Cutting Edge: The Murine High-Affinity IgG Receptor Fc γRIV Is Sufficient for Autoantibody-Induced Arthritis

David A. Mancardi, Friederike Jönsson, Bruno Iannascoli, Huot Khun, Nico Van Rooijen, Michel Huerre, Marc Daéron and Pierre Bruhns

*J Immunol* 2011; 186:1899-1903; Prepublished online 19 January 2011; doi: 10.4049/jimmunol.1003642
http://www.jimmunol.org/content/186/4/1899

Supplementary Material
http://www.jimmunol.org/content/suppl/2011/01/19/jimmunol.1003642.DC1

References
This article cites 29 articles, 12 of which you can access for free at:
http://www.jimmunol.org/content/186/4/1899.full#ref-list-1

Subscription
Information about subscribing to *The Journal of Immunology* is online at:
http://jimmunol.org/subscription

Permissions
Submit copyright permission requests at:
http://www.aai.org/About/Publications/JI/copyright.html

Email Alerts
Receive free email-alerts when new articles cite this article. Sign up at:
http://jimmunol.org/alerts
Cutting Edge: The Murine High-Affinity IgG Receptor FcyRIV Is Sufficient for Autoantibody-Induced Arthritis

David A. Mancardi,*†,1 Friederike Jönsson,*†,1 Bruno Iannascoli,*†,1 Huot Khun,‡ Nico Van Rooijen,§ Michel Huerté,‡ Marc Daéron,*†,1 and Pierre Bruhns*‡,†

K/BxN serum-induced passive arthritis was reported to depend on the activation of mast cells, triggered by the activating IgG receptor FcyRIIIA, when engaged by IgG1 autoantibodies present in K/BxN serum. This view is challenged by the fact that FcyRIIIA-deficient mice still develop K/BxN arthritis and because FcyRIIIA is the only activating IgG receptor expressed by mast cells. We investigated the contribution of IgG receptors, IgG subclasses, and cells in K/BxN arthritis. We found that the activating IgG2 receptor FcyRIV, expressed only by monocytes/macrophages and neutrophils, was sufficient to induce disease. K/BxN arthritis occurred not only in mast cell-deficient W/Wv mice, but also in mice whose mast cells express no activating IgG receptors. We propose that at least two autoantibody isotypes, IgG1 and IgG2, and two activating IgG receptors, FcyRIIIA and FcyRIV, contribute to K/BxN arthritis, which requires at least two cell types other than mast cells, monocytes/macrophages, and neutrophils. The Journal of Immunology, 2011, 186: 1899–1903.

Rheumatoid arthritis (RA) is a systemic autoimmune disease due to autoantibodies in the serum of patients (e.g., anti–glucose-6-phosphate-isomerase [GPI] autoantibodies) (1). IgG anti-GPI autoantibodies are present in the serum of offspring of KRN-transgenic C57BL/6 crossed to NOD mice (2) (K/BxN serum), which develop spontaneously an RA-like disease. Normal mice injected with K/BxN-serum develop passive arthritis (K/BxN-PA). IgG1 autoantibodies represent the majority of IgG anti–GPI autoantibodies, and they are therefore thought to account for K/BxN-PA. K/BxN serum, however, also contains IgG2 anti–GPI autoantibodies (3).

Among the three murine activating IgG receptors (FcγR), FcyRIIIA can be engaged by IgG1 and IgG2, whereas FcyRI and FcyRIV can be engaged by IgG2 only (4). K/BxN-PA is abrogated in mice lacking the FcγR subunit (5, 6) that is required for the expression and function of these FcγRs (7). Interestingly, K/BxN-PA is reduced, but not abolished, in FcyRIIIA−/− mice (5, 6), suggesting that FcyRI and/or FcyRIV contribute to disease. K/BxN-PA is, however, unaffected in mice lacking FcγRI (5, 6). The role of FcyRIV has not been investigated.

FcyRIV is expressed by monocytes/macrophages and neutrophils, and FcyRIIIA by monocytes/macrophages, neutrophils, and mast cells. These three cell types have been reported to be mandatory for K/BxN-PA. K/BxN-PA is, indeed, abrogated in wild-type (wt) mice depleted of monocytes/macrophages (9), depleted of neutrophils (10), or lacking mature neutrophils (11). Based on experiments performed in mast cell-deficient W/Wv mice, mast cells are considered necessary for K/BxN-PA (12). A requirement for mast cells in K/BxN-PA appears, however, in contradiction with the fact that K/BxN-PA is not abolished in FcyRIIIA−/− mice, because FcyRIIIA is the only activating FcγR expressed by mast cells. W/Wv mice display many abnormalities other than mast cell deficiency that may explain these contradictory results (13–15).

We therefore investigated the role of FcyRIV, as well as the requirement for mast cells, in K/BxN-PA. We found that mast cell-deficient W/Wv mice and mice expressing no FcγR but FcyRIV developed K/BxN-PA. FcyRIV is indeed sufficient to induce arthritis in the absence of other activating IgG receptors. FcyRIV-dependent arthritis was induced by IgG2 autoantibodies and required both monocytes/macrophages

*Institut Pasteur, Unité d’Allergologie Moléculaire et Cellulaire, Département d’Immunologie, F-75015 Paris, France; †INSERM, U760, F-75015 Paris, France; ‡Institut Pasteur, Unité de Recherche et d’Expertise Histotechnologie et Pathologie, Département de Pathologie, F-75015 Paris, France; and §Department of Molecular Cell Biology, Vrije Universiteit Medical Center, Amsterdam, The Netherlands

1D.A.M. and F.J. contributed equally to this work.

Received for publication November 4, 2010. Accepted for publication December 20, 2010.

This work was supported by Institut Pasteur, INSERM, Agence Nationale de la Recherche (Grants 05-JCJC-0236-01 and 09-GENO-034-01), and funding under the Sixth Research Framework Program of the European Union (Project MUGEN, LSHG-CT-2005-005203). D.A.M. was financially supported by the Fondation pour la Recherche Médicale and is currently a recipient of a fellowship from the Institut Pasteur (Bourse Roux). F.J. was financially supported by Agence Nationale de la Recherche (Grants 05-JCJC-0236-01 and 09-GENO-014-01), and funding under the Sixth Research Framework Program of the European Union (Project MUGEN, LSHG-CT-2005-005203). D.A.M. and F.J. performed experiments and designed part of the research; B.I. generated mice and produced essential reagents; H.K. and M.H. performed histology and provided expertise; N.V.R. provided reagents; P.B., M.D., F.J., and D.A.M. analyzed and discussed results; P.B., M.D., and F.J. wrote the manuscript; and P.B. designed and supervised the research.

Address correspondence and reprint requests to Dr. Pierre Bruhns, Unité d’Allergologie Moléculaire et Cellulaire, Département d’Immunologie, Institut Pasteur, 35 Rue du Docteur Roux, 75015 Paris, France. E-mail address: bruhns@pasteur.fr

The online version of this article contains supplemental material.

Abbreviations used in this article: FcR, neonatal Fc receptor; GPI, glucose-6-phosphate-isomerase; K/BxN-PA, K/BxN serum-induced passive arthritis; RA, rheumatoid arthritis; wt, wild-type.

Copyright © 2011 by The American Association of Immunologists, Inc. 0022-1767/11/$16.00
and neutrophils. FcγRII also contributed to arthritis in wt mice. Importantly, we identified FcγRIIIA and FcγRIV as the IgG receptors responsible for K/BxN-PA in wt mice.

**Materials and Methods**

**Mice**

The wt mice were purchased from Charles River Laboratories and FcγRIIB<sup>-/-</sup>, FcγRIIIA<sup>-/-</sup>, FcγRI<sup>-/-</sup>, W/W<sup>+</sup>, and W/W<sup>-</sup> mice from The Jackson Laboratory (Bar Harbor, ME). FcγRIIB/IIIA<sup>-/-</sup> and 5KO mice were described previously (4). hFcRn<sup>-/-</sup> mFcRn<sup>-/-</sup> mice were obtained from D. C. Roopenian (The Jackson Laboratory) and crossed to SKO mice to obtain 6KO and hFcRn tg mice. KRN<sup>-/-</sup> mice were provided by D. Mathis, C. Benoist (Harvard Medical School, Boston, MA), and the Institut de Génétique et de Biologie Moléculaire et Cellulaire (Strasbourg, France). Mice used in experiments were on the C57BL/6J background (6th–12th generation backcross), except W/W<sup>-</sup> mice. All mice were used between 7 and 9 wk of age. All mouse protocols were approved by the Animal Care and Use Committees of Paris, Ile de France, France.

**Reagents**

Anti-mFcγRIIIA (275003) and anti-mFcγRI (293322) were from R&D Systems; anti-mouse FcγRIIB/IIIA (2A2G2), CD11b, CD11c, Gr1, SiglecF, CD117, DX5, and IgE were from BD Biosciences; HRp-coupled anti-mouse IgG subclasses were from Southern Biotechnology Associates; and GPI and laminin were from Sigma-Aldrich. Hybridomas producing anti-mFcγRI mAb (4E9) were provided by J.V. Ravetch (The Rockefeller University, New York, NY), anti-Gr1 mAb (RB6-8C5) by R. Coffman (DNAx, Palo Alto, CA), and anti-platelet mAb (6A6) by Dr. R. Good (University of South Florida College of Medicine, Tampa, FL). Purified anti-mFcγRII (217A, 2179) was provided by M.P. Hogarth (ARI, Heidelberg, Victoria, Australia) and anti-CD200R3 mAb (Ba103) by H. Karasuyama (Tokyo Medical and Dental University, Tokyo, Japan). PBS-liposomes and clodronate-liposomes were prepared as published (16).

Anti-GPI IgG were purified from K/BxN serum using protein G, polyclonal IgG1, and IgG2 fractions using anti-mlgG1 or anti-mlgG2 Sepharose beads (Nordic Immunology). IgG subclasses were determined by ELISA using HRP-coupled anti-mouse IgG1, anti-mouse IgG2 plus anti-mouse IgG2c, or anti-mouse IgG2b (Southern Biotechnology). Specific anti-GPI levels were measured by anti-subclass ELISA on GPI-coated plates using IgG1, IgG2a, and IgG2b anti-GPI mAbs (obtained in collaboration with the Ab Production Platform, Institut Pasteur, Paris, France) as internal standards.

**K/BxN-PA**

K/BxN serum was generated, and arthritis was scored as described (6). When not otherwise specified, arthritis was induced by an i.v. injection of 150 μl K/BxN serum. Anti-FcγRII (200 μg/mouse) and anti-FcγRIIIA (100 μg/mouse) blocking mAbs were injected i.v. 30 min before K/BxN serum and on days +1/+2/+4. Liposomes (2.1 mg/mouse) and anti-CD200R3 (100 μg/mouse) were injected i.v. 24 h before K/BxN serum. 6A6 (50 μg/mouse) or anti-Gr1 (500 μg/mouse) mAbs were injected i.v. on days −1/+1/+3/+5. Sections of paraffin-embedded ankle joints were stained with H&E. Bioluminescence from mice injected with 10 mg/mouse luminol i.p. was acquired on an IVIS-100 (Caliper LifeSciences).

**Cell counts and flow cytometry analysis**

Cell counts in whole blood from 7–9-wk-old mice were determined using an ABC Vet automatic blood analyzer (Horiba ABX). Ex vivo cells were defined as follows by flow cytometry: monocytes/macrophages (blood/peritoneum: CD11b<sup>+</sup>/Gr1<sup>+</sup>; bronchoalveolar lavage: CD11c<sup>+</sup>/Gr1<sup>+</sup>), neutrophils (Gr1<sup>+</sup>/SiglecF<sup>+</sup>), basophils (IgE<sup>+</sup>/DX5<sup>+</sup>), and mast cells (IgE<sup>+</sup>/CD117<sup>+</sup>).

A total of 2 × 10<sup>6</sup> Chinese hamster ovary-K1 transfectants expressing mFcγRs (4) was incubated for 30 min at 4°C with indicated mAbs before flow cytometry analysis.
**Results and Discussion**

Classically, K/BxN-PA is thought to depend on FcγRIIIA. Arthritic symptoms are indeed reduced, but they are not abolished in FcγRIIIA−/− mice (5) (Fig. 1A). The clinical score was higher in double-deficient FcγRIIIB/IIIA−/−/− mice that also lack inhibitory FcγRIIB compared with the clinical score of FcγRIIIA−/− mice (Fig. 1A). FcγRIIB deficiency has indeed been reported to increase the susceptibility to K/BxN-PA (17), as well as to other arthritis models (18, 19). FcγRIIIA-independent K/BxN-PA is therefore negatively regulated by FcγRIIB. No K/BxN-PA could be induced in FcγRI−/− mice, as reported (5, 6, 17). Together these observations suggest the involvement of activating FcγR other than FcγRIIIA (i.e., FcγRI and/or FcγRIV) in K/BxN-PA.

Although the deletion of FcγRI prevented arthritis in an active model of RA (20), FcγRI−/− mice developed K/BxN-PA as wt mice (5, 6) (data not shown). Supporting the latter finding, this receptor was reported not to be expressed in naive mice on blood monocytes, tissue macrophages, or neutrophils, but only on dendritic cells and elicited or derived macrophages (21). Indeed, we observed FcγRI on macrophage cell lines (Supplemental Fig. 1A) and on bone marrow-derived macrophages (Supplemental Fig. 1B), as expected (20, 21), but not on freshly isolated monocytes, macrophages, neutrophils, or other blood, splenic, or peritoneal cells from naive C57BL/6J mice (Supplemental Fig. 1B) when stained with specific (Supplemental Fig. 1C), nonblocking (Supplemental Fig. 1D), anti-FcγRI mAbs. In addition, FcγRII expression was undetectable on Mac-1+ cells in blood or peritoneum even following K/BxN serum injection (Supplemental Fig. 1E). These data do not support a contribution of FcγRI to K/BxN-PA (5, 6), and we therefore investigated the possible contribution of FcγRIV.

Supporting this possibility, K/BxN-PA was reported to be reduced but not abolished in double-deficient FcγRIIIB/IIIA−/− mice (8). We used FcγRIIIB/IIIA−/− FcγRII/II/− (5KO) mice (4) to demonstrate the role of FcγRIV in K/BxN-PA. These mice express no activating IgG FcR, but FcγRIV. We found that K/BxN serum (Fig. 1A, red curve) or IgG purified from K/BxN serum (data not shown) induced arthritis in 5KO mice. Clinical scores and histological inflammation induced under these conditions were, however, milder than in wt mice (Supplemental Fig. 1F). Blocking of FcγRIV with anti-FcγRIV mAbs prevented the development of arthritis (Fig. 1B, Supplemental Fig. 1G) in 5KO mice. FcγRIV is therefore sufficient for K/BxN-PA. FcγRIV-dependent arthritis was abolished when monocytes/macrophages or neutrophils were depleted in 5KO mice (Fig. 1C), as reported for wt mice (9, 10). A recent report demonstrating that K/BxN-PA could be restored in neutrophil-deficient mice by trans-weathering wt or FcγRIIIA−/− bone marrow, but not by transferring FcγRII−/− bone marrow (11), supports the role of FcγRIV on neutrophils in K/BxN-PA. Activated neutrophils and inflammatory monocytes/macrophages can release myeloperoxidase. Myeloperoxidase can oxidize luminol, leading to photon emission that can be detected by bioluminescence imaging (22). Following luminol injection, luminescence was detected in the joint areas, as early as 1 d after K/BxN serum injection in both wt and 5KO mice (Fig. 1D). Whereas K/BxN-PA was reported to require mast cell activation (23), FcγRIV is not expressed on mouse mast cells. We therefore investigated how FcγRIV could induce K/BxN-PA without being expressed on mast cells and whether FcγRIV contributes to K/BxN-PA in wt mice.

We used mast cell-deficient mouse strains, W/Wv and Wsh, to further investigate the role of mast cells in K/BxN-PA. We found, as previously described (12, 17), that most W/Wv mice did not develop K/BxN-PA. Importantly, all Wsh mice developed arthritis when injected i.v. (Fig. 1E) or i.p. (Supplemental Fig. 1H) with K/BxN serum (in agreement with unpublished data discussed in Ref. 23). Similar results were reported for these two mouse strains in another passive model of arthritis (15). In addition to their mast cell deficiency (Supplemental Fig. 2A), W/Wv and Wsh mice have many other abnormalities (14, 15) (Supplemental Fig. 2B). Noticeably, we found that W/Wv mice display basopenia, whereas Wsh mice display basophilia (Fig. 1F). Blood depletion, however, did not prevent K/BxN-PA in Wsh mice (Fig. 1G, Supplemental Fig. 2C). Basophils could therefore not replace mast cells and explain why Wsh, but not W/Wv mice, developed arthritis. Similarly, depletion of platelets did not abolish K/BxN-PA in Wsh mice, indicating that the higher number of platelets found in Wsh compared with W/Wv mice could not explain
the difference in susceptibility to K/BxN-PA between these two strains (Supplemental Fig. 2B, 2D). Higher neutrophil (15) and/or monocyte numbers in W/W^v than in W/W^v^mice (Supplemental Fig. 2B) may explain this difference. Supporting this hypothesis, a transfer of neutrophils was recently reported to be sufficient to restore K/BxN-PA in W/W^v^mice (24). Lower numbers of neutrophils may therefore protect W/W^v^mice from K/BxN-PA. Altogether, these results suggest that mast cells may not be mandatory for K/BxN-PA. This conclusion is strengthened by our results showing that mice that do not express activating FcγRI on their mast cells, and basophils still develop K/BxN-PA (i.e., FcγRIIIA^-/- mice, FcγRIIIB/IIIA^-/- mice, and 5KO mice). Mast cells may, however, participate in K/BxN-PA (12, 25) and human RA, as high numbers of degranulated mast cells can be observed in the joints of patients (26).

K/BxN-PA was reported to depend primarily on IgG1 autoantibodies (3). FcγRIV, however, has no affinity for IgG1 (27). The finding that K/BxN serum could induce arthritis in 5KO mice can be explained by the presence of IgG2 anti-GPI Abs (3) in K/BxN serum (Fig. 2A). Indeed, IgG1 purified from K/BxN serum induced arthritis in wt mice, but not in 5KO mice, whereas purified IgG2 induced arthritis similarly in both mice (Fig. 2B). Endogenous IgG2 is protected from degradation by FcRn in 5KO, but not in 5KO mice lacking FcRn (6KO mice) (Fig. 2C, left panel). In accordance with these data, FcγRIV-dependent arthritis was strongly inhibited in 6KO mice following K/BxN serum injection (Fig. 2D), probably due to the lower in vivo persistence of anti-GPI IgG2b Abs in 6KO than in 5KO mice (Fig. 2C, right panel) as expected (28). K/BxN-PA was restored when 6KO mice were transgenic for human FcRn (Fig. 2D). Indeed, human FcRn has an affinity for mouse IgG2 (29) that it can protect from degradation (30). It has no affinity for mouse IgG1. Incidentally, the low affinity of human FcRn for mouse IgG2 had not been previously reported to be sufficient for in vivo function. Taken together, these results demonstrate that IgG2 autoantibodies are sufficient to induce K/BxN-PA not only in 5KO mice but also in wt mice. Importantly, blocking FcγRIV reduced K/BxN-PA in wt mice (Fig. 2E). These results indicate that FcγRIV, and therefore IgG2 autoantibodies, contribute to K/BxN-PA in normal mice. Supporting this conclusion, blocking FcγRIIIA markedly reduced but blocking both receptors was required to abolish arthritis in wt mice (Fig. 2E). Similar results were obtained in FcγRIIIB/IIIA^-/- (Supplemental Fig. 2E) or in FcγRIIIA^-/- mice (Supplemental Fig. 2A), in which FcγRIIIB accounted for arthritis. FcγRIV therefore contributes significantly to arthritis together with FcγRIIIA in wt mice, even though the contribution of FcγRIIIA is predominant.

In conclusion, genetically modified mice, expressing a restricted set of activating IgG receptors, enabled us to demonstrate that the high-affinity IgG receptor FcγRIV was sufficient to induce K/BxN-PA (i.e., in the absence of FcγRI, FcγRIIIB, and FcγRIIIA). IgG2 autoantibodies contained in K/BxN serum can, by themselves, induce and significantly contribute to K/BxN-PA. Our results also demonstrate that, together, FcγRIIIA and FcγRIV are responsible for K/BxN-PA symptoms in wt mice. In addition, our results provide two independent pieces of evidence demonstrating that mast cells are not mandatory for K/BxN-PA. Indeed, K/BxN-PA was unaltered in mast cell-deficient W^v^mice, and mice for which mast cells could not be activated directly by autoantibodies from K/BxN serum developed K/BxN-PA. Finally, our results demonstrate that activation of neutrophils and monocytes/macrophages is sufficient to induce autoantibody-induced arthritis.

**Acknowledgments**

We thank S. Darrevelle, F. Nato (Plate-forme de Production de Protéines Recombinantes et d’Anticorps, Institut Pasteur, Paris, France) for generation, cloning, and characterization of anti-GPI mAbs, A.-M. Nicola (Plate-Forme d’Imagerie Dynamique, Institut Pasteur, Paris, France) for help with the bioluminescence experiments, and C. Dechepare for administrative help. We also thank our colleagues for generous gifts: S. Verbeek, J.-P. Kinet, M. Lamers, D.C. Roopenian, D. Mathis, and C. Benoist for mice and J.V. Ravetch, H. Karayumak, R. Coffman, R. Good, and M.P. Hogarth for Abs. Cl3MDP was a gift from Roche Diagnostics GmbH.

**Disclosures**

The authors have no financial conflicts of interest.

**References**


Supplemental Figure 1. (A-C) Clone 290322 is a non-blocking anti-FcγRI specific mAb. (A) FcγRI-expressing macrophage cell line. Histograms show the binding of indicated mAbs to RAW cells. (B) FcγRI is not expressed in naïve C57BL/6 mice. Representative expression of FcγRI on bone marrow-derived macrophages (BMDM) differentiated in the presence of murine M-CSF for 8 days, and in the presence or not of IFNγ or LPS for the last 24 hours before analysis, or on monocytes/macrophages or neutrophils from indicated tissues. (C) Representative staining of FLAG-tagged mouse FcγRs CHO-K1 transfectants by indicated mAbs analyzed by flow cytometry. (D) Density plots show the binding of monomeric murine IgG2a or anti-mouse FcγRI when incubated with mFcγRI-expressing CHO-K1 transfectants in the indicated order. (E) K/BxN serum injection does not induce FcγRI expression in wt mice. Representative expression of FcγRI on Mac-1+ cells from blood or peritoneum of untreated or K/BxN serum-injected wt mice (day 6 post-injection). (F) Milder arthritic symptoms in 5KO than in wt mice. Representative hematoxilin-eosin staining of sections of paraffin-embedded decalcified ankle joints from mice from Fig.1A on day 6 injected with K/BxN serum (acute inflammation with focal recruitment of polymorphonuclear cells and monocytes) or not injected (no signs of inflammation). Magnification: 20x. (G) FcγRIV is responsible for K/BxN-PA in 5KO mice. K/BxN-PA in 5KO mice injected with indicated mAbs (n=4). Representative paraffin-embedded ankle sections of 5KO mice stained with hematoxilin-eosin, on day 6. Magnification: 200x. (H) K/BxN-PA develops in mast cell-deficient Wsh mice. K/BxN PA in Wsh mice injected with K/BxN serum i.v. or i.p. (n=3). (A-H) Data are representative of at least two independent experiments and (G,H) represented as mean +/-SEM.
**Supplemental Figure 2.** (A) *W/W* and *Wsh* mice lack peritoneal mast cells. Percentages of IgE+/CD117+ mast cells among peritoneal cells in indicated mice. (B) Blood cell population abnormalities in *W/W* and *Wsh* mice. Cell counts in the blood of indicated naive mice were acquired on an automatic blood analyzer, and the percentage of neutrophils among WBC was determined by flow cytometry following CD11b and Gr-1 staining (n=8). (C) Efficient basophil depletion in *Wsh* mice. Representative percentages of IgE+/DX5+ basophils among blood leukocytes in *Wsh* mice from Fig.1G. (D) High platelet numbers are not mandatory for K/BxN-PA in *Wsh* mice. K/BxN-PA in mice injected i.v. with 80μL K/BxN serum and indicated mAbs (Statistical differences are indicated for each time point if significant), and platelet counts from these mice acquired on an automatic blood analyzer (n=4). (E,F) FcγRII is responsible for FcγRIIIA-independent K/BxN-PA. K/BxN-PA in indicated mice injected with indicated mAbs (n=4). (A-E) Data are representative of at least two independent experiments and (D-F) represented as mean +/-SEM.