Cutting Edge: Intravenous Ig Inhibits Invariant NKT Cell-Mediated Allergic Airway Inflammation through FcγRIIIA-Dependent Mechanisms

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Intravenous Ig (IVIg) is a therapeutic molecule prepared from pools of plasma obtained from several thousand healthy blood donors. In addition to its use in the treatment of primary and secondary immune deficiencies, IVIg has been used as a therapeutic option in a large number of autoimmune, allergic, and inflammatory conditions including idiopathic thrombocytopenic purpura, Guillain-Barre syndrome, myasthenia gravis, and Kawasaki disease (1–6). Considering studies conducted in mouse models, several mutually nonexclusive mechanisms may account for the therapeutic effects of IVIg (1–3, 7–11). It is believed that the beneficial effect of IVIg may be related to its content of natural polyreactive Abs reactive with a large number of immunologically relevant molecules (12–14). Notably, anti-inflammatory activities of IVIg are mediated through both FcγRIIB- and/or FcγRIIA-dependent and FcγR-independent mechanisms. Thus, IVIg has been shown to exert a regulatory role on both the humoral and cellular compartment of the immune system.

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a variety of specific and nonspecific stimuli, mucus hypersecretion, pulmonary eosinophilia, Th2 cytokine production, hyperplasia and hypertrophy of smooth muscle, and elevated concentrations of serum IgE (28). IVlg has been considered as one of the therapeutic options in the treatment of asthma, although the underlying mechanisms have not been explored (29, 30). Given the critical role of iNKT cells in AAI, we surmised that IVlg targets this cellular population to exert its anti-inflammatory effect.

Materials and Methods

**Mice**

Six- to 8-wk-old male C57BL/6 wild-type (WT) and Jα18^−/− mice were bred and maintained in our animal facility under specific pathogen-free conditions. FcγRII^−/− mice (N7 C57BL/6J) were purchased from The Jackson Laboratory. Jα18^−/− mice were backcrossed for 13 generations onto a C57BL/6 background. Animal experiments were performed according to the French Institutional Committee.

**Induction of AAI and IVlg treatment**

Mice were sensitized with OVA (100 µg, i.p., per mouse; Sigma-Aldrich) absorbed to 1.6 mg aluminum hydroxide gel (Merck). After 7 d, mice were exposed to intranasal Ag (50 mg/d for OVA) or PBS on 3 consecutive d. Inhibition of AAI by IVlg in OVA-sensitized mice was assessed by injecting IVlg (10 mg, i.p., per mouse) 1 h prior to the first of the three consecutive challenges with OVA. In some experiments, OVA-sensitized WT or Jα18^−/− mice were adoptively transferred with total splenocytes (2.5 × 10^5 iNKT cell equivalents) or sorted iNKT cells (2.5 × 10^4) from WT mice that were pretreated with PBS or IVlg 1 h prior to sacrifice and transfer. Bronchoalveolar lavage fluid (BALF) and lungs were recovered 24 h after the last challenge. Total and differential cell counts were determined in the BALF, and histological analysis of lung sections was evaluated in a blinded fashion by a histopathologist (M.H.L.) as previously described (25). Peribronchial and perivascular inflammation was graded on a subjective scale of 0, 1, 2, and 3 corresponding to no, mild, moderate, or severe inflammation, respectively, with an increment of 0.5 if the inflammation fell between two integers.

**Analysis of iNKT cells**

The proportion of iNKT cells as well as their surface expression of CD69 was determined in splenocytes by flow cytometry using fluorochrome-conjugated anti–TCR-α (clone H57-597), anti-CD5 (clone 55-7.3), and anti-CD69 (clone H1.2F3) from BD Biosciences (Le Pont de Claix, France) and an allophycocyanin-conjugated α-galactosylceramide (α-GC)–loaded CD1d tetramer (CD1d–α-GC–TT) provided by the National Institutes of Health Tetramer Core Facility. To assess iNKT cell activation in vivo, mice received an injection of α-GC (Kirin Brewery; 1 µg/dose, i.v.). The in vivo modulatory effect of IVlg on iNKT cells was determined by injecting IVlg 1 h before α-GC challenge. Sera were recovered 2 h later. To compare iNKT cell activity between WT and FcγRII^−/− mice, FACS-sorted iNKT cells as CD1d–α-GC–TT–CD5^+ cells (2.5 × 10^5/well) were stimulated with α-GC–pulsed dendritic cells (DC) for 48 h (20).

Levels of cytokines in the BALF, homogenate lung, serum, and cell-free culture supernatants were assessed using ELISA Duoset kits (R&D Systems).

Statistical analysis

Data are expressed as the mean values ± SEM for each group of mice. We analyzed statistical comparisons with two-tailed unpaired Student t test and Mann–Whitney U test. We considered a p value <0.05 significant.

Results and Discussion

**IVlg inhibits airway inflammation in OVA-sensitized and challenged mice**

We first examined the protective effect of IVlg on the evolution of AAI in OVA-sensitized C57BL/6 mice. As shown in Fig. 1, IVlg treatment inhibited the recruitment of inflammatory cells in the airway passage. Thus, the total number of infiltrating cells (Fig. 1A) and, in particular, the percentage (Fig. 1B) and number (Fig. 1C) of eosinophils, one of the major mediators of allergic responses, was significantly downregulated following IVlg treatment. Despite the notion that C57BL/6 strain develops poor airway hyperreactivity compared with other strains (24, 25), IVlg treatment of OVA-sensitized C57BL/6 mice led to a significant decrease of this cardinal feature of asthma (Supplemental Fig. 1A). However, the production of pro-Th2 cytokines was unaffected by IVlg (Supplemental Fig. 1B). These results thus document the therapeutic benefit of IVlg in severe childhood asthma (4, 29, 30).

**IVlg downregulates the activation and function of iNKT cells**

Activated iNKT cells have been shown to play a crucial role in development of allergic asthma following OVA sensitization and challenge (18, 24, 25). Absence of iNKT cells indeed abolishes experimental AAI. In view of the observed protective effect of IVlg in AAI, we asked whether IVlg treatment has repercussion on the activation and cytokine production by iNKT cells. Following injection of naive or α-GC–pretreated mice with IVlg, we assessed the expression level of the activation marker CD69 on iNKT cells. As shown in Fig. 1D, IVlg treatment significantly downregulated the mean fluorescence intensity (MFI) of CD69 on iNKT cells both in naive or α-GC–pretreated mice. Furthermore, IVlg treatment also reduced significantly the serum levels of IL-4 (Fig. 1E) and IFN-γ (Fig. 1F) following in vivo activation of iNKT cells by α-GC. Moreover, in vitro addition of IVlg alleviates
production of IL-4 by sorted iNKT cells that were activated by α-GC–loaded DC (Supplemental Fig. 2). These data indicate that IVIg modulates the activation and function of iNKT cells.

**FIGURE 2.** IVIg treatment blocks the capacity of iNKT cells to restore AAI in Jα18−/− mice. Groups of OVA-sensitized Jα18−/− mice were adoptively transferred with sorted iNKT cells from PBS or IVIg-treated WT mice 1 h prior to the first challenge with OVA. Total infiltrating cells (A) and eosinophils (B) were determined in the BALF in recipient Jα18−/− mice 24 h after the last OVA challenge. Results represent means ± SEM from a representative experiment out of two. n = 3–5 mice per group. Mice that did not receive iNKT cells (none) did not respond to OVA challenge.

**FIGURE 3.** Inhibitory effect of IVIg on iNKT cells is FcγRIIIA dependent. WT and FcγRIIIA−/− mice were injected with PBS or IVIg before administration of α-GC. After 2 h, the animals were bled and sacrificed. A, MFI of the early activation marker CD69 on splenic iNKT cells. IL-4 (B) and IFN-γ (C) levels were determined in the serum. Data are pooled results from two independent experiments. n = 4 mice per group per experiment. Data represent means ± SEM.

**FIGURE 4.** Inhibitory effect of IVIg on airway inflammation is mediated by FcγRIIIA. WT and FcγRIIIA−/− mice were sensitized with OVA and treated with IVIg or PBS 1 h prior to the first challenge with OVA or PBS. Infiltrating total cells (A) and eosinophils (B) in the BALF and histological analysis (C–K) were determined 24 h after the last challenge. Peribronchial scores for PBS- or IVIg-treated OVA-sensitized/challenged WT and FcγRIIIA−/− groups of mice are represented in C. Results represent means ± SEM from a representative experiment out of two. WT mice: n = 3 or 5; FcγRIIIA−/− mice: n = 5 or 6. Periodic acid-Schiff staining of lung sections did not display robust presence of mucus in both WT and FcγRIIIA−/− (not shown). Representative H&E-stained tissue sections of lungs from each group of mice are shown: WT mice treated with PBS (D, E) or IVIg (F, G), and FcγRIIIA−/− mice treated with PBS (H, I) or IVIg (J, K). D, F, H, J, original magnification ×200. E, G, I, K, original magnification ×200.
challenge with OVA (Supplemental Fig. 3). These results demonstrate that IV Ig has a suppressive effect on effector iNKT cells but is unable to modulate these cells and render them protective.

The inhibitory effect of IV Ig on activated iNKT cells and AAI is FcγRIIIA dependent

The blockade of cell-surface FcγR is a possible mechanism for the anti-inflammatory properties of IV Ig. In view of the fact that iNKT cells constitutively express surface FcγRIIIA but not FcγRI, -IIB, or -IV (33), we examined the anti-inflammatory effect of IV Ig on iNKT cells in FcγRIIIA−/− mice. iNKT cell counts were normal in FcγRIIIA−/− mice compared with WT mice (Supplemental Fig. 4A, 4B). In addition, iNKT cells from both strains produced similar levels of IL-4 after in vitro stimulation with α-GC–pulsed DC, suggesting normal functioning of iNKT cells in FcγRIIIA−/− mice (Supplemental Fig. 4C).

To determine whether FcγRIIIA are involved in the inhibitory effect of IV Ig on iNKT cells, FcγRIIIA−/− and WT mice were injected with IV Ig 1 h before α-GC treatment. Interestingly, the inhibitory effect of IV Ig on iNKT cell activation as measured by the expression of CD69 (Fig. 3A) and by the production of IL-4 (Fig. 3 B and IFN-γ (Fig. 3C) was lost in FcγRIIIA−/− mice as compared with PBS-treated mice. These findings indicate that the inhibitory effect of IV Ig on iNKT cells requires FcγRIIIA.

These findings led us to determine whether IV Ig inhibits iNKT cell-mediated AAI through FcγRIIIA-dependent mechanisms. Consistent with this view, we found that FcγRIIIA deficiency led to a quasicomplete loss of the anti-inflammatory effect of IV Ig treatment in OVA-sensitized and challenged animals (Fig. 4). Indeed, the total number of infiltrating cells (Fig. 4A) and eosinophils (Fig. 4B), as well as peribronchial and perivascular inflammation (Fig. 4C–K), was significantly decreased following IV Ig treatment in WT mice but not in FcγRIIIA−/− mice. It is of note that WT and FcγRIIIA−/− mice had a similar capacity to develop AAI in response to OVA immunization and challenge. Together, our data demonstrate an FcγRIIIA-dependent inhibitory effect exerted by IV Ig on activated iNKT cells that confers protection in AAI. Together, these data allow us to infer that the beneficial effect of IV Ig on iNKT cell-mediated allergic airway inflammation implicates FcγRIIIA, although we do not provide evidence of a direct effect of IV Ig on FcγRIIIA expressed by iNKT cells in vivo in our model.

A well-accepted paradigm is that the inhibitory functions of IgG are mediated by FcγRIIB, which contains a cytoplasmic immune tyrosine-based inhibitory motif that recruits phosphatases, leading to suppression of intracellular signal transduction (34). By contrast, FcγRIIIA is established as an activating receptor that is required for multiple Ab–immune complex-dependent inflammatory responses in vitro and in vivo. However, Park-Min et al. (35) have shown that inhibition of IFN-γ responses by immune complexes is independent of FcγRIIB. These authors revealed that immune complexes that are contained in IV Ig inhibit IFN-γ signaling in macrophages by mechanisms dependent on FcγRIIIA, although being an activating receptor, and suggest that inhibition of IFN-γ signaling contributes to the therapeutic efficacy of IV Ig (35, 36). Consistent with these data, our results demonstrate an inhibitory role for FcγRIIIA in IV Ig-mediated suppression of iNKT cell activation. This suppressive effect on iNKT cells contributes to the anti-inflammatory effects of IV Ig in airway inflammation. Interestingly, the NK cell-dependent effect of IV Ig has also been suggested to be of relevance in the prevention of recurrent pregnancy loss (5). Strategies aimed at functional inhibition of iNKT cells by targeting through IV Ig alone or in combination with other appropriate therapeutics should help in paving the way for fighting allergic conditions and in maintaining a critical balance between tolerization and self-tolerance.

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Disclosures

The authors have no financial conflicts of interest.

References


