IDENTIFICATION OF SOLUBLE Fc RECEPTORS IN MOUSE SERUM AND THE CONDITIONED MEDIUM OF STIMULATED B CELLS

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The ability of cells to bind immunoglobulin (Ig) and immune complexes is mediated by receptors that recognize the Fc portion of Ig. Fc receptors (FcR) have been described on subsets of most cell types of the immune system (reviewed in 1 and 2). The binding of immune complexes to FcR on macrophages and polymorphonuclear leukocytes triggers phagocytosis, cidal mechanisms, and the release of mediators of inflammation (3, 4). Several lines of evidence suggest that FcRs play a role in regulation of the immune response. Fc receptors that are specific for each of the Ig isotypes have been reported (5–8) and, in several cases, isotype-specific FcR are induced on T cells after administration of Ig (9–11). In addition, soluble Ig-binding factors (IBF) that have suppressive or enhancing activity on antibody responses have been described (12–14). These factors may be related to Fc receptors described on cell membranes (15).

The isolation of monoclonal antibodies directed against the Fc receptor specific for IgG2b and IgG1 aggregates (Fc\textsubscript{G2b/\gamma1}R) (16) has led to the purification of the receptor (17) and the production of specific polyclonal anti-receptor sera. The monoclonal and polyvalent anti-Fc\textsubscript{G2b/\gamma1}R antibodies have been used to develop a monoclonal sandwich radioimmunoassay with a sensitivity of ~1 fmol of Fc\textsubscript{G2b/\gamma1}R (18). In the studies reported here we have used this radioimmunoassay to study the expression of Fc\textsubscript{G2b/\gamma1}R by murine spleen cells after polyclonal activation in vitro, the release of "soluble" Fc\textsubscript{G2b/\gamma1}R by lipopolysaccharide (LPS)-activated splenocytes, and the presence of Fc\textsubscript{G2b/\gamma1}R-like material in mouse serum.

Materials and methods

Animals. CD\textsubscript{1}F\textsubscript{1}, germ-free CD\textsubscript{1}, and their sex- and age-matched controls were obtained from Charles River Breeding Laboratories (Wilmington, MA). A/J, C57BL/6J,

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Abbreviations used in this paper: BSA, bovine serum albumin; Con A, concanavalin A; FBS, fetal bovine serum; FcR, Fc receptor; Fc\textsubscript{G2b/\gamma1}R, receptor for the Fc portion of IgG2b and IgG1; HBSS, Hank's balanced salt solution; HSB, high-salt buffer; IBF, immunoglobulin-binding factor; LPS, lipopolysaccharide; NP-40, Nonidet P-40; PD, Dulbecco's modified phosphate-buffered saline; RAMlg, rabbit anti-mouse Ig; RIA, radioimmunoassay; SDS, sodium dodecyl sulfate; SDS-PAGE, SDS–polyacrylamide gel electrophoresis.
B6A/J, BALB/c nu/nu and BALB/c nu/+ controls were from The Jackson Laboratories (Bar Harbor, ME). Swiss mice were from the Rockefeller University colony.  

**Antibodies.** Affinity-purified rabbit antibodies against mouse Ig (RAMIg) and μ (Ram), and rat Ig were generously provided by Dr. E. S. Vitetta (University of Texas Health Science Center, Dallas, TX). Affinity-purified rabbit anti-mouse γ was purchased from Jackson ImmunoResearch Laboratories, Inc. (Avondale, PA). Two monoclonal anti-Thy-1.2 antibodies were used. Anti-Thy-1.2 (IgM) is the product of the HO-13.4 hybridoma (19), and anti-Thy-1.2 (rat IgG) is the product of the HO-12.4 hybridoma. The rat anti-Lyt-1 (53.7.313) and anti-Lyt-2 (52.6.72) hybridomas (20) were obtained from Dr. E. S. Vitetta, and purified as previously described (21). Monoclonal anti-Fcγb/γ1R antibody, 2.4G2, was purified from hybridoma ascites fluid by ion exchange chromatography on DE52 (Pharmacia Fine Chemicals, Piscataway, NJ). The papain Fab fragment was prepared as described (16) and purified on an LKB TSK 3000 column (LKB Produkter, Bromma, Sweden). A rabbit anti-Fcγb/γ1R serum was prepared and adsorbed as described (18).  

**Depletion of T Cells.** T cells were removed by treatment of spleen cells with monoclonal anti-Thy-1.2 (HO-13.4) and baby rabbit serum as a source of complement (C) (Pel-Freez Biologicals, Rogers, AR). Alternatively, cells were treated with a cocktail of rat hybridoma antibodies directed against Thy-1.2 (HO-12.4), Lyt-1, and Lyt-2, followed by rabbit anti-mouse γ chain and C. These treatments abolished the proliferative response to concanavalin A (Con A).  

**Adherent Cell Depletion.** Adherent cells were depleted by passage of spleen cells twice through Sephadex G-10. Alternatively, splenocytes were allowed to adhere to plastic tissue culture dishes for 2 h at 37°C. The nonadherent fraction was replated for an additional 2 h after which the nonadherent cells were harvested by gentle pipetting.  

**Depletion of B Cells.** B cells were removed by panning on RAMIg-coated dishes (22) followed by passage through a nylon wool column (23). LPS-stimulated [³H]thymidine incorporation and Ig secretion of the depleted population was <5% that of the untreated control.  

**Culture Conditions.** Spleen cells were cultured in 96-well microculture plates (Costar, Cambridge, MA) or 75-cm² flasks (Corning Glass Works, Corning, NY) at 0.5-1 × 10⁶ cells/ml in Hepes-buffered RPMI 1640 supplemented with penicillin (100 U/ml), streptomycin and gentamycin (10 µg/ml), 50 µM 2-mercaptoethanol, and 10% heat-inactivated fetal bovine serum (FBS) (KC Biological Inc., Lenexa, KS). Cultures were incubated in an atmosphere of 7% CO₂ at 37°C. Cells were stimulated with 5 µg/ml Con A (Miles Laboratories, Inc., Elkhart, IN) or 20–50 µg/ml LPS (Salmonella typhosa; Difco Laboratories, Inc., Detroit, MI) for the indicated intervals. Proliferation was measured by incorporation of [³H]thymidine added during the last 16 h of culture. J774 cells and 849.1 cells were grown in spinner cultures in Dulbecco’s modified Eagle’s medium plus 5% FBS and α-minimum essential medium with 10% FBS, respectively. The BCL1 clone, CW 13.20-3B3 (CW 13.20), was generously provided by Drs. K. Brooks and E. S. Vitetta and maintained as described (24).  

**Radioiodination of Protein.** Protein (<50 µg) was labeled with ¹²⁵I as previously described (18). However, iodinated Fcγb/γ1R was separated from free iodide by dialysis against Dulbecco’s modified phosphate-buffered saline (PD).  

**¹²⁵I-2.4G2-binding Assay.** Cells were washed by centrifugation in Hanks’ balanced salt solution (HBSS) containing 1 mg/ml bovine serum albumin (HBSS/BSA). Cells (5–10 × 10⁵) were then incubated for 1 h at 4°C with 0.5 µg/ml ¹²⁵I-2.4G2 Fab (sp act, 5,000 cpm/ng) in 100 µl of HBSS/BSA. Cells were washed extensively in HBSS/BSA and the cell pellets were assayed for radioactivity.  

**Radioimmunoassays (RIA).** Supernatants from cultures of stimulated cells were assayed for the presence of secreted IgM and IgG by a solid phase RIA as previously described (25). Fcγb/γ1R present in whole cell Nonidet P-40 (NP-40) lysates, culture supernatants, or serum was detected by a monoclonal sandwich RIA (18). Briefly, aliquots of the cell-free supernatants, cell lysates, or serum were incubated with ¹²⁵I-2.4G2 Fab (0.5 µg/ml, 5,000 cpm/ng) in a total volume of 50 µl at 1 h at room temperature. The resultant 2.4G2 Fab-antigen complexes were immunoprecipitated with either anti-Fcγb/γ1R or
normal rabbit serum bound to heat-killed formaldehyde-fixed Staphylococcus aureus (Zymed Laboratories, Burlingame, CA). The bacteria were washed by centrifugation in PD containing 1% NP-40 and 0.2% sodium dodecyl sulfate (SDS) buffer, and the bacterial pellets were assayed for radioactivity. The relative amount of soluble Fc_{2b/g}R is expressed either by the amount of ^{125}I-2.4G2 Fab precipitated or in comparison with standards of J774 or S49.1 cell lysates, assuming 10^6 and 2 x 10^5 receptors per cell, respectively.

Preparation of Serum and Plasma. Mice were anesthetized with ether and bled by cardiac puncture. When plasma was prepared, blood was collected in the presence of heparin.

Affinity Purification. Circulating Fc_{2b/g}R was affinity purified on 2.4G2 Fab-Sepharose 4B immunoadsorbent columns by passing serum three times through the column. The immunoadsorbent was then washed with 10 column volumes of PD, 10 column volumes of a high-salt buffer (HSB) (0.6 M NaCl, 0.0125 M KPO_4, pH 7.4, and 0.02% NaN_3), followed by 10 column volumes of a mixed detergent solution (0.05% NP-40, 0.1% SDS, 0.3 M NaCl, and 10 mm Tris-HCl, pH 8.6), and again with 10 column volumes of HSB and PD. Bound material was then eluted with 1 M acetic acid, dialyzed into ammonium bicarbonate, and lyophilized. The purified protein was iodinated by the iodoogen method (26) and analyzed by immunoprecipitation and SDS–polyacrylamide gel electrophoresis (SDS-PAGE).

Immunoprecipitation. Labeled protein in PD was precleared by incubation with S. aureus precoated with normal rabbit serum. The unadsorbed protein was then mixed with normal rabbit or rabbit anti-Fc_{2b/g}R antibody–precoated, formaldehyde-fixed S. aureus and incubated for 1 h at 4°C. The immunoadsorbent was collected by centrifugation, washed twice in HSB, twice with mixed detergent solution, and finally with PD. The pellets were suspended in Neville’s SDS-PAGE running buffer (27) and boiled for 5 min and centrifuged at 10,000 g.

SDS-PAGE. SDS-PAGE was performed according to the method of Neville and Glassman (27) using 0.75-mm-thick slab gels with a 4–11% polyacrylamide gradient in the running gel. ^{125}I-containing lanes were dried and exposed at -70°C on Kodak XR-5 X-omat film using image intensification screens. Apparent molecular weights (M_r) were estimated by comparison with standard proteins (Bio-Rad Laboratories, Richmond, CA).

Results

Fc_{2b/g}R Expression by LPS-activated Spleen Cells. We have investigated the expression of Fc_{2b/g}R by murine splenocytes after polyclonal activation by LPS or Con A in vitro for 4–6 d. Compared with untreated spleen cells or spleen cells incubated with Con A, treatment of spleen cells with LPS resulted in an increase in the amount of cell-associated Fc_{2b/g}R measured by RIA in detergent lysates (Fig. 1A). The increase in total cell-associated Fc_{2b/g}R is reflected by the increased number of Fc_{2b/g}R on the cell surface of LPS-activated cells, as detected by the binding of ^{125}I-2.4G2 (Fig. 1 and Table I). In contrast, Con A had no effect of Fc_{2b/g}R expression (Fig. 1).

The increase in cell-associated Fc_{2b/g}R was accompanied by the appearance in the culture supernatants of soluble material that was detected by the RIA (Fig. 1B). The soluble factor must express the determinant recognized by the 2.4G2 Fab as well as at least one additional determinant recognized by the rabbit anti-Fc_{2b/g}R antiserum, since the assay is dependent upon the immunoprecipitation by polyvalent rabbit anti-Fc_{2b/g}R serum of ^{125}I-2.4G2 Fab–antigen complexes, and the rabbit antiserum is adsorbed to remove any antibody reactive with 2.4G2 Fab. The soluble factor is thus antigenically related to Fc_{2b/g}R and will be referred to as soluble Fc_{2b/g}R.

The soluble Fc_{2b/g}R was not removed from the culture supernatant by
FIGURE 1. LPS-induced spleen cell-associated and soluble Fc_{y}R. GD_{1}F_{1} spleen cells were cultured at 5 × 10^5/ml in 75-cm^2 flasks for 5 d with no stimuli (open bars), 20 μg/ml LPS (hatched bars), or 5 μg/ml Con A (stippled bars). Cells and cell-free supernatants were harvested at day 5 and cells were lysed in NP-40 at 1 × 10^7 cell equivalents per milliliter. (A) Results of assaying 1 × 10^5 cell equivalents of cell lysates. (B) Radioimmunoassay results obtained with 10 μl of culture supernatant in a representative experiment.

TABLE I
Kinetics of LPS-induced Fc_{y}R

| Cells               | Fc_{y}R per cell (×10^{-4}) |
|---------------------|-----------------------------|
|                     | Day | LPS | Cell surface | Soluble |
| T-depleted spleen*  | 0   | +   | 1.47         | NA^†    |
|                     | 1   | +   | 0.95         | ND^‡    |
|                     | 2   | +   | 5.14         | 2.2     |
|                     | 3   | +   | 2.03         | 2.3     |
|                     | 4   | +   | 6.07         | 2.4     |
|                     | 6   | +   | 17.3         | 47.0    |
| BCL1 CW13.20        | 2   | -   | 20.0         | ND      |
|                     | +   | 120.0 | ND           |
|                     | 4   | -   | 20.0         | 20.0    |
|                     | +   | 32.4 | 145.0        |

* GD_{1}F_{1} spleen cells were depleted of T cells by anti-Thy-1.2 and C as described in Materials and Methods.
‡ Not applicable.
† Below the level of detectability.

centrifugation at 100,000 g for 90 min or by 100,000 g centrifugation followed by filtration through a 0.45 μm filter, which resulted in 88 and 83% recovery, respectively (data not shown). These results suggest that the soluble Fc_{y}R is not associated with membrane fragments.

**LPS-induced Fc_{y}R Is Associated with B Cells.** The cell population responding to LPS with elevated Fc_{y}R expression was examined by depleting adherent cells and/or by killing T cells with antibody and complement (C). T-depleted spleen cells responded to LPS as efficiently as whole spleen cell cultures with respect to synthesis of soluble and cell-associated Fc_{y}R (Table II). Similarly, spleen cells depleted of adherent cells by passage through G-10 Sephadex responded to LPS by producing increased cell-associated and soluble Fc_{y}R.
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Table II

Effect of T Cell Depletion on LPS-induced FcR

| Exp. | Culture supernatants (FcR/cell recovered, x10^-4) | Cell-associated FcR (FcR/cell recovered, x10^-4) |
|------|-----------------------------------------------|-----------------------------------------------|
|      | Untreated                                    | T depleted                                    |
|      | None  | LPS                           | None  | LPS                           |
| 1    | ND    | 0.82                          | 0.16  | 0.96                          |
| 2    | 1.3   | 12.0                          | 1.1   | 11.0                          |
| 3    | 0.7   | 7.2                           | 0.5   | 4.8                           |
| 4    | ND    | 1.3                           | ND    | 2.6                           |
| 5    | ND    | 1.0                           | ND    | 0.7                           |

Con A proliferative responses were inhibited >90% by anti-Thy-1.2 + C or by anti-Thy-1 + anti-Lyt-1 + anti-Lyt-2 followed by anti-rat-γ and C treatment. The number of FcR per cell was calculated by comparing the amount of ^125I-2.4G2 Fab precipitated compared with a standard curve obtained with J774 or S49.1 cell lysates, assuming 10^6 and 10^5 receptors per J774 and S49.1, respectively. The limit of the radioimmunoassay is 2 x 10^5 receptors per cell; all samples below our level of detection are represented by ND. NT, not tested.

Figure 2. Effect of adherent cell depletion of the LPS-induced FcγRI/RII response. Spleen cells were passed twice through Sephadex G-10 (hatched bars) and then cultured as in Fig. 1 in parallel with untreated spleen cells (open bars). Cell lysates (A) (2.5 x 10^6 cell equivalents) and culture supernatants (B) (5 μl) were assayed as in Fig. 1.

(Fig. 2). Finally, we prepared enriched B cell populations by successive depletion of T cells and adherent cells and found that neither T cells nor adherent cells were required for this response (Fig. 3). To confirm this, we tested spleen cells depleted of B cells by panning on anti-Ig-coated dishes followed by passage through a nylon wool column. The B cell-depleted population was unable to proliferate or secrete Ig in response to LPS (data not shown), and stimulation of these cells with LPS had no effect on FcγRI/RII measured in cell lysates or cell-free supernatants (Fig. 4).

We have obtained similar data using a cloned B cell tumor line, BCL1 CW13.20-3B3. These cells respond to LPS, as do normal B cells, by differentiating into IgM-secreting cells (24). The BCL1 cell line also responds to LPS with increased surface FcγRI/RII and soluble FcγRI/RII (Table I).

The increase in cell-associated FcγRI/RII on spleen cells stimulated with LPS precedes the detection of soluble FcγRI/RII in cell-free culture supernatants.
FIGURE 3. Induction of Fcγ2b/γ1R by LPS treatment of B cell-enriched spleen cells. Spleen cells were depleted of T cells and adherent cells as described above and the B cell population (hatched bars) cultured as in Fig. 1 in parallel with untreated spleen cells (open bars). Cell lysates (5 x 10^4 cell equivalents) and culture supernatants (10 µl) were assayed as in Fig. 1.

FIGURE 4. Effect of B cell depletion on LPS-induced Fcγ2b/γ1R expression. Splenic B cells were depleted by panning on RAMIg-coated dishes (solid bars) or by panning followed by passage through nylon wool (hatched bars) and were then cultured in parallel with untreated spleen cells (open bars) as described in Fig. 1. 1 x 10^5 cell equivalents of the lysates or 5 µl of culture supernatant were assayed for Fcγ2b/γ1R by the monoclonal radioimmunoassay.

(Table I). The increase in cell surface Fcγ2b/γ1R was apparent by day 2 and continued to increase through day 5. In contrast, levels of soluble Fcγ2b/γ1R did not significantly increase until day 4 or 5. The cell viability ranged from 65 to 85% throughout these experiments. Similar observations were made for the BCL1 cell line, except that the kinetics were more rapid (Table I). On the second day after LPS stimulation, a sixfold increase in cell surface Fcγ2b/γ1R was observed but no soluble Fcγ2b/γ1R was detected. Interestingly, at 4 d, the amount of surface
TABLE III

| Strain | Sex | Preparation          | Soluble FcR concentration (M⁻⁹)* |
|--------|-----|----------------------|----------------------------------|
| BALB/c | F   | Unadsorbed           | 2.4                              |
|        |     | 2.4G2 Fab adsorbed   | ND                               |
|        |     | Rat Fab adsorbed     | 2.2                              |
| B6AJ   | F   | Unadsorbed           | 2.0                              |
| C3H/HeJ | F | Unadsorbed          | 1.7                              |
|        |     | Plasma               | 1.5                              |
| CB6F1  | F   | Unadsorbed           | 11.8                             |
| CD₁F₁  | M   | Unadsorbed           | 7.0                              |
|        |     | 2.4G2 Fab adsorbed   | ND                               |
|        |     | Rat Fab adsorbed     | 6.6                              |
| A/J    | M   | Unadsorbed           | 1.0                              |
| Swiss  | F   | Unadsorbed           | 9.0                              |
|        |     | 2.4G2 Fab adsorbed   | ND                               |
|        |     | Rat Fab adsorbed     | 8.6                              |

* FcR concentration was calculated by determining the number of J774 cell equivalents per sample and assuming 10⁶ receptors per J774 cell and an Mᵦ of 50,000 based on the Mᵦ of purified FcR from cell lysates. Not detectable (ND) indicates the sample contained undetectable levels of FcR in 20 µl (10 times the volume assayed for positive samples).

Serum was adsorbed by incubation with 2.4G2 Fab or normal rat Fab coupled to Sepharose 4B, each at 2 mg protein/ml Sepharose for 1 h at 4°C.

FcR declined compared with day 2, and the amount of soluble Fcγ2b/γ1R increased sevenfold in comparison with controls. The viability of the cell line was >90% in both control and LPS-stimulated cultures.

In Vivo Analog of Soluble Fcγ2b/γ1R. The observation of Fcγ2b/γ1R-cross-reactive material in the cell-free culture supernatants of LPS-activated splenocytes prompted us to search for an in vivo equivalent of this molecule. Serum or plasma was prepared from blood obtained from mice by cardiac puncture and was assayed for soluble Fcγ2b/γ1R by RIA. As shown in Table III, pooled serum and plasma from all strains tested contained soluble Fcγ2b/γ1R at a level of 10⁻⁹ to 10⁻⁸ M. This material was quantitatively removed by passage over a 2.4G2 Fab-Sepharose column but not over a control rat Fab column (Table III).

To assess if the level of Fcγ2b/γ1R in serum could be correlated with the state of activation of the immune system, we assayed serum from neonatal and germ-free mice. The quantity of soluble Fcγ2b/γ1R in serum increased with the age of the animal (Table IV). The only adult mice that had low levels of soluble Fcγ2b/γ1R in their serum were germ-free animals (Table IV). To further analyze the significance of circulating Fcγ2b/γ1R, we quantitated soluble serum Fcγ2b/γ1R in mice with immunologic defects, including T cell-deficient nude mice, autoim-
**TABLE IV**

*Serum FcR in Individual Germ-free Mice and Mice with Immune Defects*

| Strain | Defect            | n  | Sex | Age (M [X 10^-9] ± SEM) |
|--------|-------------------|----|-----|-------------------------|
|        |                   |    |     |                          |
| CDt    | Control           | 6  | F   | 2.5                      |
|        | Germ-free         | 5  | F   | 2.5 ± 0.5                |
| BALB/c | nu/+              | 10 | F   | 2.5                      |
|        | nu/nu             | 10 | F   | 1.7 ± 0.83               |
|        |                   |    |     | 2.5 ± 0.23               |
| MLR lpr/lpr | Autoimmune     | 5  | F   | 1  |
|        |                   |    |     | 3.9 ± 1.2                |
|        |                   | 5  | F   | 5  |
|        |                   |    |     | 16.0 ± 1.5               |
|        |                   | 5  | F   | 1  |
|        |                   |    |     | 0.9 ± 1.1                |
| MRL/N  | Autoimmune        | 5  | F   | 5  |
|        |                   |    |     | 5.2 ± 1.5                |
|        |                   | 5  | F   | 14|
|        |                   |    |     | 6.2 ± 1.6                |
| BXSB   | Autoimmune        | 5  | M   | 1  |
|        |                   |    |     | 3.8 ± 0.8                |
| NZB    | Autoimmune        | 5  | F   | 1  |
|        |                   |    |     | 0.8 ± 0.5                |
| NZB × NZW |                | 5  | F   | 1  |
|        |                   |    |     | 3.0 ± 0.65               |
|        |                   | 5  | F   | 7  |
|        |                   |    |     | 1.8 ± 0.65               |
| C57 lpr/lpr | Immunoproliferative | 5  | F   | 1  |
|        |                   |    |     | 4.7 ± 2.15               |
|        |                   | 5  | F   | 10 |
|        |                   |    |     | 6.6 ± 0.9                |
|        |                   | 5  | M   | 1  |
|        |                   |    |     | 2.8 ± 1.3                |
|        |                   | 5  | M   | 10-14|
|        |                   |    |     | 5.8 ± 1.6                |
| C3H lpr | Immunoproliferative | 5  | F   | 1  |
|        |                   |    |     | 0.76 ± 0.3               |
|        |                   | 5  | F   | 10|
|        |                   |    |     | 2.4 ± 0.8                |
| C3H    | Control           | 5  | F   | 1  |
|        |                   |    |     | 1.6 ± 0.3                |
|        |                   | 5  | F   | 7  |
|        |                   |    |     | 4.2 ± 0.8                |
| C57    | Control           | 5  | F   | 2  |
|        |                   |    |     | 6.4 ± 1.5                |
|        |                   | 5  | F   | 7  |
|        |                   |    |     | 6.3 ± 0.96               |
| BALB/c | Control           | 5  | F    | 1  |
|        |                   |    |     | 2.6 ± 1                |
|        |                   | 5  | F    | 7  |
|        |                   |    |     | 6.4 ± 0.8               |

* Serum was prepared from individual mice.
* Concentration of soluble FcR was determined as in Table III and expressed as the average ± standard error of the mean for each group.

mune mice (NZB and NZB × NZW), and mice with autoimmune immunoproliferative disorder (MRL 1pr/lpr) (Table IV). BALB/c nude mice (BALB/c nu/nu) were found to have levels of soluble Fc_{y2b/γ1}R comparable to that found in their H-2, sex- and age-matched controls (BALB/c nu/+). Adult mice with autoimmune diseases were found to have levels of soluble Fc_{y2b/γ1}R comparable to that found in their H-2 sex- and age-matched controls. However, MRL, C57BL/6-congenic for the lpr gene of MRL, and BXSB mice, which display
marked hypergammaglobulinemias, have adult levels of serum Fcγ2b/γ1R at 1 mo, whereas normal mice do not reach adult levels until ~2 mo. Male BXSB mice show this high level of Fcγ2b/γ1R at 1 mo but females do not. The autoimmune disease of this strain is more prominent and appears earlier in males compared with females (28).

Ig-binding Activity of Serum FcR-like Material. To determine whether the molecule(s) detected in serum that are antigenically related to Fcγ2b/γ1R are also functionally related to the receptor we investigated the Ig-binding capacity of this material. Mouse serum was adsorbed on normal rabbit IgG or the F(ab′)2 fragment of rabbit IgG or BSA coupled to Sepharose 4B. The adsorbed serum was then tested in the RIA for Fcγ2b/γ1R. As shown in Table V, 39–54% of the 2.4G2-reactive material was nonspecifically adsorbed to BSA-Sepharose or the F(ab′)2 fragment of IgG. However, comparing the adsorption to the intact IgG-Sepharose with that adsorbed to the F(ab′)2 fragment, ~75% of the material was specifically bound to the intact IgG, demonstrating its binding activity for the Fc portion of Ig.

Affinity Purification and Characterization of Serum Fcγ2b/γ1R-like Molecules. Mouse serum (or rat serum as a control), was adsorbed to 2.4G2 Fab–Sepharose, washed, and the bound protein eluted with 1 M acetic acid as described in Materials and Methods. The eluate was dialyzed, lyophilized, and then dissolved in PD. The mouse and rat proteins were radioiodinated in parallel and aliquots of each were then precleared with normal rabbit Ig–Sepharose and immunoprecipitated with rabbit anti-mouse Fcγ2b/γ1R (Fig. 5, B and C) or normal rabbit antiserum (Fig. 5, A and D) adsorbed to fixed S. aureus. The immunoprecipitates were subjected to electrophoresis on a 4–11% gradient SDS-polyacrylamide gel and analyzed by autoradiography. A polypeptide species of Mr 48,000 was immunoprecipitated from the affinity-purified mouse serum protein by the rabbit anti-Fcγ2b/γ1R (Fig. 5, B), whereas this 48,000 Mr protein was absent in the normal rabbit serum control (Fig. 5, A). Furthermore, no 48,000 Mr protein was immunoprecipitated by the rabbit anti-Fcγ2b/γ1R serum from rat serum affinity-purified on 2.4G2 Fab–Sepharose. Rat macrophages lack the 2.4G2

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### Table V

|                          | Fcγ2b/γ1R (J774 cell equivalents/ml $\times 10^{-5}$) |
|--------------------------|------------------------------------------------------|
|                          | Exp. 1 | Exp. 2 |
| Unadsorbed               | 19.8   | 48.0   |
| Rabbit IgG-Sepharose     | 3.2    | 4.8    |
| Rabbit (Fab')2-Sepharose | 12.1   | 22.0   |
| BSA-Sepharose            | NT     | 19.0   |

Percent nonspecific adsorption*  
Percent specific adsorption*

* Nonspecific adsorption = [100 - (rabbit (Fab')2-Sepharose)/(Unadsorbed)] $\times 100$.  
* Specific adsorption = [100 - (rabbit IgG-Sepharose)/(rabbit (Fab')2-Sepharose)] $\times 100$. 

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Figure 5. Immunoprecipitation of circulating FcγR2b/γ1R. 2.4G2 Fab affinity-purified mouse (A and B) or rat (C and D) serum proteins were precleared with normal rabbit sera adsorbed to S. aureus. The unadsorbed material was then immunoprecipitated with normal rabbit sera (A and D) or rabbit anti-FcγR2b/γ1R sera (B and C) bound to S. aureus. The precipitates were collected by centrifugation and washed as described in Materials and Methods. The precipitates were then subjected to electrophoresis on a 4–11% SDS-polyacrylamide gel and analyzed by autoradiography. The numbers indicated by arrows on the left represent the $M_r$ ($\times 10^5$) of standard proteins run in parallel. The arrow at the right marks the 48,000 $M_r$ species that is specifically immunoprecipitated from the affinity-purified mouse serum proteins.

determinant and rat serum does not react in the RIA for murine FcγR2b/γ1R (E. Pure, unpublished results). The dominant 23,000 $M_r$ band precipitated by the rabbit anti-mouse FcγR2b/γ1R from both preparations (Fig. 5, B and C) is 2.4G2 Fab stripped from the immunoabsorbent column that reacts with anti-rat IgG reagents (data not shown). The 23,000 $M_r$ material is the dominant iodinated species in the partially purified receptor, and the rabbit anti-FcγR2b/γ1R antiserum, despite adsorption, still immunoprecipitates some of this material.

Discussion

Polyclonal activation of murine splenocytes with LPS in vitro results in an increased expression of FcγR2b/γ1R and in the appearance of a soluble non-membrane-associated molecule that is antigenically related to the FcγR2b/γ1R. The increase in cell-associated and soluble FcγR2b/γ1R after stimulation of spleen cells with LPS is attributable primarily to B cells. The kinetics of appearance of the soluble FcγR2b/γ1R, in both spleen cells and BCL1 cells stimulated by LPS, lags somewhat behind the increase in cell-associated FcγR2b/γ1R. It is possible that Fc receptors may be synthesized in two distinct forms, one that is released as soluble protein and a second anchored in the plasma membrane. Precedents for such soluble and membrane-bound alternatives exist for Ig (20, 30) and H-2 (31, 32) molecules in which different exons encoding the carboxyl termini of the two forms are preferentially selected during RNA processing. Another possible mechanism is that the soluble FcγR2b/γ1R and the membrane forms are products of closely related genes. Alternatively, the soluble form may be derived from the cell surface molecule by proteolysis.

The in vivo analog of the soluble FcγR2b/γ1R is probably the 2.4G2-cross-reactive material that we detect in mouse serum by RIA. Based on titrations of FcγR2b/γ1R in cell lysates by RIA, we estimate that circulating FcγR2b/γ1R is present at $1 \times 10^{-9}$ to $1 \times 10^{-8}$ M in serum or plasma. Soluble FcγR2b/γ1R was present in the serum of all male and female mice ranging in age from 3 d to 18 mo and was not restricted to any particular H-2 haplotype. That the quantity of FcγR2b/γ1R in T
cell-deficient nude mice was not markedly different from that found in the normal controls supports our in vitro data that mature T cells are not required for the production of soluble Fcγ2b/γ1R. In agreement with Khayat et al. (33), we find the level of circulating Fcγ2b/γ1R generally higher in adult compared with neonatal mice. Interestingly, the only adult mice that differed markedly in their level of circulating Fcγ2b/γ1R were germ-free mice, which had very low or undetectable levels of Fcγ2b/γ1R in their serum compared with the sex- and age-matched controls. This suggests that expression of soluble Fcγ2b/γ1R in normal mouse serum may also be modulated by activation of the immune system.

The circulating Fcγ2b/γ1R from serum that was affinity-purified on a 2.4G2 Fab–immunoadsorbent column and immunoprecipitated with rabbit anti-Fcγ2b/γ1R has an Mr of 48,000 in SDS-PAGE, and migrates in gels as a reasonably narrow species. In contrast, the cell-associated receptor isolated by the same method from BCL1 (E. Pure, unpublished results) or mouse macrophage cell lines (17) was considerably more diffuse, ranging from 47,000 to 68,000 Mr. A soluble FcR has been isolated by affinity chromatography from metabolically labeled P388D1 cells by Loube and Dorrington (34). The purified protein was a clearly defined doublet in the Mr range 55,000–65,000. The circulating form of the Fcγ2b/γ1R described here is intriguingly similar with respect to molecular weight to the lower molecular weight species isolated from cells. However, further biochemical studies are needed to clarify the relationships among the different molecules.

The role of Fc receptors in the regulation of humoral immune responses and the relationship of soluble Ig-binding factors (IBF) to membrane-bound Fc receptors or the soluble Fcγ2b/γ1R–like material described is not yet clear, but the emerging theme is that IBF from T cells regulate B cell Ig synthesis and that IBF may represent a soluble form of T cell Fc receptor. Both we and Khayat (33) have shown that the circulating Fcγ2b/γ1R is capable of binding to IgG. Fc receptors specific for various Ig classes have been described on T and B cells (5, 10, 11, 16, 35–37). Indeed, it has been shown (14, 38) that T cells bearing FcR regulate the synthesis of IgM and IgG antibodies, in part by secretion of soluble T cell factors that bind IgG. Others have shown (13, 39) that T cells bearing Fc receptors specific for IgG (FcR) regulate IgE antibody production via the release of T cell factors having affinity for IgE. Future studies will therefore need to address the relation and function of B cell–derived soluble Fcγ2b/γ1R and T cell–derived IBF.

**Summary**

We have evaluated the expression of surface Fcγ2b/γ1R by lipopolysaccharide (LPS)-activated murine spleen cells, the release of soluble Fcγ2b/γ1R by activated spleen cells, and the presence of circulating Fcγ2b/γ1R in mouse serum. LPS activation of murine spleen cells and a cloned B cell line, BCL-1 CW 13.20-3B3, resulted in a 5–10-fold increase in surface Fcγ2b/γ1R and the concomitant appearance in the culture medium of a soluble molecule that is antigenically related to the Fcγ2b/γ1R. The increase in cell-associated and soluble Fcγ2b/γ1R after LPS activation is attributable primarily to B cells.

Circulating Fcγ2b/γ1R was also detected in normal mouse serum at a concentra-
tion of $10^{-9}$ to $10^{-8}$ M. Levels of circulating $\text{Fc}_{\gamma 2b/\gamma 1}\text{R}$ increased with the age of the animals, and were low in adult germ-free mice and elevated in young mice with certain autoimmune diseases. The circulating $\text{Fc}_{\gamma 2b/\gamma 1}\text{R}$ bound to $\text{IgG-Sepharose}$, and was partially purified by affinity chromatography on $2.4\text{G2 Fab-Sepharose}$. After radiolabeling and immunoprecipitation with rabbit anti-$\text{Fc}_{\gamma 2b/\gamma 1}\text{R}$ serum, one component, of $M_r$ 48,000, was detected.

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