-2, 500 μg) caused weak deposition of IgG and distinct deposition of mC3 at the DEJ but showed a low potential to induce blister formation in the injected mouse (positive: two of six) (Table IV). Low doses of monoclonal mlgG1 Abs (TS39-3, TS21-1, and TS66-1, 25 μg) induced blisters in all of the neonatal C3-deficient COL17-humanized mice (Table IV), showing that monoclonal mlgG against the R7 region of hNC16A also induces blister formation in mice in a complement-independent manner.

### Table I. Passive transfer of BP-IgG into neonatal mice

<table>
<thead>
<tr>
<th>Injected Neonatal Mice</th>
<th>Abs</th>
<th>Ratio of Mice with Skin Detachment</th>
</tr>
</thead>
<tbody>
<tr>
<td>COL17-humanized</td>
<td>BP-IgG1 (1000 μg)</td>
<td>5/5</td>
</tr>
<tr>
<td></td>
<td>BP-IgG2 (1000 μg)</td>
<td>4/5</td>
</tr>
<tr>
<td></td>
<td>BP-IgG3 (1500 μg)</td>
<td>5/5</td>
</tr>
<tr>
<td></td>
<td>BP-IgG4 (1500 μg)</td>
<td>5/5</td>
</tr>
<tr>
<td></td>
<td>Normal hlgG (1500 μg)</td>
<td>0/5</td>
</tr>
<tr>
<td>C3−/−/COL17-humanized</td>
<td>BP-IgG1 (1000 μg)</td>
<td>5/5</td>
</tr>
<tr>
<td></td>
<td>BP-IgG2 (1000 μg)</td>
<td>5/5</td>
</tr>
<tr>
<td></td>
<td>BP-IgG3 (1500 μg)</td>
<td>4/5</td>
</tr>
<tr>
<td></td>
<td>BP-IgG4 (1500 μg)</td>
<td>4/5</td>
</tr>
<tr>
<td></td>
<td>Normal hlgG (1500 μg)</td>
<td>0/5</td>
</tr>
</tbody>
</table>

*Gentle skin rubbing test performed at 48 h in neonatal mice.

### Table II. Time course of passive transfer of BP-IgG1 into neonatal mice

<table>
<thead>
<tr>
<th>Abs (1000 μg Each)</th>
<th>COL17-Humanized Mice with Skin Detachment</th>
<th>C3−/−/COL17-Humanized Mice with Skin Detachment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 h</td>
<td>6 h</td>
</tr>
<tr>
<td></td>
<td>12 h</td>
<td>12 h</td>
</tr>
<tr>
<td>BP-IgG1</td>
<td>3/4</td>
<td>6/7</td>
</tr>
<tr>
<td>Normal hlgG</td>
<td>0/4</td>
<td>0/3</td>
</tr>
</tbody>
</table>

ND, not done.
manner. These results further indicate that the induction of BP blister formation is more directly related to the deposition of Ab against hNC16A than to that of complement.

Next, we sought to examine the necessity of complements in the induction of skin lesions in adult mice, because BP patients are adult humans and not newborns. For this, we s.c. transferred mIgG1 hybridoma or mIgG2c hybridoma into the backs of Rag-2−/− mice that we previously generated (9). Four weeks after the transfer, each hybridoma formed a large mass on the back. Mild skin changes develop on the ear and snout in the mIgG2c (TS4-2) hybridoma-transferred mice, which are associated with distinct mC3 deposition and with weak mIgG deposition (Fig. 6A, 6E). Meanwhile, significantly severer skin changes, that is, erythema, erosions with crusts, and hair loss, were observed on the snout and ears and around the eyes, legs, and tail in the mIgG1 (TS39-3, TS21-1, or TI66-1) hybridoma-transferred mice, which are associated with strong deposition of mIgG but not mC3 (Fig. 6B–E). Blister formation was not apparent. Ear samples from

![Image](https://example.com/image.png)

**FIGURE 2.** Monoclonal rhIgG1 and rhG4 Abs react to hNC16A with different ability to fix complement to the DEJ. (A) Scheme for expression vectors of rhIgGs. CH, C region H chain; SS, signal sequence; TT, terminator. (B) Coomassie blue staining of affinity-purified rhIgGs separated by SDS-PAGE on 12.5% polyacrylamide gel. Lane 1, marker; lane 2, 1 μg rhIgG1; lane 3, 1 μg rhIgG4; lane 4, 1 μg control IgG1. (C and D) The reactivity of the rhIgGs against hNC16A was examined by indirect IF using NHS and COL17-humanized mouse skin (C) or using HEK293 cells expressing full-length human COL17 (HEK293-COL17), HEK293 cells expressing human COL17 other than the NC16A domain (HEK293-ΔNC16A), or HEK293 cells (D). Linear deposition of hlgG at the DEJ is indicated by arrows, and negative results are indicated by arrowheads. (E) Epitopes of mlgG were examined by dot blot using four small synthesized peptides of hNC16A. (C and E) Original magnification ×20. (D) Original Magnification ×40.
each group showed similar extents of inflammatory cell infiltration of neutrophils, lymphocytes, and histiocytes (Fig. 6A–D). Dermal/epidermal separation was also seen in some of the ear samples (positive/total: TS4-2, one of five; TS39-3, two of four; TS21-1, one of four; TI66-1, two of five; untreated, none of five). At day 28, most of the mice that were transferred with the mlgG1

FIGURE 3. Monoclonal rhlgG Abs against hNC16A induce blister formation in mice regardless of complement activation. (A) The complement-fixing activity of the rhlgGs was evaluated by indirect IF using NHS and mouse serum complement (MSC). Linear deposition of mC3 at the DEJ is indicated by arrows, and negative results are indicated by arrowheads. (B) The C1q-binding activity of the rhlgGs was determined by human C1q-binding assay by ELISA. One representative result out of three is shown. (C–R) Representative clinical presentations, H&E staining, and hlG and mC3 deposition 48 h after the passive transfer of rhlgG1, control hlG1, rhlgG4, and control hlG4 into neonatal COL17-humanized mice. Doses of rhlgGs were determined by the results of hNC16A ELISA. (S) Representative clinical presentations and hlG and mC3 deposition in neonatal human COL17-transgenic (COL17m+/+,h+) mice at 48 h after passive transfer of rhlgG4. Linear deposition of hlG at the DEJ in direct IF is indicated by arrows. Negative results are indicated by arrowheads. H&E, original magnification ×20; direct IF, original magnification ×20.

Table III. Passive transfer of rhlgG1 and rhlgG4 against human COL17 NC16A into neonatal mice

<table>
<thead>
<tr>
<th>Injected Neonatal Mice</th>
<th>Abs</th>
<th>Ratio of Mice with Skin Detachment*</th>
</tr>
</thead>
<tbody>
<tr>
<td>COL17-humanized</td>
<td>rhlgG1 (4.5 μg)</td>
<td>0/4</td>
</tr>
<tr>
<td></td>
<td>rhlgG1 (9 μg)</td>
<td>6/8</td>
</tr>
<tr>
<td></td>
<td>rhlgG1 (18 μg)</td>
<td>7/8</td>
</tr>
<tr>
<td></td>
<td>rhlgG1 (30 μg)</td>
<td>5/5</td>
</tr>
<tr>
<td>Control hlG1 (30 μg)</td>
<td>rhlgG4 (7.5 μg)</td>
<td>5/8</td>
</tr>
<tr>
<td></td>
<td>rhlgG4 (15 μg)</td>
<td>4/8</td>
</tr>
<tr>
<td></td>
<td>rhlgG4 (30 μg)</td>
<td>6/6</td>
</tr>
<tr>
<td></td>
<td>rhlgG4 (50 μg)</td>
<td>0/4</td>
</tr>
<tr>
<td></td>
<td>Control hlG4 (50 μg)</td>
<td>6/7</td>
</tr>
<tr>
<td></td>
<td>FcγR blocker (20 μg) plus rhlgG4 (50 μg)</td>
<td>6/7</td>
</tr>
<tr>
<td></td>
<td>FcγR blocker control (20 μg) plus rhlgG4 (50 μg)</td>
<td>6/7</td>
</tr>
<tr>
<td></td>
<td>rhlgG4 (50 μg) plus MG-132</td>
<td>6/7</td>
</tr>
<tr>
<td></td>
<td>COL17m+/+,h+</td>
<td>4/5</td>
</tr>
<tr>
<td></td>
<td>rhlgG1 (30 μg)</td>
<td>4/4</td>
</tr>
<tr>
<td></td>
<td>Control hlG1 (30 μg)</td>
<td>0/4</td>
</tr>
<tr>
<td></td>
<td>rhlgG4 (50 μg)</td>
<td>6/6</td>
</tr>
<tr>
<td></td>
<td>Control hlG4 (50 μg)</td>
<td>0/4</td>
</tr>
<tr>
<td></td>
<td>rhlgG4 (50 μg)</td>
<td>0/6</td>
</tr>
</tbody>
</table>

*Gentle skin rubbing test performed at 48 h in neonatal mice.
hybridoma developed skin fragility on the tail (positive/total: TS39-3, four of four; TS21-1, four of four; TI66-1, four of five), whereas only one of the mice that were transferred with the mIgG2c hybridoma showed skin detachment (positive/total: TS4-2, one of five). We also examined the levels of circulating IgG against hNC16A in the sera of hybridoma-transferred mice by ELISA. The mean OD values in each group are as follows: TS4-2, 0.465 ± 0.033; TS39-3, 0.404 ± 0.013; TS21-1, 0.410 ± 0.017; TI66-1, 0.417 ± 0.028; untreated, 0.023 ± 0.001 (mean ± SD). Thus, each hybridoma produced roughly the same level of Abs in the host mice. As shown in Fig. 6F, disease severity in individual mice did not relate to the level of circulating anti-hNC16A IgG. Altogether, blister formation in adult mice seems to correlate more directly with the amount of hNC16A-binding IgG Abs than with the extent of complement deposition or inflammatory cell infiltration.

Treatments of Abs against COL17 reduce the amount of COL17 both in vivo and in vitro

The results above strongly suggested that complement- and FcγR-independent effects would induce blister formation in vivo. Recent studies showed that Abs against COL17 deplete the amount of COL17 in cultured NHKs in a complement-independent manner.
To investigate this mechanism in the present experimental system, we first examined the amount of COL17 in the skin of BP-IgG–treated C3"/COL17-humanized mice at 48 h after injection. When compared with untreated mice as normalized to β-tubulin, the amount of COL17 was found to be reduced by ∼15–25% by BP-IgG treatment, although the difference was not statistically significant (Fig. 7A). We then performed in vitro experiments. When compared with the results of control IgG treatments, ∼50% (p < 0.01) of the COL17 treated with BP-IgG1, BP-IgG3, and BP-IgG4, or 40% (p < 0.05) of the COL17 treated with BP-IgG2 was depleted from the cells at 6 h (Fig. 7B). Additionally, rhIgG1, rhIgG4, and mIgG1s, but not mIgG2c, significantly depleted COL17 in NHKs when compared with the results of control-IgG–treated cells (Fig. 7C, 7D). Combined with the results of passive transfer experiments, these findings suggest that the induction of blister formation correlates with the affinity of Abs to hNC16A and with COL17 depletion.

Ab-bound COL17 is ubiquitinated and degraded by proteasome

We attempted to further investigate the mechanism whereby COL17 is depleted by pathogenic Ab binding. The ubiquitin/proteasome pathway is well known as a major system for protein degradation (39). To assess whether the pathway is involved in COL17 depletion, the ubiquitination of COL17 in rhIgG4-treated NHKs was examined. Before that, we confirmed that up to 12.5 μM MG-132, a very potent proteasome inhibitor, did not inhibit the degradation of COL17 in control-IgG–treated NHKs (39). The results of these experiments are shown in Fig. 7C. Together with the results of the in vitro experiments, these findings suggest that the induction of blister formation correlates with the affinity of Abs to hNC16A and with COL17 depletion.

Table IV. Passive transfer of murine IgG1 and IgG2c against human COL17 NC16A into neonatal mice

<table>
<thead>
<tr>
<th>Abs (Subclass)</th>
<th>COL17-Humanized Mice with Skin Detachment*</th>
<th>C3&quot;/COL17-Humanized Mice with Skin Detachment*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500 μg</td>
<td>100 μg</td>
</tr>
<tr>
<td>TS4-2 (IgG2c)</td>
<td>2/6</td>
<td>0/3</td>
</tr>
<tr>
<td>TS39-3 (IgG1)</td>
<td>ND</td>
<td>3/3</td>
</tr>
<tr>
<td>TS21-1 (IgG1)</td>
<td>ND</td>
<td>3/3</td>
</tr>
<tr>
<td>TI66-1 (IgG1)</td>
<td>ND</td>
<td>3/3</td>
</tr>
<tr>
<td>Normal IgG</td>
<td>0/4</td>
<td>0/4</td>
</tr>
</tbody>
</table>

*Gentle skin rubbing test performed at 48 h in neonatal mice.
ND, not done.
affect the viability in cultured NHKs (data not shown). COL17 was purified from NHKs after the treatment of rhIgG4 and/or MG-132 by immunoprecipitation using IgG Ab against hNC16A (TS39-3), and ubiquitination was checked by immunoblotting. Ubiquitination of COL17 in NHKs treated with rhIgG4 was more clear than that in untreated NHKs, indicating that rhIgG4 treatment promotes the ubiquitination of COL17 (Fig. 7E). Ubiquitination of rhlgG4-bound COL17 was more obvious when the COL17/rhlgG4 complex was purified from NHKs by immunoprecipitation using protein G beads (Fig. 7F). Next, we added different concentrations of MG-132 to NHKs with or without rhlgG4, or BP-IgG1 and examined the expression of COL17. MG-132 was found to significantly inhibit the COL17 depletion in a dose-dependent manner (Fig. 7G). These results indicate that the ubiquitin/proteasome pathway might be involved in the degradation of IgG-bound COL17. We further evaluated the effect of proteasome inhibitor in vivo. Intraperitoneal injection of MG-132 prior to the injection of rhlgG4 did not prevent the induction of blister formation in the treated mice (Table III), suggesting that several steps might exist between the blister formation by IgG binding and the COL17 depletion.

Discussion
To our knowledge, this study is the first to demonstrate the pathogenicity of Abs against COL17 in complement-deficient mice. BP-IgG caused blisters in neonatal C3-deficient COL17-humanized mice, of course, without complement activation. We recently reported that differences in Ab epitopes may considerably influence blister formation in neonatal COL17-humanized mice (13). To exclude the influence of the difference in epitopes, we generated novel rhlgG1 and rhlgG4 mAbs that strongly bind to an identical epitope on hNC16A. It was not only rhlgG1, which has...
FIGURE 7. IgG binding to COL17 induces COL17 depletion via the ubiquitin/proteasome pathway. (A) Neonatal C3(−/−)/COL17-humanized mice were injected with BP-IgG. The amount of COL17 (180 kDa) in the skin was examined by immunoblotting. COL17 content was normalized to β-tubulin. The COL17/β-tubulin ratio of untreated mice skin was calculated at 100%. Results are expressed as means ± SEM (n = 5). (B) Cultured NHKs were incubated with BP-IgGs or control hIgG. The amount of COL17 (180 kDa) in the cell lysates was detected by immunoblotting. Results are expressed as means ± SEM (n = 6). *p < 0.05, **p < 0.01 versus control hIgG. (C) Cultured NHKs were incubated with rhIgG1, control hIgG1, rhIgG4, or control hIgG4 for 6 h. The amount of COL17 (180 kDa) in the cell lysates was detected by immunoblotting. Results are expressed as means ± SEM (n = 6). *p < 0.05 versus control hIgG1, **p < 0.01 versus control hIgG4. (D) Cultured NHKs were incubated with mIgGs from hybridomas or control normal mIgG for 6 h. The amount of COL17 (180 kDa) in the cell lysates was detected by immunoblotting. Results are expressed as means ± SEM (n = 5). **p < 0.01 versus control mIgG. (E) NHKs were untreated or treated with rhIgG4 and/or MG-132, and lysates were subjected to immunoprecipitation with anti-hNC16A. The amount of ubiquitinated COL17 was detected by immunoblotting. Results are expressed as means ± SEM (n = 6). *p < 0.05 versus control hIgG.
BP AUTOANTIBODIES INDUCE BLISTER FORMATION WITHOUT COMPLEMENT

high complement activation ability, that led to blister formation in neonatal COL17-humanized mice. rhlgG4, which lacks complement activation ability, also led to such formation. Additionally, we showed that monoclonal mlgGs against the different epitope of hNC16A from those recognized by rhlgGs also cause blister formation in a complement-independent manner both in neonatal and adult mice. Thus, we confirmed the complement-independent pathogenicity of IgG Abs against COL17 in three distinct ways.

Previous studies using a polyclonal rabbit IgG passive transfer mouse model suggested that complement activation has primary importance in the pathogenesis of BP (16, 40). Our previous study showed that the administration of Fab fragments to hNC16A into neonatal COL17-humanized mice inhibits the complement pathway and ameliorates skin detachment (10). We also reported that hlG1 against hNC16A with mutations at the C1q-binding Fc portion has lower pathogenicity in neonatal COL17-humanized mice than has nonmutated hlG1 (11). More recently, we demonstrated that passive transfer of F(ab')2 fragments of BP-IgG or rabbit IgG against hNC16A induces skin detachment in neonatal COL17-humanized mice (13). These contradictory results can be explained by the differences in the target epitopes on COL17, the applied dose of Abs, the affinity of Abs to the target molecules, or the clonality of Abs in each experimental system. Our present data demonstrate that, at low doses, rhlgG4 has less potential to induce blister formation than does rhlgG1 (Table III). Thus, complement activation may make some contribution to blister formation in neonatal mice, although it is dispensable under our experimental system.

We also demonstrated that blockade of FcγRII/III does not inhibit skin detachment in rhlgG-injected mice. Little inflammatory cell infiltration was observed in skin samples from the rhlgG-injected neonatal mice. Taken together, cellular immune responses mediated by the Fc portions of rhlgG may not be involved in the pathogenesis of our experimental system. A recent study showing FcR-independent effects of BP-IgG and BP-IgE on cultured NHKs and human skin organ cultures (23) is consistent with our results.

Although the IgG4 subclass accounts for only ∼5% of total IgG in normal human sera, IgG4 autoantibodies have been reported to predominate in BP (41, 42). The capacity of the predominant IgG4 to induce tissue damage has been demonstrated by cryosection assay (34). In that study, IgG4 autoantibodies were found to have no capacity to fix complements but did show lower pathogenicity than did IgG1 with inducing the activation of leukocytes in an FcR-dependent manner in vitro. Our present data demonstrate that rhlgG4 induces blister formation in neonatal mice in complement- and FcγR-independent ways. These findings strongly suggest that not only do IgG1 autoantibodies contribute to the development of BP blister formation, but also do IgG4 autoantibodies.

COL17 depletion has been proposed as an alternative pathomechanism of BP. BP-IgG has been demonstrated to reduce the amount of COL17 in cultured NHKs (22). Additionally, we recently reported that the pathogenic IgG autoantibodies against hNC16A depletes COL17 in cultured NHKs (13). The present study shows that the administration of IgG against hNC16A reduces the amount of COL17 in mice skin and in cultured NHKs. We also demonstrated that the administration of rhlgG4 to human COL17-transgenic (COL17mouse/human) mice, which express both human and murine COL17, induces no blister formation, suggesting that the rhlgG which binds to hNC16A does not affect the function of murine COL17 in vivo. These findings show that IgGs against hNC16A directly deplete human COL17, which results in the impairment of hemidesmosomal formation and the decrease of adhesive strength. Additionally, monoclonal mlgG2c (TS4-2), which has a low affinity to hNC16A, a low ability to deplete COL17, and a high ability to activate complements, did not induce skin detachment in most treated mice. This strongly suggests that IgG binding to COL17 and subsequent COL17 depletion more directly correlate with the induction of blister formation than does complement activation. As a possible mechanism of COL17 depletion by IgG binding, the internalization of COL17 has been shown (43, 44). It was recently reported that BP-IgG induces COL17 internalization via a macropinocytic pathway and that intracellular and extracellular domains of COL17 are internalized simultaneously, suggesting that ectodomain shedding of COL17 does not necessarily occur in COL17 internalization and would not be essential to BP disease onset (45). Intracellular proteins are degraded to amino acids and replaced by newly synthesized proteins. Most proteins destined for degradation are labeled by ubiquitin and then digested to small peptides by a proteasome (39). We demonstrated that COL17 is ubiquitinated by the treatment of rhlgG and that a proteasome inhibitor inhibits the COL17 depletion in a dose-dependent manner. These indicate the contribution of the ubiquitin/proteasome pathway to COL17 depletion. Administration of a proteasome inhibitor to the rhlgG-injected mice did not prevent the induction of blister formation, suggesting that additional processes such as the internalization of COL17 cause the reduction of the adhesive strength before degradation by proteasomes. A recent study showed that the administration of mAbs against anaplastic lymphoma kinase induces the internalization of cell surface anaplastic lymphoma kinase, resulting in degradation by proteasomes (46). Further investigations of the mechanism of the internalization of COL17 caused by IgG binding may provide a new insight into the pathomechanisms of BP.

In interpreting the results, the limitations of each experimental system should be taken into consideration. In this study, we evaluated the pathogenicities of BP-IgG and human and murine mAbs mainly based on the blister formation of neonatal mice subjected to artificial rubbing. From the passive transfer model, IgG binding to COL17 seems to have enough of a direct effect to significantly weaken the adhesive strength of the neonatal skin. The COL17 depletion must induce blister formation in humans, because mutations in COL17 seen in junctional epidermolysis bullosa patients cause subepidermal blistering without neutrophil infiltration (47). Nevertheless, we cannot exclude the possibility that subsequent inflammatory immune reactions are necessary for spontaneous blister formation in human BP patients, because BP patients generally develop itchy edematous erythema as well as tense blisters. Similarly, an active adult BP mouse model that may more closely reproduce human BP than the neonatal model shows itchy erythema and blisters associated with strong deposition of mlgG and mC3 at the DEJ (9). Also note that the mechanically
induced blister formation in the passive transfer model does not exactly reproduce the spontaneous blistering that characterizes the human disease. Additionally, the transient disease activity does not fully allow us to examine the pathogenic mechanisms of the chronic disease. To address these limitations of the passive transfer model, we also performed a hybridoma transfer study using adult mice. Remarkably, to our knowledge, that study is the first demonstration that adult mice develop skin lesions such as erythema, erosions, and hair loss by the binding of IgG Ab against COL17 without complement deposition. However, spontaneous blister formation was not observed in the hybridoma transfer model, and its skin changes were less severe than those seen in the active adult BP mouse model mentioned above, suggesting a possible contribution of complement activation in the development of skin lesions in adult mice. Previous in vivo and in vitro studies have demonstrated that blister induction in BP depends on the presence of neutrophils (18, 48). As previously mentioned (22), a combination of COL17 depletion and nonspecific inflammatory enzymatic activity at the DEJ induced by Abs against COL17 may be necessary for the development of the severe BP disease phenotype observed in BP patients and in the active adult BP mouse model. Interestingly, the mlgG1 hybridoma-transferred mice showed inflammatory cell infiltration including neutrophils despite a lack of mC3 deposition. It has been reported that Abs against COL17 directly promote the production of IL-6 and IL-8, proinflammatory cytokines that are reported to be elevated in the sera and tissues of BP patients, by keratinocytes (23, 49). This pathway would enable Abs against COL17 to recruit neutrophils to the DEJ regardless of complement activation.

We should also consider species-related differences between human IgGs (BP-IgGs and rhlgGs) and murine innate immune components, for example, complement and neutrophils, in our experimental systems. Human autoantibodies against COL17 have been reported to have a lower capacity to fix murine complement and a reduced ability to activate murine leukocytes when compared with human complement and cells, respectively (50). In this study, complement activation was observed in the skin of neonatal COL17-humanized mice that were injected with BP-IgGs or rhlgG1, although this experimental system may not reflect the in vivo situation in BP patients in terms of species difference. To overcome this issue, we further performed experiments using mlgGs and reached the same conclusion.

Although humanization of COL17 enables us to evaluate the pathogenicity of BP-IgGs against hCOL17 in vivo, it raises the disadvantage of cross-species interaction between hCOL17 and other murine hemidesmosomal components. Hemidesmosomes are multimolecular complexes that promote the stable adhesion of epithelial cells to the underlying extracellular matrix. COL17 is known to interact with BP230, plectin, α6β4 integrin, laminin 332, and collagen IV (51–53). There is a possibility that COL17-humanized mice have less skin stability than do wild-type mice presumably followed by the internalization, ubiquitination, and degradation of COL17 molecules by proteasomes in the cytoplasm.

Our results indicate that the blocking of autoantibody binding to COL17, but not the prevention of complement activation, should be considered as the foremost therapeutic strategy for BP.

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Disclosures

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References


