A Novel Role for the Fc Receptor γ Subunit: Enhancement of FcyRI Ligand Affinity

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Summary

The Fc receptors (FcR), which belong to the immunoglobulin (Ig) superfamily, bind to specific Ig isotypes with varying affinities triggering complex immune defense responses. Several of the FcR that lack signaling motifs in their cytoplasmic domains rely on associated subunits to transmit signals. Two classes of FcR that bind the Fc portion of IgG, FcyRI, and FcyRIIa associate with a subunit shared among several FcR, the γ chain, which is involved in receptor expression and signal transduction. In this report, we propose that a novel role for γ chain is to enhance the affinity of FcyRI for ligand. Our findings demonstrate that FcyRI requires γ-chain association to attain high affinity binding for monomeric IgG, and suggest that the intermediate binding affinity of the FcyRIIa isoform results from its association with γ chain. The affinity increase conferred by γ chain appears to be mediated through the transmembrane domain of the FcyR, with no requirement for the cytoplasmic domain of the receptor.

Materials and Methods

Cells and Cell Culture. U937, a human monocyte cell line from American Type Culture Collection (Rockville, MD), and N10F7, a mouse 3T3 fibroblast cell line stably transfected with human FcγRI cDNA, were maintained in RPMI 1640 (Life Technologies, Gaithersburg, MD) supplemented with 10% fetal bovine serum (HyClone Laboratories, Logan, UT), 2 mM...
l-glutamine, 100 U/ml penicillin, and 100 μg/ml streptomycin. COS-7 cells were cultured in DMEM with the supplements listed above. The N10F7 medium also contained 0.5 mg/ml G418 (Life Technologies). U937 cells were cultured with 100 U/ml human IL-4 (Genentech, San Francisco, CA) 48 h before each experiment to increase FcYRI expression.

**Plasmid Constructs and Transfections.** The human FcYRI cDNA cloned into the pCDM vector was described by Ernst et al. (3). The human γ-chain cDNA in vector pSVL was a kind gift from Dr. Jean-Pierre Kinet (National Institute of Allergy and Infectious Diseases, Bethesda, MD). FcyRIIIB, FcyRIIIa, FcyRIIIa GPI, and murine γ-chain cDNAs were all generous gifts from Dr. Jeffrey V. Ravetch (Memorial Sloan-Kettering Cancer Center, New York). FcyRIIIa and FcyRIIIB cDNA were further subcloned in the vector pCDNA1 (Invitrogen, San Diego, CA). The murine FcYRI cDNA was a kind gift from Dr. Duane W. Sears (University of California, Santa Barbara, CA), the human macrophage mannose receptor cDNA in the vector pHMR was from Dr. Benjamin A. Kruskal (Children's Hospital, Boston, MA), and the pRSVCAT vector was from Dr. Lai-Chu Wu (The Ohio State University, Columbus, OH). A truncated human FcYRI, designated FF, was constructed by PCR amplification using FcyRI cDNA as a template, and truncation was confirmed by sequencing. The FcYRI sense primer, containing a stop codon at the predicted amino acid residue 319, was 5'-GAC AAT ACG TAA 3', and the antisense primer was 5'-ACT GAG CCG CTG CTA CGT GG-3'. The cDNAs were transiently transfected into COS-7 cells by the diethylaminoethyl-dextran method described previously (3), using 1–2 μg/ml DNA, and the cells were analyzed 48 h after transfection.

**Ligand-binding Assays and Scatchard Analysis.** Approximately 5 × 10^5 COS-7 cell transfectants or N10F7 cells per well were cultured in 24-well plates overnight to confluence. Cells were incubated in triplicate for 2–4 h on ice with 0.15 ml of increasing concentrations (0.5–10 or 30 μg/ml) of monomeric 125I-IgG2a labeled with an efficiency of 95% by the chloroglycouril method. After the cells were washed to remove unbound 125I-IgG, they were solubilized in 0.5 ml 3 N NaOH, and radioactivity was determined in the Scatchard plots (Table 1). The human and the murine FcyRIIIB mAb 3G8 and with FITC-labeled F(ab')2 fragments of goat anti-mouse IgG, and were analyzed on an Elite EPICS Profile flow cytometer (Coulter, Hialeah, FL). Fluorescence data from 10,000 cells were expressed as the number of positive cells (percentage of the cells brighter than the mock-transfected COS-7 cells) and as the mean fluorescence intensity (MFI) of the positive cells.

**Results**

The Affinity for Ligand of Both the Human and the Murine FcYRI Increased when the Receptors were Cotransfected with the γ-Chain Subunit in COS Cells. Both the human and the murine FcYRI cDNAs were transfected into COS cells either alone or with γ chain, and the affinity of FcYRI for IgG was measured in ligand-binding assays using 125I-labeled IgG2a, a murine IgG isotype that both species of FcYRI bind with high affinity (11). The saturation binding data, corrected for nonspecific binding and analyzed by the Scatchard method, produced a straight line for both the human FcYRI and murine FcYRI COS cells transfected with and without γ chain, which is indicative of a single population of receptors with a single affinity for IgG (Fig. 1). The equilibrium association constants (K_a) of the FcYRI transfectants were determined from the slope of the line obtained in the Scatchard plots (Table 1). The human and the murine FcYRI transfected into COS cells bound monomeric IgG2a with a K_a of 3.2 ± 0.3 × 10^7 M^-1 and a K_a of 4.9 ± 0.4 × 10^7 M^-1, respectively (Table 1), similar to affinities previously reported for these transfectants (8, 14). The affinity for the ligand of FcYRIIIB expressed in another fibroblast cell line, a murine 3T3 cell line stably transfected with a human FcYRI cDNA, was found to be nearly identical, with a K_a of 3.5 × 10^7 M^-1.

When the human γ chain was cotransfected with human FcYRI in COS cells, the binding affinity of the receptor for monomeric IgG2a was increased fivefold to a K_a of 15.6 × 10^7 M^-1 (Fig. 1 and Table 1). The binding affinity of FcYRIIIB expressed on IFN-γ-treated U937 cells, a human monocytic cell line that naturally expresses both FcYRI and γ chain, was also measured and an average K_a of 19.0 × 10^7 M^-1 was found, which was in agreement with previous reports (11) and very similar to the binding affinity measured on the COS cells cotransfected with the human FcYRI and γ chain.
Figure 1. Scatchard plots of monomeric IgG binding to human and murine FcγRI transfected with and without γ chain in COS-7 cells. The Scatchard plot of one representative 125I-ligand binding assay is shown in which all points were done in triplicate and corrected for nonspecific binding, demonstrating the binding of ligand by FcγRI transfected alone (△) or with γ chain (●). (A) Human FcγRI (hFcγRI) with and without human γ chain (hγ). (B) Murine FcγRI (mFcγRI) with and without murine γ chain (mγ). B, bound, molar concentrations of 125I-IgG2a bound specifically to transfectants; F, free, molar concentration of unbound 125I-IgG2a.

Table 1. Equilibrium Association Constants for Binding of Monomeric IgG to FcγRI with and without γ Chain

| Cell type | Transfected cDNA | Affinity for 125I-IgG2a |
|-----------|------------------|-------------------------|
|           |                  | Human (10^7 M⁻¹) | Murine (10^7 M⁻¹) |
| U937      |                  | 19.0           | 2                 |
| P388DI    |                  |                | 11.0*               |
| N10F7     | FcγRI            | 3.5            | 2                 |
| COS-7     | FcγRI            | 3.2 ± 0.3       | 13     |
|           | FcγRI + hγ       | 15.6 ± 1.4*     | 10     |
|           | FcγRI + mγ       | 14.5 ± 0.3*     | 5       |
|           | FcγRI + control  | 3.2 ± 0.3       | 9       |
|           | FF               | 6.9 ± 0.8       | 3       |
|           | FF + hγ          | 20.3 ± 4.3*     | 3       |

The results are tabulated from ligand-binding assays and Scatchard analyses of the binding of monomeric 125I-IgG2a to various cell types and COS-7 cells transfected with human or murine FcγRI cDNAs or a truncated form of FcγRI lacking the cytoplasmic domain (FF), with or without human or murine γ chain (hγ, mγ) cotransfection. Control cDNAs (control) cotransfected with FcγRI were the human mannose receptor cDNA and several expression vectors. Kₐ represent the mean of n ligand-binding assays ± SEM.

*The differences in the affinities of FcγRI for IgG that were measured when the receptor was cotransfected with or without γ chain were statistically significant, as determined by the Student's two-tailed t test, with P < 0.001 for hFcγRI and ≤0.001 for mFcγRI.

Exclusion of the possibility that the increase in binding affinity of FcγRI for ligand was a nonspecific effect of cotransfection, both the human and the murine FcγRI were cotransfected in COS cells with several control cDNAs, including the human macrophage mannose receptor cDNA and several expression vectors, pHMR, pRSV-CAT, and pcDNAI. The binding of these FcγRI transfectants was analyzed as before, and the resulting Kₐ determined by the Scatchard method were 3.2 ± 0.3 × 10⁷ M⁻¹ and 4.1 ± 0.7 × 10⁷ M⁻¹ for human and murine FcγRI, respectively, when cotransfected with nonspecific cDNA (Table 1). Thus, cotransfection of nonspecific cDNA did not change the affinities of human and murine FcγRI.

Similar results were obtained with the murine FcγRI cotransfected with γ chain in COS cells. Cotransfection of the murine γ chain induced a twofold increase in the affinity of the receptor for mIgG2a, with a Kₐ of 9.1 ± 0.3 × 10⁷ M⁻¹, an affinity that is comparable to the one reported on the murine macrophage cell line P388D1, which had a Kₐ of 11.0 ± 10⁷ M⁻¹ (12). The difference in binding affinities for both the human and the murine FcγRI that was measured when the receptor was transfected alone or with γ chain in COS cells was demonstrated to be statistically significant when analyzed by Student's two-tailed t test.

The human and the murine γ chains, which share 86% amino acid identity (15), substitute equally for each other in increasing the binding affinity of FcγRI. The human FcγRI cotransfected with the murine γ chain showed a Kₐ of 14.5 ± 10⁷ M⁻¹, which is almost identical to the affinity that was measured when cotransfected with the human γ chain. The binding affinity of the murine FcγRI, when cotransfected with the human γ chain, was also nearly identical to what was measured when the receptor was cotransfected with the murine γ chain, a Kₐ of 9.2 ± 10⁷ M⁻¹.

To exclude the possibility that the increase in binding affinity of FcγRI for ligand was a nonspecific effect of cotransfection, both the human and the murine FcγRI were cotransfected in COS cells with several control cDNAs, including the human macrophage mannose receptor cDNA and several expression vectors, pHMR, pRSV-CAT, and pcDNAI. The binding of these FcγRI transfectants was analyzed as before, and the resulting Kₐ determined by the Scatchard method were 3.2 ± 0.3 × 10⁷ M⁻¹ and 4.1 ± 0.7 × 10⁷ M⁻¹ for human and murine FcγRI, respectively, when cotransfected with nonspecific cDNA (Table 1). Thus, cotransfection of nonspecific cDNA did not change the affinities of human and murine FcγRI.

Cotransfection of the γ chain with human FcγRI also appeared to affect the number of expressed receptors.
Binding of monomeric IgG2a to COS cells cotransfected with human FcγRI and γ chain showed a consistent decrease in the total concentration of receptor sites, as shown by the Bmax values: 5.0 ± 1.0 × 10^{-10} M for FcγRI cotransfected with γ chain, as compared to 16.0 ± 4.0 × 10^{-10} M when FcγRI was transfected alone, or 13.0 ± 1.0 × 10^{-10} M when it was cotransfected with control cDNAs. Although the expression levels in transient transfectants can be variable, the consistency with which γ chain decreased the Bmax of the human FcγRI suggested that the change in the concentration of receptor sites may be specific to γ-chain cotransfection. Unlike the human receptor, however, the Bmax measured for the murine FcγRI cotransfected with γ chain was not different from the Bmax obtained with FcγRI alone.

The Changes in Binding Affinity for IgG Correlate with the Association of γ Chain with FcγRI. We have previously shown that the association of the human FcγRI with human γ chain can be reconstituted in COS cells (3). To confirm that this association was present in our experimental conditions and to determine if the murine FcγRI association with the murine γ chain was also reconstituted in COS cell transfections, we analyzed transfectants by Western blot after immunoadsorption with antibodies against human FcγRI (197) or γ chain (4D8) (Fig. 2). Since antibody 197 is an IgG2a isotype, it was also used as a ligand to adsorb the murine FcγRI because of the lack of specific antibodies for this receptor. The anti-γ-chain immunoblot antibody recognized a 10-kD protein copurifying with FcγRI in immunoadsorbates from cells transfected with human FcγRI and human γ chain (Fig. 2 A, lane 2), and from cells transfected with murine FcγRI and human γ chain (Fig. 2 A, lane 4). A band that was the appropriate size for γ chain was also copurified from cells in which the human FcγRI was cotransfected with the murine γ chain (Fig. 2 B, lane 4), as well as from cells cotransfected with the murine FcγRI and the murine γ chain (Fig. 2 B, lane 5). Direct immunoadsorption of γ chain with anti-γ-chain antibody confirmed the presence of γ chain in the appropriate cells (Fig. 2 A, lanes 2 and 4, and B, lanes 4 and 5).

The Association of FcγRI with γ Chain and the Subsequent Increase in Binding Affinity are Independent of the Cytoplasmic Domain of the Receptor. To investigate if the transmembrane domain of FcγRI was sufficient for association with γ chain as well as for the increase in binding affinity mediated by γ chain, a truncated form of the human FcγRI containing the extracellular and transmembrane domains of the receptor without the cytoplasmic domain (FF) was constructed and transfected into COS cells with or without γ chain. Western blot analysis with an anti-γ-chain antibody showed a 10-kD band (Fig. 2 A, lane 7) in cells that had been cotransfected with the truncated construct and γ chain, and immunoadsorbed with either anti-FcγRI or anti-γ-chain antibodies, indicating that γ chain was expressed in these cells and was coinmunoadsorbed with the truncated FcγRI mutant.

The increase in binding affinity of FcγRI induced by γ chain was not affected by the absence of the cytoplasmic domain of the receptor. COS cells transfected with the truncated FcγRI alone bound monomeric ^{125}I-IgG2a with a Kd of 6.9 ± 0.8 × 10^{-7} M^{-1}, whereas after cotransfection with γ chain, cells bound ^{125}I-IgG with a Kd of 20.3 ± 4.3 × 10^{-7} M^{-1}, similar to the Kd of 19.0 × 10^{-7} M^{-1} that was measured for FcγRI on U937 cells (Table 1), indicating that the cytoplasmic domain of FcγRI is not required for enhanced binding affinity. The binding affinity of the truncated FcγRI transfected without γ chain was twofold higher than that of the wild-type receptor (P = 0.025); however, no significant difference was seen in the affinity of the two receptors that were cotransfected with γ chain (P = 0.400).

Association with γ Chain Confers Medium Affinity Binding to FcγRIII. To determine if the medium affinity of FcγRIIIa
for monomeric IgG is caused by its association with γ chain, COS cells were transfected with either the FcγRIIIa isoform, which requires cotransfection and association with γ chain for cell-surface expression, or the FcγRIIIb isoform, a GPI-linked form of the receptor that does not associate with γ chain. We also transfected an FcγRIIIa mutant, resulting in a GPI-linked form of the receptor whose expression was independent of γ-chain association. The three FcγRIII constructs transfected in COS cells were analyzed simultaneously for ligand affinity by IgG-binding assay and for expression by flow cytometry. Table 2 shows the results of representative Scatchard and flow cytometric analyses of the same set of transfected COS cells, comparing ligand binding affinity and surface expression of the three FcγRIII. The affinity of FcγRIIIa cotransfected with γ chain (1.2 × 10^7 M^-1) demonstrated an ~10-fold increase when compared to the affinity measured for the FcγRIIIa GPI mutant (0.1 × 10^7 M^-1), while the affinity of FcγRIIIb could not be calculated because of the low level of ligand binding. The expression of the three FcγRIII constructs was analyzed with an anti-FcγRIII antibody by flow cytometry to insure that the lower binding and affinities that were measured for FcγRIIIb and FcγRIIIa GPI were not caused by low levels of expression (Table 2). The three FcγR were expressed in COS cells, with FcγRIIIa/γ chain expressing less than the FcγRIIIb or FcγRIIIa-GPI mutant, confirming an absence of correlation between binding affinity and levels of receptor expression. Similar results were obtained in two additional ligand-binding assays and flow cytometric analyses.

Discussion

The functions that the γ chain provides in its association with FcγR continue to be defined. We have now shown that γ chain, in addition to its roles in receptor expression and signal transduction, modifies the affinity of FcγR for ligand. In this study, we demonstrated that the high affinity for monomeric IgG that characterizes both the human and murine FcγRI was dependent upon γ-chain cotransfection with the receptor, thus explaining the discrepancy between the lower binding affinity reported for FcγRI transfected into COS cells and the higher affinity measured on cells that naturally express the receptor. Association of γ chain increased the binding affinity of human FcγRI fivefold, and the affinity of the murine receptor twofold. While the level of affinity increase was lower in the mouse, the γ chain brought the affinity of both species of FcγRI to the levels reported on cells that naturally express the receptors. The differences observed between the human and the murine FcγRI when cotransfected with γ chain in COS cells did not appear to be related to the species of γ chain that was cotransfected with the receptors, since similar results were obtained when each receptor was cotransfected with the γ chain from the other species, suggesting differences within the structure of the receptors themselves. In fact, the reported range of binding affinity for the human FcγRI, Kd of 10^8-9 M^-1 (10), is slightly higher than the affinity reported on murine macrophages, Kd of 1.1 × 10^8 M^-1 (12), an observation our data supports. Our findings also suggest that the FcγRIIIa isoform, the "medium affinity" FcγR, has a higher affinity for monomeric IgG than the FcγRIIIb isoform because of its association with γ chain. The affinity of an FcγRIIIa GPI mutant, expressed without the requirement of the γ chain, was 10-fold less than the affinity measured for FcγRIIIa cotransfected with the γ chain.

We had previously postulated that γ chain associated with FcγRI through the transmembrane domain of the receptor due to homology of this region to the transmembrane domains of FceRI and FcγRIIIa (3), both shown to associate with γ chain through their transmembrane domains (16). With only five putative extracellular amino acids (15), it is unlikely that γ chain associated with FcγRI or induced its change in affinity through an interaction at the extracellular level. Analysis of a truncated FcγRI lacking its cytoplasmic domain not only supported the hypothesis that γ chain associated with the transmembrane domain of the receptor, but also demonstrated that the cytoplasmic domain of the receptor was not required for the increased binding affinity conferred by association with γ chain. In fact, we observed a slight but significant increase in the affinity of the truncated FcγRI when compared to the wild-type FcγRI, which suggests that the cytoplasmic domain may actually have an inhibitory effect upon binding affinity. When the receptors were cotransfected with γ chain, however, there was no longer a significant difference in the binding affinity of the truncated FcγRI compared to the wild-type receptor, suggesting γ-chain association may overcome any inhibitory effect of the FcγRI cytoplasmic domain to confer the appropriate receptor structure for high affinity binding.

It has been inferred previously that the unique third extracellular domain of FcγRI is responsible for its high affinity binding of monomeric IgG (8, 14). In one study, a mu-

Table 2. Analysis of Ligand Binding and Expression of FcγRIII Transfected in COS-7 Cells

| Transfectant | Binding affinity Kd (10^7 M^-1) | % + cells | MFI |
|--------------|---------------------------------|-----------|-----|
| FcγRIIIa + γ | 1.2                             | 10.9      | 28.5|
| FcγRIIIb     | <0.1                            | 22.0      | 62.6|
| FcγRIII a GPI mutant | 0.1 | 22.1 | 56.3|

Equilibrium association constants of one representative ligand-binding assay of monomeric 125I-IgG2a to COS-7 cells transfected with FcγRIIIa and the γ chain, FcγRIIib, and an FcγRIIIa GPI mutant, each point done in triplicate as described in Fig. 1. The surface expression of the three FcγRIII constructs from the same set of transfected COS-7 cells was analyzed in flow cytometry with the anti-FcγRIII mAb 3G8. The results are expressed as the mean of the percentage of cells brighter than negative controls (% + cells) and the MFI of the positive cells. Similar results were obtained in two additional ligand-binding assays and flow cytometric analyses.
rine FcyR chimera lacking the third extracellular domain and containing only the first two extracellular domains of FcyRI spliced to the transmembrane and cytoplasmic domain of FcyRII bound IgG with the same low affinity and binding specificity as FcyRII (13). While we have shown that γ chain association is required for maximum binding affinity, FcyRI expressed without the γ chain still bound IgG with an affinity higher than the other FcyRs, indicating that the high affinity binding of this receptor may be a result of contributions from the extracellular domain along with the association to the γ-chain subunit. The role of the extracellular domain was also apparent in our FcyRIII experiments. Both of the two GPI-linked forms of FcyRIII, a and b, bound ligand with low affinity; however, the affinity of FcyRIIIa could be measured, while the binding of FcyRIIIb was too low for an accurate affinity to be determined, even though the two receptors were expressed at similar levels. These findings suggest that the six-amino acid differences between the extracellular domain of FcyRIIIa and FcyRIIIb (17), in addition to association with γ chain, contributed to the higher binding affinity of this receptor. For both FcyRI and FcyRIII, it appeared that the structure of the extracellular domains affects binding affinity, and that association with γ chain further increases the affinity for ligand, probably through a change of the quaternary structure of the receptors.

While increased binding affinity due to an associated subunit is a novel observation among FcyRs, a similar phenomenon has been described for members of the cytokine receptor family. Like FcyR, hematopoietic cytokine receptors are characterized by pleiotropy and redundancy, and lacking a tyrosine signaling motif in their cytoplasmic domain, they associate with common subunits including gp130, KH97, and the IL receptor γ chain (18-22), which are responsible for mediating the receptor signal. Like FcyRI, these cytokine receptors when expressed alone bind ligand with relatively low affinity but are transformed to high affinity receptor complexes upon association with their subunits. An explanation has been proposed for the affinity increase of these receptors upon association with the signaling subunit: receptors that do not have built-in signaling motifs and instead rely upon associated subunits might require a higher binding affinity for ligand to give the receptor the time that is necessary to transmit signals through the associated subunit (18). This hypothesis may also be relevant to FcyR, since FcyRII, which contains a signaling motif within its cytoplasmic domain, binds monomeric IgG with lower affinity than FcyRI and FcyRIIIa, both of which rely on association with the γ chain to transmit signals to the cell. It would appear that the ability of the γ chain to modify the affinity of FcyR for ligand is not only a novel observation among FcRs, but it may also have a wider significance, suggesting that in addition to their roles in signal transduction, associated subunits may regulate receptor-ligand interaction.

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