Interleukin 1 receptor antagonist mediates the beneficial effects of systemic interferon beta in mice: implications for rheumatoid arthritis

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ABSTRACT

Objectives Interferon beta (IFNβ) therapy is effective in multiple sclerosis and murine models of arthritis. Surprisingly, systemic IFNβ treatment induces only minimal improvement in rheumatoid arthritis (RA). To explain this paradox, the authors evaluated the mechanism of IFNβ benefit in passive K/BxN arthritis and the effect of IFNβ treatment on RA synovium.

Methods Interleukin 10 (IL-10) null, IL-1 receptor antagonist (IL-1Ra) null, IL-1Ra transgenic and wild-type mice were administered K/BxN serum and used in some cases treated with IFNβ or normal saline. Clinical response and histological scores were assessed. Gene expression was measured by quantitative PCR. Serum IL-1Ra and IL-6 were measured by ELISA. Paired synovial biopsy specimens from RA patients pre-IFNβ and post-IFNβ treatment (purified natural fibroblast IFNβ) subcutaneously three times weekly 6 million IU, 12 million IU or 18 million IU were immunostained for IL-1Ra and IL-10.

Results Il10−/− transgenic mice had an attenuated course of arthritis, whereas Il10−/− mice had higher severe serum transfer arthritis than wild-type mice. Daily IFNβ treatment significantly decreased arthritis severity in Il10−/− but not Il10−/− mice. IFNβ treatment did not reduce the histological scores in Il10−/− mice or gene expression of articular cytokines and chemokines. Paired synovial biopsy specimens from RA patients treated with IFNβ demonstrated a trend towards increased IL-1Ra and reduced IL-10 expression on day 85 levels compared with pretreatment specimens.

Conclusions The anti-inflammatory effects of IFNβ in passive K/BxN arthritis are dependent on IL-1Ra, but not IL-10. Systemic IFNβ treatment in RA increases synovial IL-1Ra production, but also decreases IL-10 production.

Despite the promising in-vitro and animal model results trials with systemic IFN therapy in RA did not demonstrate efficacy by clinical, radiographic, biochemical and histological parameters.

We previously reported the increased sensitivity to IFNβ therapy in mutant mice that had a genetic disruption in a gene associated with the proinflammatory response to type I IFN. IFNβ receptor (IKKε) deficient mice had less arthritis than wild-type mice and responded to a lower dose of IFN than controls. IFN-treated mice had an increase in Il10 (which encodes IL-1Ra) transcripts in their paws and serum; however, there was no difference in the levels of IL-10 compared with saline-treated mice. Therefore, IL-1Ra could be implicated as the potential mediator of the beneficial effects of IFN therapy.

To test the relative contributions of IL-10 and IL-1Ra as the key mediators of the beneficial effects of IFN therapy we examined mice that had targeted mutations in these two genes. Using the K/BxN serum transfer model we examined the relative severity of arthritis induction in these two strains and their response to IFN treatment. To correlate the findings with human disease, previously banked paired pre-IFN and post-IFN synovial tissue samples from a previous trial were stained for IL-1Ra and IL-10. Overall, the results suggest that the IFNβ benefit is dependent on IL-1Ra in passive K/BxN arthritis in mice, and that systemic IFNβ increases synovial IL-1Ra yet also diminished IL-10 expression in RA.

METHODS

Mice

KRN T-cell receptor transgenic mice were a gift from Drs D Mathis and C Benoist (Harvard Medical School, Boston, Massachusetts, USA) and Institut de Génétique et de Biologie Moléculaire et Cellulaire (Strasbourg, France), and were maintained on a C57Bl/6 background (K/B). Arthritic mice were obtained by crossing K/B with NOD/Lt (N) animals (K/BxN). C57Bl/6, Il10 transgenic, Il10−/−, Il10−/− mice and NOD/Lt mice were purchased from the Jackson Laboratory (Bar Harbor, Maine, USA). The mice were bred and maintained under standard conditions in the University of California, San Diego Animal Facility, which is accredited by the American Association for Accreditation of Laboratory Animal Care. All animal protocols receive previous approval by the institutional review board.
Serum transfer and arthritis scoring
Arthritic adult K/BxN mice were bled and the sera were pooled. Recipient mice were injected with 150 μl intraperitoneally on day 0. Some groups of mice also received IFNβ (Chemicon (3.6×10^7 U/mg or 1000 U=28 ng)) intraperitoneally, or normal saline (NS). Clinical arthritis scores were evaluated using a scale of 0–4 for each paw for a total score of 16. Ankle thickness was measured with a caliper (Mitutoyo, Kawasaki, Japan) in mm.\(^\text{13}\)

Histology
Whole knee joints and hind paws were fixed in 10% formalin, decalcified, trimmed and embedded. Sections were prepared from the tissue blocks and stained with haematoxylin and eosin and Safranin O (HistoTox, Boulder, Colorado, USA). Histopathological scoring was performed as previously described on a scale of 0–4 for inflammation, erosion and cartilage damage.\(^\text{13}\)

Gene expression
The wrists of mice were snap frozen and pulverised as a pool. Total RNA was isolated using the PerfectPure RNA Fibrous Tissue Kit (5 PRIME, Gaithersburg, Maryland, USA) and complementary DNA was prepared with the qScript cDNA SuperMix kit (Quanta, Gaithersburg, Maryland, USA). The messenger RNA levels for matrix metalloproteinase 3 (MMP3), IFN regulatory factor 7 (IRF7), C-X-C motif chemokine 10 (CXCL10)/interferon gamma-induced protein 10 (IP-10), IL-6, IFNβ and IL-1Ra were quantified by real time reverse transcriptase PCR using commercially designed and prepared primer and probe sets (Applied Biosystems, Foster City, California, USA) on a Bio-Rad MiQ detection system. Fold induction was calculated by 2^(-ΔΔCt), normalising to actin and using RNA from un.injected mice of the same genotype as the baseline comparator. Each sample was analysed in triplicate.

Cytokine measurement
The sera were assayed for IL-1Ra and IL-6 using commercial capture ELISA (R&D Systems, Minneapolis, Minnesota, USA).

Immunohistochemistry and semi quantitative scoring
Synovial biopsy specimens from a previously reported phase I trial were retroactively examined.\(^\text{8}\) Briefly, all mice fulfilled the American College of Rheumatology criteria for RA. Active RA was defined as six tender joints, six swollen joints and at least one of the following two criteria: duration of morning stiffness 45 min or an erythrocyte sedi 

Statistics
Significance was assessed using area under the curve analysis, analysis of variance for multiple comparisons and the Mann–Whitney U test was used for pairwise comparisons using Prism software (version 5.0).

RESULTS
Regulation of passive K/BxN arthritis by IL-1Ra and IL-10
We previously reported that genetic deficiency in IFNα/β accelerated arthritis in K/BxN serum transfer arthritis, and C57BL/6 mice had an attenuated clinical course when treated with IFNβ.\(^\text{7}\) We noted that diminished arthritis in IFNβ-treated mice correlated with higher serum levels of IL-1Ra and mRNA levels of sIL-1Ra in arthritic paws.\(^\text{7}\) Although IL-10 has been implicated as a mediator of the anti-inflammatory response to IFNβ, serum levels of IL-10 in IFNβ-treated mice were similar to controls. To assess further the relative contributions between IL-1Ra and IL-10 we examined the effects of the constitutive production of IL-1Ra and genetic disruption in the Il1rn gene (figure 1). The IL-1Ra overexpressing transgenic mice had a very mild clinical course and minimal damage after 10 days by histology. Histology scores for IL-1Ra transgenic mice averaged 0.3±0.2, 0.3±0.2 and 0±0 compared with 3.7±0.8, 3.7±0.2 and 3±0.2 for wild-type mice for inflammation, bone erosion and cartilage damage, respectively (n=6 per group, p<0.001). In contrast the IL-1Rn-deficient mice had more severe paw swelling than wild-type littermates (p<0.01) (figure 1B). IL-10 deficiency also increased arthritis severity (p<0.01) (figure 1C).

II1rn^-/- mice are refractory to IFNβ therapy whereas II10^-/- mice are responsive
Our previous studies suggested that IL-1Ra, but not IL-10, is regulated by IFNβ in passive K/BxN.\(^\text{7}\) Because this model is exquisitely dependent on IL-1, we hypothesised that the protective effect of IFNβ is mediated by IL-1Ra. The effect of IFNβ on arthritis in II1rn^-/- mice was determined to test this possibility. Unlike wild-type mice (figure 2A) the II1rn^-/- mice did not clinically respond to IFNβ treatment (figure 2B). However, the IL-10 null mice responded to daily IFNβ injections (p<0.05 treated compared with controls) (figure 2C). Synovial inflammation, bone erosion and cartilage damage were also unaffected by IFNβ treatment in II1rn^-/- mice. Treatment with IFNβ significantly improved the histological scores in wild-type littermates (p<0.01) (figure 3). The IL-10^-/- mice treated with IFNβ had a reduction in their histology score, with means of 0.4±0.2, 1±0.3 and 0.4±0.2 for inflammation, bone erosion and cartilage damage, respectively, compared with 1.8±0.5, 3.0±0.0 and 2.0±0.5 for NS-treated mice (n=5/group, p<0.05).

Enhanced expression of proinflammatory cytokine and MMP3 transcripts in II1rn^-/- mice
IFNβ treatment reduced the levels of IL-6 and MMP3 mRNA transcripts and modestly increased the IFN response gene transcription (IRF7 and IP-10) in wild-type mice compared with NS (p<0.01) (figure 4). In contrast IFNβ treatment did not reduce the
Synovial samples post-IFNβ treatment have increased IL-1Ra and decreased IL-10 by immunostaining

During a previous phase I trial, patients were treated for 12 weeks with purified natural fibroblast IFNβ, which was injected intra-peritoneally on day 0 with 150 µl of pooled K/BxN sera and with 1000 IU IFNβ, or normal saline (NS) daily. Ankle thickness was measured daily with a caliper. Shown are the means ±SEM from (A) 10 wild-type (WT) mice/group, (B) 13 Il1m mice/group and (C) 10 Il10−/− mice/group from two to three pooled experiments each. WT and Il10−/− mice significantly responded to daily 1000 IU IFNβ (p<0.05), whereas the Il1m−/− mice did not.

**Figure 1**  Genetic manipulation of Il1m and Il10 modulates arthritis. Groups of adult mice were injected with pooled K/BxN sera on day 0 and the ankle thickness was serially measured. (A) Il1m transgenic mice (closed circle) have an attenuated course of arthritis compared with wild-type littermates (black square). Shown are the averages ±SEM for 15 mice/group pooled from three experiments (p<0.001). (B) IL1Ra-deficient mice (open circle) have an accentuated course of arthritis relative to wild-type littermates (black square). Shown are the averages ±SEM for 10 mice/group pooled from three experiments (p<0.01). (C) Interleukin 10-deficient mice (open triangle) have an accelerated course of arthritis and wild-type littermates (black square). Shown are the averages ±SEM for nine mice/group pooled from two experiments (p<0.01).

**Figure 2**  Interleukin 10 (IL-10) null mice are sensitive to interferon β (IFNβ), but not IL-1 receptor antagonist null mice. Groups of mice were injected intraperitoneally on day 0 with 150 µl of pooled K/BxN sera and with 1000 IU IFNβ, or normal saline (NS) daily. Ankle thickness was measured daily with a caliper. Shown are the averages ±SEM for (A) 15 mice/group pooled from three experiments (p<0.001). (B) 13 Il1m mice/group and (C) 10 Il10−/− mice/group from two to three pooled experiments each. WT and Il10−/− mice significantly responded to daily 1000 IU IFNβ (p<0.05), whereas the Il1m−/− mice did not.

Persistently elevated IL-6 serum levels in Il1m−/− IFNβ-treated mice

Control arthritic mice had increases in the levels of IL-6 in their sera (figure 5). The level of IL-6 was lower in IFNβ-treated wild-type and Il10−/− mice, but not Il1m−/− mice. Both the wild-type and the Il10−/− mice had increases in the levels of serum IL-1Ra in response to IFN treatment. Serum levels of IL-1Ra in Il1m−/− mice were below the sensitivity of the assay.

**DISCUSSION**

IFNβ was developed as a therapeutic agent in autoimmune diseases due to its anti-inflammatory activities. Similar to other
biological therapies, this treatment has not been uniformly effective. In preclinical studies IFNβ demonstrated efficacy in rodent and non-human primate models of RA. Daily systemic administration of IFNβ reduced paw swelling, decreased serum levels of anticollagen antibodies and improved histological scores in DBA/1 mice with collagen-induced arthritis (CIA). Similarly, systemic treatment with recombinant IFNβ in thesus monkeys with CIA resulted in remarkable clinical improvement and decreased serum levels of C-reactive protein. Despite the early promise therapeutic trials in with IFNβ treatment in RA had a minimal effect on synovial histology or clinical manifestations of RA. The IL-1Ra-deficient mice were, however, refractory to treatment. These results suggest that IL-1Ra is the predominant active mediator for improvement with IFNβ treatment in this model of arthritis.

Despite the lack of efficacy in RA, IFNβ has proved effective in some cases of multiple sclerosis. The murine experimental autoimmune encephalomyelitis (EAE) model of multiple sclerosis is dependent on the production of both IL-17 and IFNγ by T helper cells for the full manifestation of disease and responds to IFNβ treatment by reducing IL-17. The most pathogenic T cells in this murine model are those that co-express IL-17 and IFNγ. This effect is not limited to the EAE model as IFNβ also reduces IL-17 production by human T lymphocytes in vitro. In both humans and mice IL-1β contributes to the priming environment that is conducive to T cells developing an IL-17-secreting phenotype (Th17). Notably, the K/BxN passive transfer model is T-cell and IL-17 independent and the effects on adaptive immunity as a mechanism explain our results.

IL-1Ra is only a modestly effective therapeutic agent in RA. Other IL-1-directed therapies, including monoclonal antibodies, soluble IL-1 receptors and caspase 1 inhibitors, also show limited benefit. The minimal efficacy of systemic IFNβ in RA might be related to the limited role of IL-1 on the clinical manifestations of this particular disease. Alternatively, a reduction in the priming of Th17 cells due to IL-1Ra treatment might be circumvented by redundant priming mechanisms or the expression of IL-17 in synovial mast cells. The increase in IL-1Ra expression noted that IL-10 and IL-1Ra-deficient mice developed accelerated paw swelling compared with wild-type controls. However, the benefit of IFNβ treatment in our experiments was not due to IL-10, as IL-10 null mice responded to IFNβ. The IL-1Ra-deficient mice were, however, refractory to treatment. These results suggest that IL-1Ra is the predominant active mediator for improvement with IFNβ treatment in this model of arthritis.

Investigating the complexities of the in-vivo activities of IFNβ might lead to optimising its use clinically either as a single agent or in combination with other therapeutic options. As the IFN receptors are widely expressed, the effects of IFNβ might span both the adaptive and innate immune compartments by direct or indirect means. Although CIA is largely a T-cell-dependent model, an earlier report suggested that the effects of IFNβ were not limited to T-cell-dependent mechanisms, but were also mediated by stromal cells and osteoclasts. We thus utilised the K/BxN model in these studies as this model was not B or T-cell dependent, yet still responds to IFNβ treatment.

Previous mechanistic studies suggested the beneficial effects of IFNβ treatment including a reduction in pro-inflammatory cytokines release such as IL-1β and TNF, while enhancing IL-10 and IL-1Ra production by leucocytes and fibroblast-like synoviocytes in vitro. Consistent with these observations, we

Figure 3 Persistent joint inflammation and damage in II1m−/− mice despite interferon β (IFNβ) treatment. (A) Wild-type (WT) and II1m−/− mice were injected intraperitoneally on day 0 with 150 µl of pooled K/BxN sera and treated with daily injections of normal saline (NS) or 1000 IU IFNβ intraperitoneally. On day 10 the mice were killed, the hind limbs were removed and one ankle from each mouse was prepared for histological scoring. Representative sections with Safranin O staining are shown at 40× magnification. (B) Shown are the average inflammation, erosion and cartilage damage scores ±SEM (six mice/group). *p<0.01 by analysis of variance with Bonferroni comparison.

Figure 4 Gene expression profiles of interleukin 1 receptor antagonist null and wild-type arthritic joints. Three mice per group were injected on day 0 with 150 µl of pooled K/BxN sera and then received daily injections of 1000 U of interferon β (IFNβ) or normal saline. The wrist joints were removed on day 4, snap frozen and pulverised. RNA was isolated from pooled wrists using commercial kits and the relative levels of gene expression were assessed by quantitative PCR and normalised to actin. The fold induction is compared with the relative level of messenger RNA expression of un.injected control mice. Shown are the averages of replicates pooled from two experiments ±SEM. The amount of II1m transcript was below detection (b.d.) in the II1m−/− mice. IRF7, IFN regulatory factor 7; IL-10, interleukin 10; MMP, matrix metalloproteinase.
observed in RA synovium and in murine arthritis could thus explain the divergent results in the two species. IL-1 is a pivotal cytokine in passive K/BxN arthritis, and the disease is markedly attenuated by deficient IL-1R signalling. The increase in IL-1Ra in RA patients would not have the same impact on clinical signs and symptoms.

Reduced IL-10 in the human synovial samples after IFNβ treatment was consistently observed and could also contribute to a reduction in the immunosuppressive effect of IFNβ. The effect on IL-10 represents another difference between RA and passive K/BxN arthritis. Although IL-10-deficient mice had an exacerbated clinical course, they still responded to IFNβ treatment.

The data on IFNβ therapy in RA focus on systemic therapy. It is possible that higher concentrations or continuous delivery, such as local gene therapy in the synovium, might activate additional mechanisms that possibly suppress synovial inflammation in RA. Frequent dosing might be required to sustain the activity of intracellular molecular signalling pathways responsible for regulating IFNβ-induced gene expression. Still, IFNβ at the dosage used had a biological effect, as noted by altered IL-1Ra and IL-10 expression in the synovium of RA patients.

Alternatively, IFNβ might be more useful as part of combination therapy in RA. Our previous studies suggested that the concurrent modulation of kinases, such as IKKε in the IFN response pathway, in combination with IFNβ therapy, can enhance the anti-inflammatory response and augment potency. Those studies showed that IKKε deficiency suppressed chemokine expression, and that low-dose IFNβ provided synergistic benefit. This approach could leverage the anti-inflammatory effects of both IKKε and IFNβ.

In conclusion, our data suggest that IFNβ acts through IL-1Ra induction for its anti-inflammatory effects in passive K/BxN arthritis. This mechanism, although effective in mice, has less utility in RA. Alternative approaches, such as local gene therapy or combination therapy with specific kinase inhibitors, could overcome these limitations.

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