

On the interaction of IgG subclasses with the low affinity Fc gamma RIIa (CD32) on human monocytes, neutrophils, and platelets. Analysis of a functional polymorphism to human IgG2.

P W Parren, ... , L A Aarden, J G van de Winkel

J Clin Invest. 1992;**90**(4):1537-1546. <https://doi.org/10.1172/JCI116022>.

Research Article

An allotypic form of the low affinity IgG Fc receptor Fc gamma RIIa (CD32), termed low responder (LR) because of its weak reactivity with mouse (m) IgG1, interacts efficiently with human (h) IgG2. Fc gamma RIIaLR is the first known human FcR that binds this IgG subclass. In this study, we analyzed the role of Fc gamma RIIa in binding of stable hIgG-subclass dimers, and in induction of T cell mitogenesis using chimeric anti-CD3 mAb. We demonstrate that the functional polymorphism to hIgG2 is expressed on the majority of Fc gamma R-bearing peripheral blood cells: monocytes, neutrophils, and platelets. We were able to assess Fc gamma RII-mediated IgG-binding without interference of other Fc gamma R-classes, by blockade of Fc gamma RI on monocytes, and by using neutrophils of an individual deficient for the Fc gamma RIIIB gene. This study indicates as subclass specificity: hIgG3 > hIgG1, hIgG2 >> hIgG4 for Fc gamma RIIaLR and hIgG3, hIgG1 >> hIgG2 > hIgG4 for Fc gamma RIIaHR. Comparing the serum hIgG levels of individuals homozygous for the two Fc gamma RIIa allotypic forms, we observed significantly lower hIgG2 serum levels in individuals expressing the hIgG2-binding LR allotypic form. This observation may implicate that Fc gamma RIIa regulates hIgG subclass production or turnover in man.

Find the latest version:

<https://jci.me/116022/pdf>



On the Interaction of IgG Subclasses with the Low Affinity Fc γ RIIa (CD32) on Human Monocytes, Neutrophils, and Platelets

Analysis of a Functional Polymorphism to Human IgG2

Paul W. H. I. Parren,* Petra A. M. Warmerdam,[‡] Leonie C. M. Boeije,* Janine Arts,[‡] Nomdo A. C. Westerdaal,[‡] Arjen Vlug,* Peter J. A. Capel,[‡] Lucien A. Aarden,* and Jan G. J. van de Winkel[‡]

*Central Laboratory of the Netherlands Red Cross Blood Transfusion Service and Laboratory of Experimental and Clinical Immunology, University of Amsterdam, and [‡]Department of Immunology, University Hospital Utrecht, The Netherlands

Abstract

An allotypic form of the low affinity IgG Fc receptor Fc γ RIIa (CD32), termed low responder (LR) because of its weak reactivity with mouse (m) IgG1, interacts efficiently with human (h) IgG2. Fc γ RIIa^{LR} is the first known human FcR that binds this IgG subclass. In this study, we analyzed the role of Fc γ RIIa in binding of stable hIgG-subclass dimers, and in induction of T cell mitogenesis using chimeric anti-CD3 mAb. We demonstrate that the functional polymorphism to hIgG2 is expressed on the majority of Fc γ R-bearing peripheral blood cells: monocytes, neutrophils, and platelets. We were able to assess Fc γ RII-mediated IgG-binding without interference of other Fc γ R-classes, by blockade of Fc γ RI on monocytes, and by using neutrophils of an individual deficient for the Fc γ RIIIB gene. This study indicates as subclass specificity: hIgG3 > hIgG1, hIgG2 \gg hIgG4 for Fc γ RIIa^{LR} and hIgG3, hIgG1 \gg hIgG2 > hIgG4 for Fc γ RIIa^{HR}. Comparing the serum hIgG levels of individuals homozygous for the two Fc γ RIIa allotypic forms, we observed significantly lower hIgG2 serum levels in individuals expressing the hIgG2-binding LR allotypic form. This observation may implicate that Fc γ RIIa regulates hIgG subclass production or turnover in man. (*J. Clin. Invest.* 1992; 90:1537–1546.) Key words: chimeric anti-CD3 • T cell activation • serum IgG • CD16 • CD64

Introduction

Receptors specific for the Fc moiety of IgG (Fc γ R), expressed on a broad range of hematopoietic cells, create an important linkage between humoral and cellular defence mechanisms.

Address correspondence to Dr. Jan G. J. van de Winkel, Department of Immunology, University Hospital Utrecht, Rm G.04.614, P.O. Box 85500, 3508 GA Utrecht, The Netherlands.

Paul Parren's present address is Baxter Healthcare, Biology Skill Center, 10555 West Flagler St., Miami, FL 33174.

Received for publication 29 January 1992 and in revised form 7 April 1992.

1. Abbreviations used in this paper: Fc γ R, IgG Fc receptor; GPI, glycosyl-phosphatidylinositol; GPI-PLC, GPI-specific phospholipase C; h, human; HR, high responder (to mIgG1); IMDM, Iscove's modified Dulbecco's medium; LR, low responder (to mIgG1); m, mouse; PLC, phospholipase C; PNH, paroxysmal nocturnal hemoglobinuria; TcR, T cell receptor.

J. Clin. Invest.

© The American Society for Clinical Investigation, Inc.
0021-9738/92/10/1537/10 \$2.00

Volume 90, October 1992, 1537–1546

On human leukocytes, three distinct classes of IgG Fc receptors (Fc γ R) are currently recognized. Fc γ RI (CD64) is a 72-kD high affinity receptor ($K_a \sim 10^8 - 10^9 \text{ M}^{-1}$) that is expressed constitutively on monocytes and macrophages, and is IFN- γ - and G-CSF-inducible on neutrophils (1, 2). Fc γ RII (CD32) and Fc γ RIII (CD16) display lower affinities ($K_a < 10^7 \text{ M}^{-1}$) and primarily bind immune complexes. Both Fc γ RII and Fc γ RIII have been demonstrated on neutrophils, eosinophils, and macrophages. Fc γ RII is, furthermore, expressed on monocytes, B cells, basophils, and platelets (3, 4).

The subclass specificity of Fc γ RII (on platelets) was previously determined as human (h)IgG1 = hIgG3 > hIgG2, hIgG4 (5). This view may be incomplete; however, since cDNA cloning of Fc γ RII revealed multiple Fc γ RII-isoforms and allotypes (6–8), which may express differences in IgG subclass specificity. Three distinct genes termed hFc γ RIIA, B, and C have been described, which encode highly homologous proteins regarding the extracellular parts, but which display strong structural divergence in cytoplasmic domains (6, 7, 9, 10). This indicates that differences in subclass specificity between the various forms, and differential expression on distinct cells may have major consequences for antibody effector functions. Fc γ RII is known to be polymorphic with respect to its interaction with mouse (m)IgG1 complexes (4, 11). It was recently shown that this functional polymorphism resides in a single Arg-His amino acid change at position 131 in Fc γ RIIa (12–14). Excitingly, it was found that this change also has implications for the interaction with hIgG: transfected fibroblasts expressing Fc γ RIIa (131-His), which was termed low responder (Fc γ RIIa^{LR}) because of its weak reactivity with mIgG1, appeared to bind hIgG2 dimers efficiently, in contrast to the Fc γ RIIa high responder (Fc γ RIIa^{HR}) allotypic form (13).

Recently, we developed a matched set of mouse/human chimeric anti-CD3 mAb (15). mAb directed against the multi-molecular TcR/CD3 complex on the cell surface of human T cells, are capable of inducing T cell activation, both in vitro and in vivo (16). Accessory cells such as monocytes, however, are required to induce full activation and proliferation of the T cells and provide crosslinking of the anti-CD3 mAb via Fc receptors, as well as production of lymphokines such as IL-1 (11, 17). Using these antibodies, we demonstrated that this Fc γ RII polymorphism is functionally expressed in anti-CD3 mAb induced T cell activation, both with monocytes and Fc γ RIIa^{HR}- or Fc γ RIIa^{LR}-transfected fibroblasts as accessory cells (18).

A complication in linking the above observations to other cells expressing Fc γ RII is the potential coexpression of multiple isoforms of Fc γ RII, such as Fc γ RIIb, which expresses a distinct subclass specificity (Warmerdam, P. A. M., I. E. Oudyk, P. W. H. I. Parren, N. A. C. Westerdaal, J. G. J. van de

Winkel, and P. J. A. Capel. Submitted for publication), and coexpression of members of different Fc γ R classes on most blood cells (4). Furthermore, studies with hybrid antibodies have suggested that one IgG molecule may simultaneously interact with two distinct Fc γ R molecules (19), this might imply that potential cooperation between different classes of Fc γ R molecules may affect IgG binding avidity.

We now demonstrate the functional Fc γ RIIa polymorphism for hIgG2 complexes on the majority of Fc γ R bearing peripheral blood cells: monocytes, neutrophils, and platelets. Comparing IgG serum levels between groups of individuals homozygous for either Fc γ RIIa allotype, we found significantly lower serum hIgG2 levels in Fc γ RIIa^{LR} individuals. This observation may implicate that Fc γ RIIa^{LR}, which is the first FcR known to bind hIgG2 efficiently, may be involved in modulation of hIgG serum levels.

Methods

Monoclonal antibodies. Hybridoma cell line CLB-T3/4.1, producing a mIgG1, κ mAb reactive with the ϵ chain of the TcR/CD3 complex (20) and its heavy chain isotype variants have been described in detail (15, 21).

Anti-Fc γ RI mAb 197 (γ 2a, κ) and mAb 22 (γ 1, κ ; FITC-conjugated), anti-Fc γ RII mAb IV.3 (γ 2b, κ) and anti-Fc γ RIII mAb 3G8 (γ 1, κ) were kindly provided by Medarex, Inc. (W. Lebanon, NH). Anti-Fc γ RII mAb 41H16 (γ 2a, κ) was provided by Dr T. Zipf (University of Texas, Houston, TX), and anti-Fc γ RIII mAb CLB Gran1 (γ 2a, κ) was from the CLB. Anti-CD28 mAb CLB-CD28/1 (γ 1, κ) was provided by Dr R. van Lier (CLB, Amsterdam).

Purification of PBC. T cells were isolated by sheep E-rosette sedimentation from PBMC, obtained by Percoll density centrifugation from buffy coats, as described in (15). Residual monocytes were removed by plastic adherence. T cell purity was checked by measuring LPS-induced monocytic IL-6 production (22), which was found < 5 pg/ml IL-6 in an overnight incubation of 200,000 cells/ml, whereas unseparated PBMC produced 2,000 to 10,000 pg/ml.

Monocytes were isolated from PBMC by counterflow centrifugation, as described elsewhere (23), and were > 95% pure, as determined in cytocentrifuge preparations after staining for nonspecific esterase, and May Gr \ddot{u} nwald-Giemsa.

Granulocytes were separated from PBMC and platelets by centrifugation of trisodium citrate (14 mM) anticoagulated blood on 1.076 g/ml Percoll. Erythrocytes were removed from the granulocyte pellet by lysis in isotonic NH₄Cl on ice, resulting in a PMN preparation containing > 95% neutrophils (24). Induction of PMN-Fc γ RI was analyzed after incubation of cells in culture medium (see below) supplemented with 300 U/ml IFN- γ (Genentech, San Francisco, CA), inhibition analyses of IFN- γ induced effects were performed by supplementing inhibitory anti-IFN- γ mAb MD-1 (10 μ g/ml) (25).

Platelet-rich plasma was obtained by centrifugation (15 min, 250 g) of EDTA (5 mM) anticoagulated blood. Platelets were then concentrated by centrifugation (7 min, 1,200 g) and three washes were performed with PBS/5 mM EDTA/0.5% FCS (26).

PMN expressing reduced levels of Fc γ RIII were isolated from two patients with diagnosed paroxysmal nocturnal hemoglobinuria (PNH) (27, 28). The neutrophil preparations from these patients contained ~ 80% and ~ 100% of (GPI-linked) Fc γ RIIIb deficient cells, respectively, and expressed ~ 10% of normal Fc γ RIIIb levels. Fc γ RIII-deficient (Fc γ RIII^{neg}) PMN were isolated from an Fc γ RIIIb-deficient donor. The absence of the Fc γ RIIIb gene, Fc γ RIIIb mRNA, and soluble Fc γ RIIIb in serum was previously demonstrated in a study by Hui-zinga et al. (29). PMN from this Fc γ RIIIb^{neg} donor showed a complete absence of Fc γ RIII expression in immunofluorescence studies (see Results; Fig. 4 B).

GPI-PLC treatment. Fc γ RIIIb was removed from normal PMN by incubation with GPI-specific phospholipase C (GPI-PLC). PMN were

washed and incubated for 1 h at 37°C in Iscove's modified Dulbecco's medium (IMDM) supplemented with a 1:1,000 dilution of GPI-PLC. GPI-PLC isolated from *Bacillus thuringiensis* was kindly provided by Dr. T. Schumacher (Netherlands Cancer Institute, Amsterdam).

T cell proliferation assay. Highly purified T cells were stimulated with graded amounts of anti-CD3 mAb in 200 μ l IMDM, supplemented with 5% heat-inactivated pooled human serum, 50 μ M 2-mercaptoethanol, 100 IU/ml penicillin, and 100 μ g/ml streptomycin. All incubations were performed in the presence of 1 μ g/ml anti-CD28 mAb as a T cell costimulus (18). Without accessory cells, no T cell proliferation was observed by the anti-CD28/anti-CD3 mAb combination alone. As accessory cells, either 60,000 PMN or 2 \times 10⁵ platelets were added per well. To generate optimal T cell triggering, we first titrated PMN in anti-CD3-induced T cell proliferation experiments using an optimal amount of anti-CD3 mAb (40 ng/ml). Remarkably, the optimum for mIgG1 anti-CD3 induced proliferation was reached by supplementing ~ 30,000 PMN per well, whereas the potency of hIgG2 anti-CD3 induced T cell proliferation still increased significantly up to PMN concentrations of ~ 60,000 cells per well (observed in five experiments using cells from different donors). Since this increase of PMN-density did not affect the mIgG1 anti-CD3 induced mitogenicity, further experiments were performed using ~ 60,000 PMN per well.

Titration of platelet concentration in the presence of an optimal amount of anti-CD3 mAb, revealed an optimal T cell proliferation at a density of ~ 2 \times 10⁵ platelets per well.

Inhibition by anti-Fc γ R mAb was assessed by incubation of T cells with an optimal amount of anti-CD3 mAb (40 ng/ml) in the presence of either mAb 197 (20 μ g/ml), mAb IV.3 (5 μ g/ml), mAb CLB Gran1 (10 μ g/ml), CLB Gran1 F(ab')₂ fragments (20 μ g/ml), or mAb 3G8 (20 μ g/ml). These inhibitory mAb were preincubated for 1 h with accessory cells before purified T cells were added to the cultures. A 4-h [³H]thymidine (0.2 μ Ci/well) incorporation assay was performed on day 4. All incubations were performed in triplicate, and SD were always < 10%.

We performed control experiments to check for (nonspecific) effects of anti-Fc γ R mAb on anti-CD3 induced T cell proliferation, (via potential activation and subsequent degranulation of PMN) during culture. Anti-Fc γ R mAb were added to an Fc γ R-independent T cell activation system (30). In this assay, mIgA anti-CD3 mAb were coated at high density to culture wells; a condition inducing potent proliferation of purified T cells (this mIgA mAb is a heavy chain isotype switch variant (21) of the anti-CD3 mAb used in rest of our studies). No inhibitory effects of any anti-Fc γ R mAb were observed in this system.

Purification of IgG paraproteins. Purified hIgG subclass proteins with kappa light chains were isolated from sera of patients with multiple myeloma by (NH₄)₂SO₄ precipitation and DEAE-Sephadex (Pharmacia, Uppsala, Sweden) ion-exchange chromatography. If necessary, proteins were further purified on protein A or anti-hIgG subclass Sepharose. All preparations were checked for impurities and IgG subclass content in immunoelectrophoresis, radial immunodiffusion, and hemagglutination assays (31, 32). The hIgG paraproteins used in this study were > 98% pure, as evaluated with these methods. Purified hIgG was either used in a monomeric form, after removal of aggregates by ultracentrifugation (1 h at 150,000 g), or as stable dimeric complexes (see below).

Dimer binding studies. Purified IgG paraproteins were incubated overnight with F(ab')₂ fragments of a mouse anti-human κ -light chain mAb K35, in a molar ratio of 1:1, which resulted in stable tetrameric complexes, as detailed in (24). Human monocytes (3 \times 10⁵ in 100 μ l PBS/1% BSA) were incubated with 25 μ l of anti-Fc γ R mAb 197 (7 μ g/ml) and 25 μ l of an optimal amount of hIgG dimers (~ 25 μ g/ml) for 45 min at 4°C. The amount of mAb 197 was optimized to result in complete blockade of both monomeric IgG binding to Fc γ RI, and Fc γ RI-mediated EA-rosetting (see below). After washing, cells were subsequently incubated with FITC-conjugated F(ab')₂ fragments of goat anti-hlg antiserum (Cappel, Cochranville, PA), and FITC-conjugated F(ab')₂ fragments of rabbit anti-goat antiserum (Cappel), each

for 45 min at 4°C. Cell-bound hIgG dimers were detected flow cytometrically by a FACScan® (Becton Dickinson Immunocytometry Sys., Mountain View, CA). To remove crossreactive antibodies, all FITC-conjugates were absorbed with mIgG-coated Sepharose beads prior to use. Statistical analysis was performed using a Student's *t* test.

Dimer binding to PMN was essentially performed as detailed above, but without addition of mAb 197. Since hIgG4 dimers did not bind to FcγRII of either monocytes or PMN of any donor tested, we checked the integrity of this binding reagent by assessing dimer binding to U937 cells, which were incubated with IFN-γ (300 U/ml overnight) before use to enhance FcγRI expression (1).

EA-rosetting; specificity of inhibitory anti-FcγRI and anti-FcγRII mAb. To check for specific inhibition by anti-FcγRI and anti-FcγRII mAb in our assays, we tested these mAb in EA-rosetting experiments. Two types of indicator erythrocytes were used: rhesus-D positive human erythrocytes were optimally sensitized either with a human antiserum directed against rhesus-D (EA-hIgG; Merz and Dade, Düringen, Switzerland), or with a mIgG1 anti-glycophorin A mAb (EA-mIgG1) (23, 33). Rosetting was scored microscopically as described before (33).

Inhibition of FcγRI- or FcγRII-mediated IgG-binding was performed by adding mAb 197 (7 μg/ml) or mAb IV.3 (2.5 μg/ml), respectively. Both antibodies were used at concentrations that inhibited specific EA-rosetting via FcγRI or FcγRII using purified monocytes and EA-hIgG or EA-mIgG1, respectively (23, 33). Rosettes were readily observed after incubation of monocytes with EA-hIgG: 70±3% of cells were scored positive (*n* = 3). Formation of rosettes was not inhibited by addition of mAb IV.3 (73±4% rosetting cells; *n* = 3), in contrast to mAb 197, which blocked EA-hIgG rosetting efficiently (2±2% rosettes; *n* = 3). FcγRII-mediated rosetting was measured by adding EA-mIgG1 to HR monocytes, which resulted in 58±3% rosettes (*n* = 3). Addition of identical concentrations of the blocking anti-FcγR mAb as above, resulted in efficient inhibition of EA-mIgG1 rosetting by mAb IV.3 (3±1% rosettes; *n* = 3), whereas mAb 197 did not significantly impede rosette formation (56±2% rosettes; *n* = 3).

We next evaluated whether FcγRI was efficiently blocked by preincubation with mAb 197 and, therefore, could be used to study specific binding to FcγRIIa on monocytes. Monocytes were first incubated for 30 min at 37°C in RPMI 1640 medium (without serum) to remove cytophilic IgG. Cells were washed twice in medium and incubated for 15 min at 4°C in PBS/0.5% BSA/0.1% NaN₃ alone, or supplemented with either anti-FcγRI mAb 197 (7 μg/ml) or mAb IV.3 (2.5 μg/ml). Subsequently, 10 μg/ml of monomeric hIgG was added, and after a 45-min incubation at 4°C, cells were washed. Cell-bound hIgG was detected flow cytometrically by a FACScan®, using FITC-conjugated F(ab')₂ fragments of goat anti-hIgG antiserum (Cappel). Addition of monomeric hIgG to monocytes resulted in 79±3% positive staining cells (*n* = 2), which was effectively blocked by preincubating the cells with mAb 197 (4±2% positive cells; *n* = 2), but not with mAb IV.3 (70±4% positive cells; *n* = 2).

Measurement of serum IgG. Sera and citrated blood samples were collected by venipuncture from 69 randomly selected volunteering colleagues, 43 males and 26 females (mean age 30±6, range 21–57 yr), and sera were stored at –20°C until used. hIgG1, hIgG2, hIgG3, hIgG4, and total hIgG concentrations were measured nephelometrically (Vlug, A., E. Nieuwenhuis, I. Knop, and R. V. W. van Eijk, manuscript in preparation). Statistical analysis was performed by a Mann-Whitney U test.

FcγRII phenotyping. The FcγRIIa phenotype of cells from different donors was compared by comparing the potency of mIgG1 and hIgG2 anti-CD3-mAb induced T cell proliferation in PBMC isolated from citrated blood, as detailed in (18). Briefly, 40,000 PBMC were cultured for 4 d in culture medium (see above) after addition of either mIgG1, or hIgG2 anti-CD3 mAb in an optimal concentration (40 ng/ml). As described before (18), three groups of donors could be discriminated: two groups with PBMC only responsive to either mIgG1, or hIgG2 anti-CD3 mAb, and one group with a comparable reactivity to both anti-CD3 mAb, indicating homozygous FcγRIIa^{HR}, homozygous

FcγRIIa^{LR}, and heterozygous FcγRIIa^{LR,HR} individuals, respectively.

In addition, FcγRIIa phenotypes of donors were assessed by using immunofluorescence analysis on a FACScan using anti-FcγRII mAb 41H16 (which selectively reacts with FcγRIIa^{HR} [34]) and mAb IV.3 (recognizing both FcγRIIa allotypic forms), followed by detection with FITC-conjugated F(ab')₂ fragments of goat anti-mouse antiserum (G26M17F, CLB) as described previously (18, 34). To avoid cytophilic binding of the mIgG2a mAb 41H16 to the high-affinity FcγRI, all mAb incubations were performed in the presence of 25% heat-inactivated human serum.

All experiments in this study were performed using cells isolated from either FcγRIIa^{LR} or FcγRIIa^{HR} homozygous donors.

Results

Human IgG dimer binding to monocytes. Human monocytes express both FcγRI and FcγRIIa constitutively (4). When used as accessory cells in anti-CD3 induced T cell proliferation, mitogenicity to chimeric hIgG1, hIgG3, and hIgG4 anti-CD3 was found to be FcγRI-mediated (18). The hIgG2 anti-CD3 mAb, however, induced FcγRIIa-mediated T cell proliferation, which was only found with PBMC of individuals expressing the FcγRIIa^{LR} allotypic form (both homo- and heterozygotes) (18). We now studied binding of well-defined stable

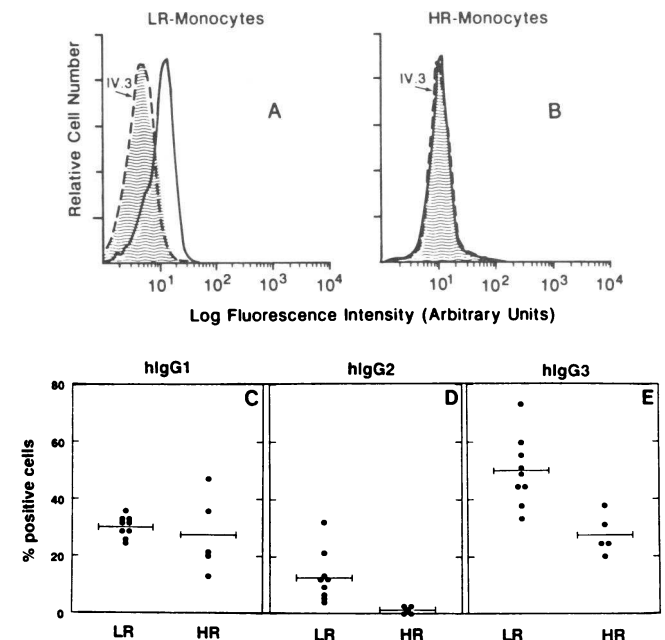


Figure 1. Binding of dimeric hIgG subclass complexes to FcγRI-blocked purified monocytes. The high affinity FcγRI on monocytes was blocked by addition of a saturating amount of inhibitory anti-FcγRI mAb 197. Stable dimeric hIgG1, hIgG2, or hIgG3 complexes were added, and binding was analyzed cytofluorometrically. In (A and B), representative experiments are shown illustrating the immunofluorescence observed after addition of hIgG2 dimeric complexes to monocytes from FcγRII^{LR} and FcγRII^{HR}-homozygous donors, respectively. Binding was assessed after addition of hIgG2-dimers alone (solid line), or in the presence of mAb IV.3 (dashed line). Background fluorescence, observed in the absence of dimeric complexes, is indicated by shading. (C–E) show the binding of hIgG1, hIgG2, and hIgG3 dimeric complexes to monocytes from FcγRIIa^{LR}- (*n* = 9), and FcγRIIa^{HR}-typed (*n* = 5) homozygous donors, represented as the percentage of cells with fluorescence intensities above background levels.

dimeric hIgG complexes of the four hIgG subclasses to these cells. To allow exclusive Fc γ RIIa-mediated binding of hIgG dimers, we blocked the high affinity IgG Fc receptor specifically using anti-Fc γ RI mAb 197 (see Methods).

Purified monocytes isolated from homozygous Fc γ RIIa-typed donors, were incubated with dimeric complexes of defined hIgG subclasses. hIgG2 dimers were bound differentially by cells from Fc γ RIIa^{LR} and Fc γ RIIa^{HR} individuals, as illustrated in Fig. 1 A, and B, respectively. Significant binding of hIgG2 dimeric complexes was only apparent to cells bearing the Fc γ RIIa^{LR} allotypic form (Fig. 1 A), whereas the homozygous Fc γ RIIa^{HR}-expressing cells remained negative (Fig. 1 B). The same pattern of binding was observed with monocytes from nine LR and five HR donors (Fig. 1 D), and with four different hIgG2 myeloma proteins (data not shown). Parallel experiments were performed using hIgG1, hIgG3, and hIgG4 dimeric complexes. Both hIgG1 and hIgG3 dimers bound effectively to monocytes from the two types of donors, as shown in Fig. 1 C, and 1 E, respectively. No difference was observed in hIgG1 dimer binding between the homozygous Fc γ RIIa^{LR} and Fc γ RIIa^{HR} monocytes (Fig. 1 C). Cells expressing the Fc γ RIIa^{LR} allotypic form, however, exhibited a significantly higher capacity to bind hIgG3 dimers ($P < 0.001$; Fig. 1 E). In none of the experiments performed we observed binding of hIgG4 dimers to Fc γ RI-blocked monocytes. The percentage of cells with fluorescence above background was always $< 2\%$, both with monocytes from Fc γ RIIa^{LR} ($n = 15$), and Fc γ RIIa^{HR} ($n = 8$) individuals. To appraise the validity of the hIgG4 dimeric complexes as binding reagents, we performed binding experiments with U937 cells (expressing Fc γ RI and Fc γ RIIa^{HR} [8]). Upon incubation of these cells with hIgG4 dimers, 99% of the U937 cells stained positive, which could be inhibited by mAb 197 (6% positive cells), but not by mAb IV.3 (99% positive cells) ($n = 2$). This susceptibility of hIgG4 binding to inhibition solely by anti-Fc γ RI mAb 197 indicates, furthermore, that Fc γ RIIa on U937 is incapable of interacting with hIgG4 dimers (as observed with monocytes).

The functional Fc γ RIIa polymorphism to hIgG2 is expressed on platelets. A substantial portion of Fc γ RII present on PBC is expressed on platelets. Platelets do not express other classes of Fc γ R (35), and seem therefore a superb model system to study Fc γ RII-IgG interactions. Consequently, we studied anti-CD3-induced T cell activation in the presence of platelets as accessory cells.

Fig. 2 A and B represents immunofluorescence analyses of platelets used in the T cell mitogenesis experiments shown in panels C and D, respectively. After staining with mAb IV.3, platelets derived from both donors displayed a comparable fluorescence intensity, indicating comparable Fc γ RIIa expression levels. Incubation of platelets with mAb 41H16 revealed similar staining as mAb IV.3 for the Fc γ RIIa^{HR} homozygous donor and background staining for the Fc γ RIIa^{LR} homozygous donor. This suggested an antigenically similar Fc γ RIIa polymorphism as found on monocytes and PMN.

In contrast to T cell mitogenesis studies with monocytes as accessory cells, addition of anti-CD3 mAb to platelets alone was insufficient to induce T cell proliferation. Platelets apparently lacked the ability to provide an accessory signal for full activation of T cells. We circumvented this requirement by adding an anti-CD28 mAb as costimulator to the incubations. Addition of anti-CD28 mAb alone or anti-CD28 combined with the anti-CD3 mAb CLB-T3/4 did not result in prolifera-

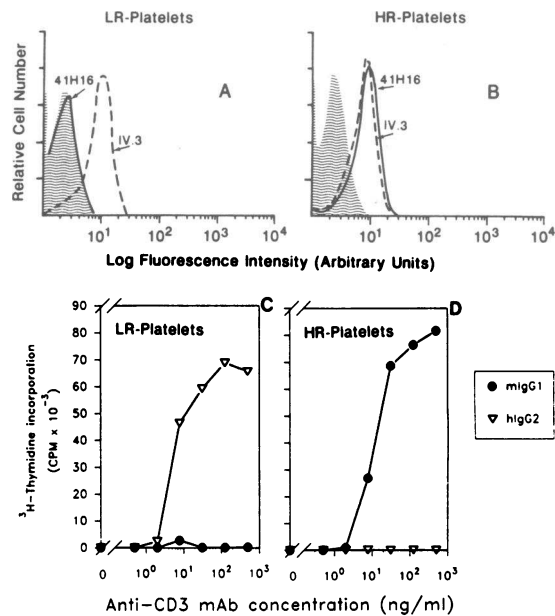


Figure 2. Characterization of platelet Fc γ R expression, and anti-CD3-induced T cell proliferation in the presence of platelets as accessory cells. Platelets, isolated from Fc γ RIIa^{LR} (A) or Fc γ RIIa^{HR} (B) homozygous donors, were incubated either with buffer alone (control; shaded), anti-Fc γ RII mAb IV.3 (dashed line), or anti-Fc γ RIIa^{HR} mAb 41H16 (solid line), followed by FITC-conjugated F(ab')₂ fragments of goat anti-mouse IgG antiserum. Platelets from these donors were subsequently used as accessory cells in mIgG1 and hIgG2 anti-CD3-induced T cell proliferation. (C and D) represent the anti-CD3-induced mitogenesis of highly purified T cells using Fc γ RIIa^{LR}-typed, and Fc γ RIIa^{HR}-typed platelets, respectively. [³H]thymidine incorporation is plotted against the anti-CD3 mAb concentration. Experiments performed with platelets derived from two Fc γ RIIa^{LR}-, and one Fc γ RIIa^{HR}-homozygous donors, respectively, yielded similar results.

tion of purified T cells. Platelets, isolated from homozygous Fc γ RIIa^{HR} or Fc γ RIIa^{LR} individuals were used to study T cell proliferation induced by quantitated amounts of mIgG1 or hIgG2 anti-CD3 mAb (shown in Fig. 2 C and D). Platelets derived from an Fc γ RIIa^{LR} individual supported hIgG2 anti-CD3-induced proliferation efficiently, whereas mIgG1 induced proliferation was hardly detectable (Fig. 2 C). Platelets isolated from Fc γ RIIa^{HR} individuals were observed to support mIgG1 anti-CD3-induced T cell mitogenesis, but not hIgG2 anti-CD3 induced activation. Addition of mAb IV.3 to these cultures resulted in complete inhibition of both hIgG2 and mIgG1 anti-CD3-induced T cell mitogenesis ($> 99\%$ inhibition; $n = 2$). Platelets expressing the Fc γ RIIa^{LR} allotypic form, furthermore supported induction of T cell proliferation by hIgG1 anti-CD3 efficiently, but not with hIgG3, or hIgG4 ($n = 2$).

Interaction between (chimeric) anti-CD3 mAb and Fc γ R on PMN. Human neutrophils constitutively express both Fc γ RIIa and a GPI-linked form of Fc γ RIII; i.e., Fc γ RIIIb. Fc γ RIII has been implicated in modulation of Fc γ RII affinity and triggering (36–38). To examine this in more detail, we studied antibody-Fc γ R interactions on normal PMN and PMN impaired in expression of Fc γ RIIIb.

PMN were isolated from healthy donors homozygous for either Fc γ RIIa phenotype, and they were used as accessory

cells in anti-CD3-induced T cell activation experiments, as shown in Fig. 3. In these experiments, we also added anti-CD28 mAb as a T cell costimulus, since anti-CD3 mAb combined with PMN alone were incapable of inducing T cell proliferation. A dose-dependent mIgG1 anti-CD3 mAb induced T cell activation was only observed using PMN expressing Fc γ RIIa^{HR}, whereas hIgG2 anti-CD3 mAb preferentially induced proliferation in the presence of Fc γ RIIa^{LR} PMN. Cells from both types of individuals supported proliferation with hIgG1 anti-CD3, but not hIgG3 or hIgG4 subclass variants (Fig. 3). Evaluation of the role of Fc γ R in these responses is complicated by expression of both Fc γ RIIa and Fc γ RIIIb on these cells. Inhibition analyses were, therefore, performed on normal and on Fc γ RIIIb negative (Fc γ RIII^{neg}) PMN.

Phenotypes of PMN used for these inhibition experiments were analyzed cytofluorometrically as shown in Fig. 4 A and B. The PMN analyzed in Fig. 4 B, isolated from a donor who showed a complete lack of PMN-Fc γ RIIIb expression caused by a genomic deletion in the Fc γ RIIIb locus (29), stained positive with anti-Fc γ RII mAb (IV.3), but not with a Fc γ RIIa^{HR}-specific (41H16) or anti-Fc γ RIII mAb (CLB Gran1). This indicated expression of the Fc γ RIIa^{LR} allotypic form exclusively on these cells. Fig. 4 A shows the analysis of a normal donor matched for expression of this Fc γ RIIa allotypic form. PMN of both these donors, furthermore, did not express Fc γ RI, as indicated by absent staining with anti-Fc γ RI mAb 197, and 22 (data not shown).

To evaluate which Fc γ R classes were involved in anti-CD3 induced T cell mitogenesis in the presence of PMN, we analyzed T cell proliferation in this system, in the presence or absence of blocking anti-Fc γ RI (197), anti-Fc γ RII (IV.3), or anti-Fc γ RIII (CLB Gran1) mAb. Inhibition patterns of anti-CD3 induced T cell proliferation by these anti-Fc γ R mAb are shown in Fig. 4 C and D. Fig. 4 C shows that PMN-dependent hIgG2 anti-CD3-induced T cell proliferation was completely inhibited upon addition of mAb IV.3. PMN derived from the

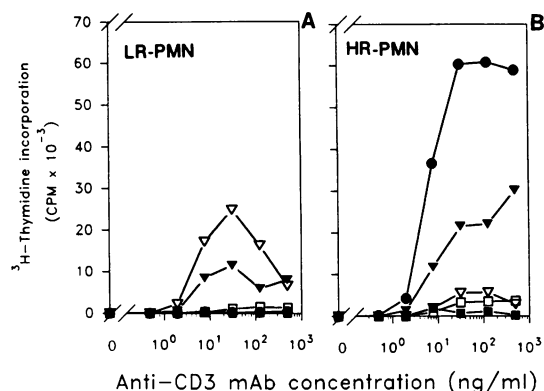


Figure 3. Induction of T cell mitogenesis by anti-CD3 isotype variants using PMN as accessory cells. Highly purified T cells were incubated with a quantitated amount of mIgG1, hIgG1, hIgG2, hIgG3, and hIgG4 anti-CD3 mAb in the presence of PMN expressing either the Fc γ RIIa^{LR} (A), or the Fc γ RIIa^{HR} allotypic form (B). Anti-CD28 mAb (1 μ g/ml) was added as a costimulatory signal. [³H]thymidine incorporation was plotted against the concentration of anti-CD3 mAb. The experiment shown is representative of two separate experiments with cells from the same donors. Similar results were obtained with PMN derived from 5 Fc γ RIIa^{LR}- and 2 Fc γ RIIa^{HR}-expressing donors. ●, mIgG1; ▼, hIgG1; ▽, hIgG2; □, hIgG3; ■, hIgG4.

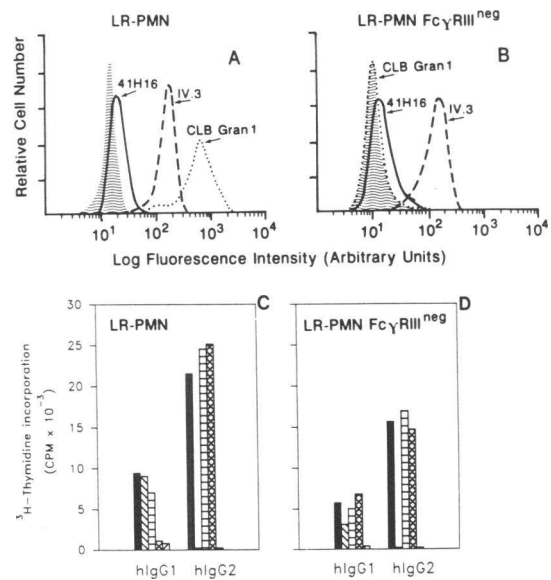


Figure 4. Characterization of Fc γ R-phenotype and hIgG1, and hIgG2 anti-CD3-induced T cell proliferation in the presence of normal and Fc γ RIII^{neg} PMN. Cytofluorometric analysis of PMN isolated from normal, and Fc γ RIII^{neg}, Fc γ RIIa^{LR}-homozygous individuals are shown in (A and B), respectively. PMN from both donors were incubated either with buffer alone (control; shaded), anti-Fc γ RII mAb IV.3 (which binds both allotypic forms of Fc γ RIIa; dashed line), anti-Fc γ RIIa^{HR}-specific mAb 41H16 (solid line), or anti-Fc γ RIII mAb CLB Gran1 (dotted line), followed by FITC-conjugated F(ab')₂ fragments of goat-anti-mouse IgG as secondary antibody. (C and D) show an analysis of hIgG1, and hIgG2 anti-CD3 induced proliferation of highly purified T cells in the presence of normal and Fc γ RIII^{neg} PMN, respectively. T cells were stimulated with an optimal amount of anti-CD3 mAb in medium alone (black bars), or in the presence of either anti-Fc γ RI mAb 197, anti-Fc γ RII mAb IV.3, anti-Fc γ RIII mAb CLB Gran1, or a combination of mAb IV.3 and mAb 197. (C) shows an experiment representative for PMN from five Fc γ RIIa^{LR} homozygous donors, (D) shows an experiment representative for two separate experiments using cells from a single Fc γ RIII^{neg} donor. ■, —; ▨, IV.3; ▩, 197; ▤, CLB Gran1; ▥, IV.3 + 197.

Fc γ RIII^{neg} donor (analyzed in Fig. 4 D), also showed complete susceptibility of hIgG2 anti-CD3-induced T cell mitogenicity to mAb IV.3, similar to Fc γ RIIa^{LR}-bearing PMN from all normal donors evaluated ($n = 12$). In contrast, hIgG1 anti-CD3-induced T cell proliferation was strongly inhibited after blockade of Fc γ RIIIb (Fig. 4 C). Surprisingly, however, the absence of Fc γ RIIIb did not affect the ability of Fc γ RIII^{neg} PMN to support T cell mitogenesis induced by this hIgG subclass. The data shown in Fig. 4 D suggested this proliferation-induction to be partly Fc γ RII mediated, supported by a decrease in T cell responsiveness after addition of mAb IV.3. Remarkably, a synergistically increased inhibition was observed by combining mAb IV.3 with mAb 197. Indeed, a complication in these culture experiments may be induction of Fc γ RI on PMN by IFN- γ (1), produced by proliferating T cells, which may then mediate binding of hIgG1 mAb. We tested this hypothesis by analyzing cells from the cultures cytofluorometrically, using a FITC-conjugate of anti-Fc γ RI mAb 22, as shown in Table I. After gating on PMN, we found a significant increase of Fc γ RI expression after culturing the cells overnight, provided anti-CD3-stimulated T cells were present in the culture. The level of Fc γ RI expression on these PMN was similar to the expres-

sion level induced after culturing overnight in medium supplemented with IFN- γ ($n = 4$). In both these experiments, Fc γ RI induction could be completely inhibited by addition of anti-IFN- γ mAb.

Turning our attention to Fc γ RIIIb, we observed a dramatic decrease in the expression level of this Fc γ R on PMN measured during the first 2 d of culture ($n = 3$), as indicated in Table II. The presence of soluble Fc γ RIII in the supernatants (data not shown) indicated that Fc γ RIIIb is shed from the cell membrane during culture (39). As a control, we stained cells with a (granulocyte-specific) CD66 mAb, CLB Gran10, which revealed all gated cells to be positive, without reduced fluorescence. The observation that Fc γ RI is rapidly induced during culture, while Fc γ RIIIb expression on the cell surface is decreased, might implicate a minor role for Fc γ RIIIb in hIgG1 anti-CD3 induced T cell mitogenesis. Expression of Fc γ RI, furthermore, posed a practical difficulty in that anti-Fc γ RIII mAb CLB Gran1 (mIgG2a subclass) may inhibit binding to Fc γ RI via its Fc-moiety. We, therefore, used CLB Gran1 F(ab')₂ fragments and mAb 3G8 (mIgG1 subclass) in inhibition analyses, which did not (CLB Gran1 [Fab']₂) or weakly (mAb 3G8) affect hIgG1 anti-CD3-induced T cell activation.

Human IgG dimer binding by normal and Fc γ RIII^{neg} PMN. We analyzed binding of dimeric hIgG subclass complexes to PMN, with normal, and absent expression of Fc γ RIIIb. Cells of a normal Fc γ RIIIa^{LR} homozygous donor and the Fc γ RIIIb^{neg} donor described above were incubated with optimal amounts of dimers (Fig. 5). 5 C and 5 D indicate that PMN of both donors were capable of binding hIgG2 dimers, which was completely inhibitable by adding mAb IV.3. PMN of both types of donors, furthermore, bound hIgG1 and hIgG3 dimers efficiently (Fig. 5 A, B, E, and F, respectively), although the binding capacity of normal PMN for dimers of these isotypes were significantly higher. On normal PMN, the major component of this binding was Fc γ RIIIb-mediated, indicated by susceptibility to inhibition by anti-Fc γ RIII mAb 3G8 (Fig. 5 A and E). The low amount of hIgG1/hIgG3 binding observed in the presence of mAb 3G8, was decreased to background level when this mAb was combined with mAb IV.3 (data not shown; $n = 2$). The experiment with Fc γ RIIIb^{neg} PMN showed that, even in the absence of

Table I. Induction of Fc γ RI on Cultured PMN

Stimuli*	% CD64-positive PMN [‡]
None	7.1
IFN- γ	68.4
hIgG1 anti-CD3	7.3
hIgG1 anti-CD3 + T cells	60.5
IFN- γ + anti-IFN- γ	11.4
hIgG1 anti-CD3 + T cells + Anti-IFN- γ	9.5

* Freshly isolated PMN were cultured overnight in culture medium supplemented with the indicated agents in the presence or absence of highly purified T cells. [‡] PMN were washed and incubated with a FITC-conjugate of anti-Fc γ RI mAb 22. After gating on PMN, the percentage of cells displaying fluorescence intensities above background level (PMN incubated in buffer without mAb 22-FITC) was assessed. [§] As a control, the cells were stained with granulocyte-specific CD66 mAb CLB Gran10, which showed all gated cells to be positive.

Table II. Expression of Fc γ RIIIb on Cultured PMN

Days of culture*	% CD16-positive cells (mean) [‡]
0	100 (1,038)
1	74 (311)
2	66 (161)

* Freshly isolated PMN were incubated in culture medium for the number of days indicated. [‡] PMN were washed and subsequently incubated with anti-Fc γ RIII mAb 3G8 and FITC-conjugated F(ab')₂ fragments of a goat anti-mouse antiserum. The percentage of cells, displaying fluorescence intensities above background level, and mean fluorescence intensities of the cell-population (between parentheses) are indicated. [§] As a control, PMN were stained with CD66 mAb CLB Gran10, which showed all cells to be positive.

Fc γ RIIIb, PMN were still capable of binding significant amounts of hIgG1 and hIgG3. This binding, however, was now completely susceptible to blockade by mAb IV.3 (Fig. 5 B and F), and, hence, Fc γ RII-mediated. Binding of hIgG4 dimeric complexes to these cells was also studied, but none of the PMN preparations evaluated in our laboratory ($n = 15$), was capable of significantly binding this hIgG subclass (Fig. 5 G and H).

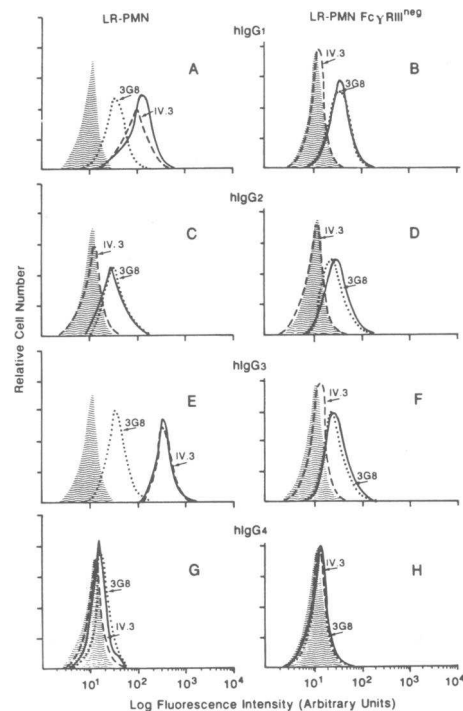


Figure 5. Binding of dimeric hIgG subclass complexes to PMN from a normal and an Fc γ RIII^{neg} individual. Highly purified PMN from a normal (A, C, E, and G), and a Fc γ RIII^{neg} (B, D, F, and H) Fc γ RIIIa^{LR}-homozygous donor were incubated with dimeric hIgG1 (A, B), hIgG2 (C, D), hIgG3 (E, F), and hIgG4 (G, H) complexes. After washing, bound dimers were quantitated cytofluorometrically. Binding to PMN was assessed after addition of hIgG dimers either alone (solid line), or in the presence of anti-Fc γ RIII mAb IV.3 (dashed line), or anti-Fc γ RIII mAb 3G8 (dotted line). Background fluorescence is indicated by shading. The experiment shown was repeated several times with normal ($n = 5$), and Fc γ RIIIb^{neg} PMN ($n = 2$) with almost identical results.

Comparing hIgG2 dimer binding to normal PMN, homozygously expressing the LR or HR allotypic form of Fc γ RIIa, we observed a similar pattern as on monocytes. Efficient binding was only apparent on PMN expressing Fc γ RIIa^{LR} (31±15% positive cells; *n* = 12), whereas Fc γ RIIa^{HR} homozygous PMN bound hIgG2 poorly (7±4% positive cells; *n* = 12). Incubation of PMN with GPI-PLC, which resulted in removal of ~ 90% of the GPI-linked Fc γ RIIIb, did not significantly affect the ability of these cells to bind hIgG2 (*n* = 3). hIgG2 dimer binding studies were, furthermore, performed with PMN isolated from two patients suffering from PNH, which is an acquired disorder resulting in strongly diminished expression of GPI-linked membrane proteins, such as Fc γ RIIIb (27, 28). PMN of both these patients were found to express Fc γ RIIa^{HR} only, and interacted weakly with hIgG2 dimers (resulting in 4 and 8% positive staining cells, respectively).

Correlation between Fc γ RIIa polymorphism and donor hIgG2 serum levels. The Fc γ RIIa^{LR} allotypic form seems unique in its ability to bind hIgG2, since no other hFc γ R has been reported to interact efficiently with this isotype ([4, 10], this study). It has been postulated that so-called Ig binding factors (most likely soluble Fc γ R) may affect Ig production and proliferation of B cells (40). This prompted us to analyze hIgG subclass levels in sera of healthy donors. We randomly analyzed 69 donors, of whom 10 were found homozygous for Fc γ RIIa^{HR}, and 22 for Fc γ RIIa^{LR}. Fig. 6 A shows the total hIgG contents measured in the sera of these 32 homozygous donors. Comparing the two groups of individuals, we found no significant differences in total hIgG concentrations. Remarkably, a striking difference was found for hIgG2 subclass levels, which were calculated relative to the hIgG1 concentration, to correct for variations in total hIgG serum levels between different individuals (indicated in Fig. 6 A). As shown in Fig. 6 B, Fc γ RIIa^{LR} individuals had significantly lower hIgG2 serum levels than Fc γ RIIa^{HR} individuals (*P* = 0.02). Significant dif-

ferences between the two groups were also found by calculating hIgG2 (*P* = 0.05) and hIgG1 (*P* = 0.008) levels relative to total hIgG concentration. In these analyses, hIgG2 levels were found decreased while hIgG1 levels appeared increased in Fc γ RIIa^{LR} versus Fc γ RIIa^{HR} donors. Absolute hIgG1 and hIgG2 levels, however, did not differ significantly. No significant differences were observed in hIgG3 or hIgG4 serum levels. If hIgG2 is more efficiently cleared by the LR compared to the HR allotypic form of Fc γ RIIa, then also heterozygous individuals might be expected to have lower relative hIgG2 subclass levels compared with homozygous Fc γ RIIa^{HR} donors. Comparing the hIgG2/hIgG1 ratio between the three groups, we found that this ratio (mean±SEM) of heterozygotes (0.54±0.04) was intermediate between the ratio of HR (0.67±0.05) and LR homozygotes (0.50±0.04). The difference between the heterozygotes and HR homozygotes was statistically significant (*P* = 0.04), whereas the difference between heterozygotes and LR homozygotes was not.

Discussion

Recently, it was shown that the classical polymorphism of hFc γ RIIa, as originally defined in mIgG1 anti-CD3-induced T cell mitogenesis (4, 11), has profound implications for hIgG2 binding. Transfected fibroblasts expressing the Fc γ RIIa^{LR} allotypic form were found to interact efficiently with this hIgG subclass, in contrast to Fc γ RIIa^{HR}-transfected cells (13). T cell mitogenesis experiments using hIgG2 anti-CD3, furthermore, indicated that differential binding of hIgG2 was inherent to normal monocytes, and was correlated with Fc γ RIIa phenotype (18).

In the present study we demonstrate that the functional Fc γ RIIa polymorphism is expressed on monocytes, PMN, and platelets. We studied this in two systems: first, by binding analyses with stable dimeric hIgG complexes, and secondly, in anti-CD3-induced T cell proliferation in which large, heavily opsonized complexes were presented to Fc γ R. Both in hIgG dimer binding and anti-CD3-induced T cell mitogenesis, we were able to displace hIgG2 from cells with mAb IV.3, supporting Fc γ RIIa-mediated binding. Fc γ RIIa, furthermore, bound antibodies of the hIgG1 and hIgG3, but not hIgG4 isotypes, as shown by dimer binding to Fc γ RI-blocked monocytes (Fig. 1). In these analyses, hIgG3 dimers were bound significantly better by Fc γ RIIa^{LR} than by Fc γ RIIa^{HR}. Since cross-talk between Fc γ RI and II has been observed in signalling in U937 cells (19), it seems possible that ligation of Fc γ RI on monocytes by mAb 197 may affect binding via Fc γ R. In our opinion, this is not supported by our studies with Fc γ RIIa-transfected fibroblasts (13), which showed identical binding characteristics of IgG dimers, as shown with the Fc γ RI-blocked monocytes in the present study. Blocking of Fc γ RI by intact mAb 197 might cause problems resulting from cross-reactivity of its Fc region with other Fc γ R classes. All available Fc γ RI mAb, however, bind to an epitope outside the ligand-binding site (41), and only one of them (mAb 197, as used in the present study) is inhibitory by an interaction of its mIgG2a Fc region to the Fc γ RI-binding site ("Kurlander phenomenon" [4]). Interference in IgG dimer binding to Fc γ RIIa, however, seems improbable since mIgG2a has only minor affinity for this class of Fc γ R (4), indicated furthermore by the inability of Fc γ RIIa transfected fibroblasts to support mIgG2a anti-CD3-induced

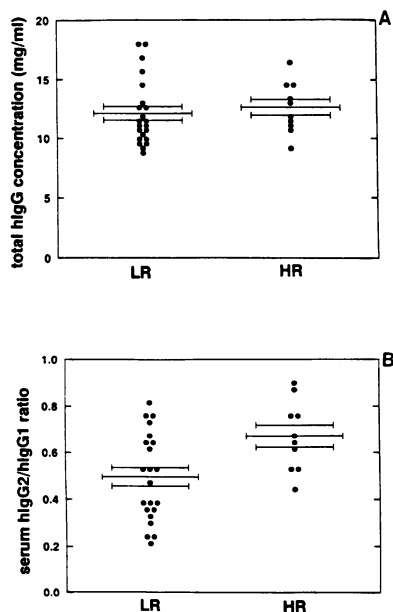


Figure 6. hIgG serum levels in Fc γ RIIa^{LR} and Fc γ RIIa^{HR} homozygous donors. Levels of hIgG1, and hIgG2 subclasses, and total hIgG were analyzed in sera of 69 randomly chosen volunteers. The serum levels of the 22 Fc γ RIIa^{LR}, and 10 Fc γ RIIa^{HR} homozygous individuals in this group are shown. (A) represents the total hIgG concentration measured in these sera. (B) shows the hIgG2 serum levels, calculated relative to the hIgG1 concentration in individuals, to correct for variations in the absolute serum hIgG levels. The mean values±SEM are indicated for each donor group.

T cell activation (18). Binding of dimers to Fc γ RII on PMN exhibited similar characteristics as on monocytes (Fig. 5). After blocking Fc γ RIIIb on these PMN by mAb 3G8, hIgG1 and hIgG3 dimers were still binding weakly to the cells, which could be abrogated by combining mAb 3G8 with mAb IV.3. The fluorescence intensities observed with hIgG1, hIgG2, and hIgG3 dimers to PMN on which Fc γ RIIIb was blocked by mAb 3G8 (Figs. 5 A, C, and E), were comparable to the staining levels observed with Fc γ RIII^{nes} PMN (Figs. 5 B, D, and F).

These data were in agreement with data from the anti-CD3-induced T cell proliferation studies. hIgG2 anti-CD3 mAb acted as a potent T cell mitogen in the presence of monocytes (18), platelets (Fig. 2), and neutrophils (Fig. 3), providing the Fc γ RIIa^{LR} allotypic form was expressed. hIgG1 anti-CD3 mAb, in contrast, induced proliferation of T cells in the presence of accessory cells from all donors, regardless of Fc γ RIIa-phenotype. This mitogenic activity was blocked almost completely by anti-Fc γ RI mAb 197 (18) or anti-Fc γ RIII mAb CLB Gran1 (Fig. 4 C) when monocytes or neutrophils were used as accessory cells, respectively. Using Fc γ RIIa^{LR}/Fc γ RIIIb^{nes} PMN as accessory cells, we also observed an induction of T cell mitogenesis by hIgG1 anti-CD3 mAb. Our observations indicate that this mitogenicity is both Fc γ RI- and Fc γ RII-mediated, suggested by low susceptibility to either mAb 197 or mAb IV.3 alone, but a synergistic inhibition by combining these anti-Fc γ R mAb with PMN from both types of donors. Cytofluorometric analyses of PMN during T cell mitogenesis experiments showed, furthermore, induction of Fc γ RI-expression on PMN, which was mediated by IFN- γ , produced by activated T cells. This is supported by inhibition of Fc γ RI-induction in the presence of a neutralizing anti-IFN- γ mAb. Culturing of PMN, furthermore, affected the level of Fc γ RIIIb expression, which was reduced dramatically. This observation, and the absent or weak inhibition by mAb CLB Gran1 F(ab')₂ fragments and mAb 3G8, respectively, suggest a minor role for Fc γ RIIIb in anti-CD3-induced T cell activation. The strong inhibition by anti-Fc γ RIII mAb CLB Gran1 of hIgG1 anti-CD3-induced T cell mitogenesis (Fig. 4 C) is, therefore, most likely mediated by the Fc-moiety of this (mIgG2a) mAb (Kurlander phenomenon [4]).

A possible explanation for the inhibition pattern of hIgG1 anti-CD3-induced T cell mitogenesis (shown in Fig. 4) may be the following: hIgG1, in first instance, most likely interacts with Fc γ RIIIb and Fc γ RIIa, supported by susceptibility of hIgG1 dimer binding on normal PMN to inhibition by mAb 3G8 and mAb IV.3, which results in activation of T cells. Production of IFN- γ by these activated T cells leads to induction of Fc γ RI. In parallel, Fc γ RIIIb is shed from the cell membrane. This implicates that these Fc γ R might be involved in hIgG1-induced T cell mitogenicity at different time points during the culture.

Anti-CD3-induced T cell proliferation with platelets as accessory cells indicated that the Fc γ RIIa polymorphism to hIgG2 was also expressed on platelets. hIgG2 anti-CD3 induced T cell proliferation was only observed in the presence of Fc γ RIIa^{LR} expressing cells (Fig. 2). The pattern of subclass-specific T cell mitogenesis in these experiments, in fact, appeared identical to T cell mitogenesis in the presence of Fc γ RIIa-transfected murine fibroblasts (18). Rosenfeld et al. (42) have shown stable interdonor variation in Fc γ RIIa expression levels. Differences resulting from this polymorphism were controlled for in this study, by matching different donors

(two Fc γ RIIa^{LR}- and one Fc γ RIIa^{HR}-homozygous) for Fc γ RIIa expression levels on their platelets (Fig. 2 A and B).

Comparing the data obtained with hIgG3 in dimer-binding and T-cell mitogenicity studies, an inconsistency was found: hIgG3- and hIgG1-dimers both bound Fc γ R positive cells efficiently, whereas the hIgG1 chimeric mAb was superior to hIgG3 in inducing T cell mitogenesis. In the present and previous studies, we have observed that hIgG3 anti-CD3 mAb, in contrast to hIgG1 anti-CD3, were poor T cell mitogens when accessory cells from most healthy donors were used (15, 18). This was observed for two different allotypic forms of hIgG3 (15). Strikingly, we observed no differences in cytophilic binding of hIgG1 and hIgG3 anti-CD3 mAb to IFN- γ treated U937 cells (P. Parren, unpublished results). Similar observations were reported by Brüggemann et al. (43) and Steplewski et al. (44), who compared the efficacy of hIgG1 and hIgG3 chimeric mAb in antibody-dependent cellular cytotoxicity, and found a greater potency of hIgG1. Consistent with our observations, the latter study also reported this remarkable difference, in spite of a similar binding of chimeric mAb of these two subclasses to Fc γ R on IFN- γ treated U937 cells (44).

Summarizing the results obtained with monocytes, PMN, and platelets, the present study suggests as subclass specificity hIgG3 > hIgG1, hIgG2 \gg hIgG4 for the Fc γ RIIa^{LR} allotypic form, and hIgG3, hIgG1 \gg hIgG2 > hIgG4 for the Fc γ RIIa^{HR} allotypic form.

Using PMN of normal and an Fc γ RIII^{nes} donor, we analyzed whether cooperation between Fc γ RIIa and Fc γ RIII is taking place. Such cooperation has been described in functional studies of Fc γ RII-mediated phagocytosis (37), immune-complex-induced PMN actin assembly (36), and release of hydrolytic enzymes induced by IgM anti-Fc γ R autoantibodies (38). The question of potential cooperation between Fc γ R classes seems relevant in that in PNH patients who have strongly diminished expression of GPI-linked proteins, the Fc γ RIIIb expression is preserved (albeit at reduced level), likely because of a preferential assembly of GPI-anchors to Fc γ RIIIb compared to other GPI-linked membrane proteins (28). This suggests that complete Fc γ RIIIb deficiency may be harmful. Apart from a diseased Fc γ RIIIb^{nes} individual suffering from systemic lupus erythematosus (45); however, two healthy Fc γ RIII^{nes} individuals have recently been described who were deficient for PMN-Fc γ RIIIb expression, probably because of a disruption of the structural Fc γ RIIIb gene (29). We have now studied hIgG dimer interactions with PMN of one of these donors in detail. Effects of Fc γ RIIIb on IgG-binding by Fc γ R, however, were not evident from our study (Figs. 4 and 5). After blockade of Fc γ RIIIb on normal PMN, no differences were observed between normal and Fc γ RIII^{nes} PMN in their ability to bind hIgG1, hIgG2, or hIgG3 dimers, which was found Fc γ RIIa^{LR}-mediated. Interestingly, the efficacy of hIgG1 anti-CD3-induced T cell proliferation was not affected when normal PMN were substituted by Fc γ RIII^{nes} cells and with both PMN populations, Fc γ RI and Fc γ RII seemed involved in sustaining T cell mitogenicity. These data raise questions about the *in vivo* role of the third class of Fc γ R, and may point to a structurally redundant system.

An important question regarding the functional Fc γ RIIa polymorphism remains: Is there an *in vivo* relevance? A study by Wee et al. (46) suggests a relevance in immunotherapy, in that differences in the efficacy of mIgG1 anti-CD8 induced clearing of T cells in kidney transplant recipients were observed

between HR and LR individuals. In the present study, we observed a significant correlation between hIgG1 and hIgG2 serum levels, and the Fc γ RIIa-phenotype in healthy donors. To correct for differences in total hIgG serum levels, which vary considerably between adults (47), we calculated hIgG1 and hIgG2 relative to hIgG serum levels in each individual. This seems correct since the proportion of each subclass relative to the total hIgG content is maintained within a narrow range (reviewed in [48]). Our data suggest that Fc γ RIIa may in some way regulate hIgG subclass production/turnover. The mechanism behind this regulation, however, remains to be elucidated. It seems unlikely that regulation occurs via Fc γ RII expressed on B cells, since B cells are equipped with Fc γ RIIb isoforms, which do not express the HR-LR polymorphism (7, 10, 34). In the murine system, modulation of Ig production and proliferation of B cells has been described by soluble FcR, collectively termed "IgG binding factors." Such factors were also demonstrated in human serum (39). Recently, molecular cloning of human Fc γ RIIIa has generated cDNA clones lacking a transmembrane domain (8, 49), these Fc γ R may represent putative soluble Fc γ RIIa-molecules expressing the polymorphism. It will, therefore, be interesting to evaluate the possible role of soluble Fc γ R further with respect to the observed differences in hIgG2 serum levels found in vivo. Interestingly, hIgG2 is the main isotype induced in the humoral response after challenge with bacterial polysaccharides, and it mediates an important role in immune responses to certain capsulated bacteria, such as *Streptococcus pneumoniae* and *Haemophilus influenzae* type b. This is indicated by an increased susceptibility to these pathogens in patients with selective hIgG2 subclass deficiency (48). On the condition that these protective properties of hIgG2 antibodies are of cell-mediated nature, suggested by a low activity in C1q-binding and complement-mediated lysis (43) (although hIgG2 may be effective at high antigen densities [50]), it is important to investigate whether the Fc γ RIIa-phenotype is linked with susceptibility to bacterial infections.

Acknowledgments

We are grateful to Dr E. van der Schoot for help with obtaining blood from donors with decreased Fc γ RIIIb expression levels. We thank M. de Haas and M. Kleijer for measuring soluble Fc γ RIII, Dr. D. Roos for critically reading the manuscript, and W. Schaasberg for help with statistical analyses.

References

1. Perussia, B., E. T. Dayton, R. Lazarus, V. Fanning, and G. Trinchieri. 1983. Immune interferon induces the receptor for monomeric IgG1 on human monocytic and myeloid cells. *J. Exp. Med.* 158:1092-1113.
2. Repp, R., Th. Valerius, A. Sendler, M. Gramatzki, H. Iro, J. R. Kalden, and E. Platzer. 1991. Neutrophils express the high affinity receptor for IgG (Fc γ RI, CD64) after in vivo application of recombinant human granulocyte colony-stimulating factor. *Blood.* 78:885-889.
3. Unkeless, J. C. 1989. Function and heterogeneity of human Fc receptors for immunoglobulin G. *J. Clin. Invest.* 83:355-361.
4. Van de Winkel, J. G. J. and C. L. Anderson. 1991. Biology of human immunoglobulin G Fc receptors. *J. Leukocyte Biol.* 49:511-524.
5. Karas, S. P., W. F. Rosse, and R. J. Kurlander. 1982. Characterization of the IgG-Fc receptor on human platelets. *Blood.* 60:1277-1282.
6. Stuart, S. G., E. Simister, S. B. Clarkson, B. M. Kacinski, M. Shapiro, and I. Mellman. 1989. Human IgG Fc receptor (hFcRII; CD32) exists as multiple isoforms in macrophages, lymphocytes and IgG-transporting placental epithelium. *EMBO (Eur. Mol. Biol. Organ.) J.* 8:3657-3666.
7. Brooks, D. G., W. Q. Qiu, A. D. Luster, and J. V. Ravetch. 1989. Structure

and expression of human IgG FcRII (CD32). Functional heterogeneity is encoded by the alternatively spliced products of multiple genes. *J. Exp. Med.* 170:1369-1385.

8. Warmerdam, P. A. M., J. G. J. Van de Winkel, E. J. Gosselin, and P. J. A. Capel. 1990. Molecular basis for a polymorphism of human Fc γ receptor II (CD32). *J. Exp. Med.* 172:19-25.
9. Qiu, W. Q., D. De Bruin, B. H. Brownstein, R. Pearse, and J. V. Ravetch. 1990. Organization of the human and mouse low-affinity Fc γ R genes: duplication and recombination. *Science (Wash. DC).* 248:732-735.
10. Ravetch, J. V., and J-P. Kinet. 1991. Fc receptors. *Annu. Rev. Immunol.* 9:457-492.
11. Tax, W. J. M., F. F. Hermes, R. W. Willems, P. J. A. Capel, and R. A. P. Koene. 1984. Fc receptors for mouse IgG1 on human monocytes: polymorphism and role in antibody-induced T cell proliferation. *J. Immunol.* 133:1185-1189.
12. Clark, M. R., S. B. Clarkson, P. A. Ory, N. Stollman, and I. M. Goldstein. 1989. Molecular basis for a polymorphism involving Fc receptor II on human monocytes. *J. Immunol.* 143:1731-1734.
13. Warmerdam, P. A. M., J. G. J. Van de Winkel, A. Vlug, N. A. C. Westerdal, and P. J. A. Capel. 1991. A single amino acid in the second Ig-like domain of the human Fc γ receptor II is critical for human IgG2 binding. *J. Immunol.* 147:1338-1343.
14. Clark, M. R., S. G. Stuart, R. P. Kimberly, P. A. Ory, and I. M. Goldstein. 1991. A single amino acid distinguishes the high-responder from the low-responder form of Fc receptor II on human monocytes. *Eur. J. Immunol.* 21:1911-1916.
15. Parren, P. W. H. I., M. E. J. Geerts, L. C. M. Boeije, and L. A. Aarden. 1991. Induction of T-cell proliferation by recombinant mouse and chimeric mouse/human anti-CD3 monoclonal antibodies. *Res. Immunol.* 142:749-763.
16. Clevers, H., B. Alarcon, T. Wileman, and C. Terhorst. 1988. The T cell receptor/CD3 complex: a dynamic protein ensemble. *Annu. Rev. Immunol.* 6:629-662.
17. Palacios, R. 1985. Mechanisms by which accessory cells contribute in growth of resting T lymphocytes initiated by OKT3 antibody. *Eur. J. Immunol.* 15:645-651.
18. Parren, P. W. H. I., P. A. M. Warmerdam, L. C. M. Boeije, P. J. A. Capel, J. G. J. Van de Winkel, and L. A. Aarden. 1992. Characterization of IgG FcR-mediated proliferation of human T-cells induced by mouse and human anti-CD3 monoclonal antibodies; identification of a functional polymorphism to human IgG2 anti-CD3. *J. Immunol.* 148:695-701.
19. Koolwijk, P., J. G. J. Van de Winkel, L. C. Pfefferkorn, C. W. M. Jacobs, I. Otten, G. T. Spierenburg, and B. J. E. G. Bast. 1991. Induction of intracellular Ca²⁺ mobilization and cytotoxicity by hybrid mouse monoclonal antibodies. Fc γ RII regulation of Fc γ RI-triggered functions or signaling? *J. Immunol.* 147:595-602.
20. Tunnacliffe, A., C. Olsson, A. Traunecker, G. W. Krissansen, K. Karjalainen, and A. De la Hera. 1989. The majority of CD3 epitopes are conferred by the epsilon chain. In *Leucocyte Typing IV: White Cell Differentiation Antigens*. W. Knapp, W. R. Gilks, E. P. Rieber, R. E. Schmidt, H. Stein, and A. E. G. Kr. Von dem Borne, editors. Oxford University Press, Eynsham, Oxon, England. 295-296.
21. Van Lier, R. A. W., J. H. A. Boot, E. R. De Groot, and L. A. Aarden. 1987. Induction of T-cell proliferation with anti-CD3 switch-variant monoclonal antibodies: Effects of heavy-chain isotype in monocyte-dependent systems. *Eur. J. Immunol.* 17:1599-1604.
22. Aarden, L. A., E. R. De Groot, O. L. Schaap, and P. M. Lansdorp. 1987. Production of HGF by human monocytes. *Eur. J. Immunol.* 17:1411-1416.
23. Van de Winkel, J. G. J., J. L. P. Van Duijnhoven, R. Van Ommen, P. J. A. Capel, and W. J. M. Tax. 1988. Selective modulation of two human monocyte Fc receptors for IgG by immobilized immune complexes. *J. Immunol.* 140:3515-3521.
24. Huizinga, T. W. J., M. Kerst, J. H. Nuijens, A. Vlug, A. E. G. Kr. Von dem Borne, D. Roos, and P. A. T. Tetteroo. 1989. Binding characteristics of dimeric IgG subclass complexes to human neutrophils. *J. Immunol.* 142:2359-2364.
25. Van der Meide, P. H., M. Dubbeld, and H. Schellekens. 1985. Monoclonal antibodies to human immune interferon and their use in a sensitive solid-phase elisa. *J. Immunol. Methods.* 79:293-305.
26. Fijnheer, R., R. N. I. Pieterz, D. De Korte, and D. Roos. 1989. Monitoring of platelet morphology during storage of platelet concentrates. *Transfusion (Paris).* 29:36-40.
27. Van der Schoot, C. E., T. W. J. Huizinga, E. T. Van 't Veer-Korthof, R. Wijmans, J. Pinkster, and A. E. G. Kr. Von dem Borne. 1990. Deficiency of glycosyl-phosphatidylinositol-linked membrane glycoproteins of leukocytes in paroxysmal nocturnal hemoglobinuria, description of a new diagnostic cytofluorometric assay. *Blood.* 76:1853-1859.
28. Edberg, J. C., J. E. Salmon, M. Whiltow, and R. P. Kimberly. 1991. Preferential expression of human Fc γ RIII-PMN (CD16) in paroxysmal nocturnal hemoglobinuria. Discordant expression of glycosyl phosphatidylinositol-linked proteins. *J. Clin. Invest.* 87:58-67.
29. Huizinga, T. W. J., R. W. A. M. Kuijpers, M. Kleijer, T. W. J. Schulpen, H. T. M. Cuyppers, D. Roos, and A. E. G. Kr. Von dem Borne. 1990. Maternal

- genomic neutrophil FcRIII deficiency leading to neonatal isoimmune neutropenia. *Blood*. 76:1927-1932.
30. Van Kooten, C., M. H. J. Van Oers, and L. A. Aarden. 1990. IL-6 enhances human Ig production, but not as a terminal differentiation factor for B lymphocytes. *Res. Immunol.* 141:341-356.
 31. Vlug, A., A. J. de Bot, H. Brouwer, G. G. De Lange, A. M. van Leeuwen, E. A. de Ron, and R. V. W. van Eijk. 1989. Monoclonal antibodies against IgG subclasses. In *Protides of the Biological Fluids, William Beaumont Hospital Series*. H. Peeters, M. D. Poulik, J. R. Hobbs, J. Mestecky, and N. E. Miller, editors. Pergamon Press, Inc., Oxford. pp. 39-47.
 32. Goosen, P. C. M. 1980. Isolation of subclass of human IgG with affinity chromatography. *J. Immunol. Methods*. 37:89-93.
 33. Van de Winkel, J. G. J., W. J. M. Tax, M. C. J. Van Bruggen, C. E. P. Roozendaal, H. W. Willems, A. Vlug, P. J. A. Capel, and R. A. P. Koene. 1987. Characterization of two Fc receptors for mouse immunoglobulins on human monocytes and cell lines. *Scand. J. Immunol.* 26:663-672.
 34. Gosselin, E. J., M. F. Brown, C. L. Anderson, T. F. Zipf, and P. M. Guyre. 1990. The monoclonal antibody 41H16 detects the Leu 4 responder form of human Fc γ RII. *J. Immunol.* 144:1817-1822.
 35. Rosenfeld, S. I., and C. L. Anderson. 1989. Fc receptors of human platelets. In *Platelet Immunobiology, Molecular and Clinical aspects*. T. J. Kunicki and J. N. George, editors. J.B. Lippincott Company, Philadelphia. 337-353.
 36. Brennan, P. J., S. H. Zigmund, A. D. Schreiber, E. R. Smith, and F. S. Southwick. 1991. Binding of IgG containing immune complexes to human neutrophil Fc γ RII and Fc γ RIII induces actin polymerization by a pertussis toxin-insensitive transduction pathway. *J. Immunol.* 146:4282-4288.
 37. Salmon, J. E., N. L. Brogle, J. C. Edberg, and R. P. Kimberley. 1991. Fc γ receptor III induces actin polymerization in human neutrophils and primes phagocytosis mediated by Fc γ receptor II. *J. Immunol.* 146:997-1004.
 38. Boros, P., J. A. Odin, T. Muryoi, S. K. Masur, C. Bona, and J. C. Unkeless. 1991. IgM anti-Fc γ R autoantibodies trigger neutrophil degranulation. *J. Exp. Med.* 173:1473-1482.
 39. Huizinga, T. W. J., M. de Haas, M. Kleijer, J. H. Nuijens, D. Roos, and A. E. G. Kr. Von dem Borne. 1990. Soluble Fc γ receptor III in human plasma originates from release by neutrophils. *J. Clin. Invest.* 86:416-423.
 40. Daëron, M., C. Sautès, C. Bonnerot, U. Blank, N. Varin, J. Even, P. M. Hogarth, and W. H. Fridman. 1989. Murine type II Fc γ receptors and IgG-binding factors. In *Structures and Functions of Low Affinity Fc Receptors*. W. H. Fridman, editor. Karger, Basel. 21-78.
 41. Guyre, P. M., R. F. Graziano, B. A. Vance, P. M. Morganelli, and M. W. Fanger. 1989. Monoclonal antibodies that bind to distinct epitopes on Fc γ RI are able to trigger receptor function. *J. Immunol.* 143:1650-1655.
 42. Rosenfeld, S. I., D. H. Ryan, R. J. Looney, C. L. Anderson, G. N. Abraham, and J. P. Leddy. 1987. Human Fc γ receptors: stable inter-donor variation in quantitative expression on platelets correlates with functional responses. *J. Immunol.* 138:2869-2873.
 43. Brüggemann, M., G. T. Williams, C. I. Bindon, M. R. Clark, M. R. Walker, R. Jefferis, H. Waldmann, and M. S. Neuberger. 1987. Comparison of the effector functions of human immunoglobulins using a matched set of chimeric antibodies. *J. Exp. Med.* 166:1351-1361.
 44. Steplewski, Z., L. K. Sun, C. W. Shearman, J. Ghrayeb, P. E. Daddona, and H. Koprowski. 1988. Biological activity of human-mouse IgG1, IgG2, IgG3, and IgG4 chimeric monoclonal antibodies with antitumor specificity. *Proc. Natl. Acad. Sci. USA.* 85:4852-4856.
 45. Clark, M. R., L. Liu, S. B. Clarkson, P. A. Ory, and I. M. Goldstein. 1990. An abnormality of the gene that encodes neutrophil Fc receptor III in a patient with systemic lupus erythematosus. *J. Clin. Invest.* 86:341-346.
 46. Wee, S. L., R. B. Colvin, J. M. Phelan, F. I. Pfeffer, T. A. Reichert, D. Berd, and A. B. Cosimi. 1989. Fc receptor for mouse IgG1 (Fc γ RII) and antibody-mediated cell clearance in patients treated with Leu2a antibody. *Transplantation*. 48:1012-1017.
 47. French, M. A. H., and G. Harrison. 1984. Serum IgG subclass concentration in healthy adults: a study using monoclonal antisera. *Clin. Exp. Immunol.* 56:473-475.
 48. Jefferis, R., and D. S. Kumararatne. 1990. Selective IgG subclass deficiency: quantification and clinical relevance. *Clin. Exp. Immunol.* 81:357-367.
 49. Rappaport, E. F., D. L. Cassel, D. O. Walterhouse, R. P. Meister, A. D. Schreiber, and E. Schwartz. 1989. Isolation and characterization of a human cDNA clone coding for a potentially soluble form of the Fc γ receptor, Fc γ RII. *Blood*. 74:169a. (Abstr.)
 50. Michaelsen, T. E., P. Garred, and A. Aase. 1991. Human IgG subclass pattern of inducing complement-mediated cytolysis depends on antigen concentration and to a lesser extent on epitope patchiness, antibody affinity and complement concentration. *Eur. J. Immunol.* 21:11-16.