

## The regulation and activity of interleukin-12

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## 1. ABSTRACT

Interleukin-12 (IL-12) is a key cytokine in the development of T helper type 1 (Th1) cell polarization, and its production of IL-12 is redundantly regulated. An important pro-inflammatory cytokine, IL-12 has been shown to have potent immunomodulatory, antitumor, and anti-infection activity *in vitro* and *in vivo*. Therefore, following a series of promising results from preclinical animal models experiments, researchers have begun to explore the clinical use of recombinant human IL-12 (rhIL-12) for treating a variety of diseases. In a series of phase I and phase II clinical trials related to cancer, viral infections, and hematopoietic stem cell transplants (HSCT), various strategies of rhIL-12 administration have been used with promising preliminary clinical results associated with tolerable toxicities.

## 2. INTRODUCTION

Interleukin-12 (IL-12) is a cytokine that plays a key role in the regulation of innate and adaptive immune responses (1). IL-12 is secreted by B cells, macrophages/monocytes, dendritic cells (DC), as well as other antigen-presenting cells (APC) (2). IL-12 stimulates polarization of naïve T helper (Th) cells into Th1 cells while inhibiting the activation of Th2 cells. IL-12 induces Th1 associated responses by stimulating T cells and natural killer (NK) cells to produce interferon- $\gamma$  (IFN- $\gamma$ ), and enhances the cytolytic activity of macrophages, T cells, and NK cells (3-7). IL-12 displays potent immuno-modulatory and antitumor activity in preclinical murine models (8-11). After a series of preclinical evaluations, recombinant human IL-12 (rhIL-12) is being tested in early phase clinical trials to evaluate its safety and efficacy in treating a variety of conditions.

IL-12 is a member of the Th1 cytokine family, which consists of IL-12p70, IL-23, IL-12p80, IL-27 and IL-35, all of which are further classified as part of the type 1 cytokine superfamily. Yet, IL-12 is distinguished from other type 1 cytokines because it is a heterodimeric complex composed of  $\alpha$  and  $\beta$  subunits. IL-12 appears to bridge the gap between APC and effector cells and thus has great control over immune regulation. Homeostasis of the immune system and the overall balance between Th1 and Th2 polarization is critically dependent upon the activity of IL-12. A relative excess of IL-12 induced Th1 responses are largely responsible for pathological inflammatory responses, including autoimmune diseases and graft rejection. Thus, a more complete understanding of IL-12-related immune physiology may offer insights into the prevention and treatment of a variety of diseases.

### 3. THE REGULATION IN THE PRODUCTION OF IL-12

The major source for IL-12 is APC such as dendritic cells, macrophages, and monocytes in response to bacteria, bacterial products, or intracellular parasites (12). IL-12 activates both the innate and acquired immune systems by stimulating NK cells and T cells, and inducing their production of IFN- $\gamma$  (13). By inducing IFN- $\gamma$  production, IL-12 not only patterns T cells towards a Th1 immune response and causes rapid T cell proliferation, but also down-regulates IL-4 secretion, thus blocking propagation of Th2 immune responses (12, 14). Notably, both IL-12 and IFN- $\gamma$  are needed for a Th1 immune effect to take place: secretion of one without the other is insufficient to initiate a Th1 immune response. Thus, IL-12 is necessary, though not sufficient, to initiate a Th1 immunity in T cells (12). The regulation of Th1 immunity appears to rely, in part, on the requirement for both IFN- $\gamma$  and IL-12 stimulation of naïve T cells. IFN- $\gamma$  secreting T cells are largely limited to those that co-express CD30, an activation antigen, suggesting that IL-12 may function physiologically through preferential interaction with CD30<sup>+</sup> T cells (14).

IL-12 production is complex and regulated by both positive and negative feedback mechanisms (1). Positive feedback regulation of IL-12 is observed through its interaction with IFN- $\gamma$ , also a Th1 cytokine, which enhances the production of IL-12 by phagocytic cells (15, 16). Furthermore, IL-12 is a potent inducer of IFN- $\gamma$  production by T and NK cells (4, 17). Observing *in vitro* cultures or following *in vivo* infections with microorganisms, IFN- $\gamma$  production appears to precede and to be required for IL-12 production (18). Thus, IL-12-induced IFN- $\gamma$  acts as a potent positive feedback mechanism in inflammation by enhancing IL-12 production, which may represent a mechanism by which Th1 responses are maintained *in vivo*. Takenaka *et al* examined the inhibitory effects of Th2 cytokines IL-10, IL-6, and IL-4 on the regulation of IL-12 production induced through T-cell-dependent and -independent pathways by using murine macrophage/DC (19). Both IL-6 and IL-4 inhibited T-cell independent IL-12 production, however, IL-4 also potentiated T-cell-dependent production of IL-12.

IL-10 inhibited IL-12 production induced through both T-cell-dependent and -independent pathways. IL-10, which is usually produced by Th2 polarized T cells, limits macrophage/DC activity and down-regulates the Th1 immune response. Following IL-12-induced STAT4 transcription factor activation, IL-10 can also be produced by Th1 T cells (20). Thus, IL-12 is also able to down-regulate Th1 immunity through a negative feedback loop (12).

### 4. ROLE OF IL-12 IN ALLOGENEIC BONE MARROW TRANSPLANTATION

Allogeneic bone marrow transplantation (BMT) involved in complicated immune responses, as a key cytokine for Th1 polarization, IL-12 is important during the process of Graft-versus-Leukemia (GvL) and Graft-versus-Host disease (GvHD). Polarization of host or donor T cells to Th1 or Th2 immune responses can result in widely different consequences that may be either desirable or undesirable in subjects with cancer and those undergoing BMT. In cancer patients, Th1 T cell polarization can be desirable when it activates the cellular arm of the immune system capable of increased cytotoxicity against the tumor. Studies show that there is a fine balance between Th1 and Th2 immune responses that must be achieved in order for the full clinical benefit of allogeneic BMT to be reached. It was previously thought that Th1 immune responses are predominate after BMT and that Th1 immunity was responsible for increased GvL and GvHD effects. In contrast, Th2 immune responses were thought to be required to limit overstimulation of the immune system. Recent studies have shown that this model of Th1 versus Th2 immune responses is an over-simplification of transplant immunology. In one study, researchers found that both Th1 and Th2 immune responses could contribute to GvHD (21), while other studies demonstrate that administration of Th1 cytokines can inhibit GvHD (11,13) and that administration of anti-IL-12 antibodies could prevent the onset of acute GvHD (22). These conflicting results show that there are other factors contributing to the net effect of Th1 cytokines in GvHD onset, such as when and how the cytokines are administered.

In allogeneic hematopoietic stem cell transplantation (HSCT), Yang and Sykes *et al* (11,13) showed using a murine BMT model that recipients of 4,900 IU of IL-12 on the day of the transplant had noticeably less acute GvHD compared with mice not receiving IL-12. Significantly, the researchers did not see a reduction of GvL activity in irradiated mice receiving IL-12, a trade-off typical of many other GvHD treatments. Furthermore, the observed GvL effect was largely due to CD8-dependent alloreactivity, as removal of CD8 cells from the spleen diminished the effect (23). Also, the effect of IL-12 on GvL and GvHD were not seen in syngenic transplant recipients. These authors proposed that the protection from CD4-mediated GvHD and increased CD8-mediated GvL activity of IL-12 works through IFN- $\gamma$  production (13, 24). IL-12-induced GvHD protection was associated with a marked reduction of GvHD-associated donor T-cell activation and expansion, which may be in part due to Fas-mediated

apoptosis of activated donor T cells (25). However, more recent studies have shown that another interleukin, IL-23, also a member of the IL-12 cytokine family, mediates inflammation and graft rejection while IL-12 delays graft rejection (26). A significant remaining question of importance to clinical translation is whether IL-12 administration or the transplantation of donor cells that secrete IL-12 can enhance GvL without increasing GvHD.

The effect of IL-12 on GvL has been partially addressed by a clinical study conducted in 2005 that enrolled 134 HSCT patients. Circulating IL-12 levels post-transplant were correlated with higher relapse free survival without an increase in observed incidence of GvHD. Furthermore, patients who started out with higher plasma levels of IL-12 had larger subsequent increases in IL-12 levels post-transplant. In patients with high levels of IL-12, 23% relapsed within 500 days post-transplant. In contrast, in patients with medium and low plasma IL-12, 40% and 49% of patients relapsed, respectively, within that timeframe. These data suggest that plasma IL-12 levels before HSCT may be associated with establishment of donor cell immunity, particularly GvL activity (27). As the primary cell that secretes IL-12, manipulation of DC subsets has been explored as a way of regulating IL-12 production *in vivo*.

The synthesis of IL-12 by distinct subsets of DC has been studied in mice and in humans. While myeloid DC (mDC) are known for their antigen presentation abilities, the function of plasmacytoid DC (pDC) is not as well characterized. DCs regulate immune responses through their production and secretion of various cytokines. In humans, mature mDC secrete IL-12 which induce Th1/Tc1 polarization (28), while immature pDC promote immune tolerance by secreting the Th2 polarizing cytokines IL-4 and IL-10 (29). pDC are able to regulate both the innate and the acquired immune system by the secretion of cytokines, and may even directly play a role in antigen presentation (30). However, the clinical significance of the content of donor DC in allogeneic HSCT remains controversial. A striking effect of enhanced relapse-free survival was seen among leukemia patients who received fewer than  $0.9 \times 10^6$  pDC/kg compared to patients who received more than  $0.9 \times 10^6$  pDC/kg as part of their transplant (31). Patients receiving fewer immature pDC showed less relapse and more chronic GvHD compared with patients who received larger numbers, with no correlation of pre-pDC content with the incidence or severity of acute GvHD. Predominance of pDC post-transplant and Th2 polarization is associated with a slower reconstitution of cellular immunity (32). Exploration of these intriguing clinical observations in pre-clinical models has been hampered by the differences between murine and human DC subsets. Murine DC subsets have a functional correspondence but incomplete phenotypic identity with human DC subsets. While both human pDC and murine pDC are important in innate immunity and synthesize large amounts of IFN- $\alpha$  in response to viral infection or CpG sequences bound to TLR9 (33,34), their effects on immune polarization of T-cells are quite different. Mature murine BM-derived pDC produce significant amounts of IL-12 and

polarize T-cells toward Th1 immune responses *in vitro* (34-37). Li *et al* showed that the net result of adding murine donor CD11b<sup>+</sup> pre-pDC to murine stem cell grafts was to enhance Th1/Tc1 polarization and GvL activity of donor T cells with limited GvHD in MHC mis-matched and MHC matched, MiHA-mismatched murine allo-HSCT models (40,41). The human DC functional analog of murine pDC (with respect to Th1 polarization) are thought to be CD11c<sup>+</sup> myeloid DC, which do produce large amounts of IL-12 and generate Th1 immune responses in effector T cells following indirect alloantigen presentation (38,39). Translation of the interesting results from graft engineering murine BMT to optimize early post-transplant IL12 production and Th1/TC1 donor T-cell polarization in humans will require early phase clinical trials to test the immunological consequences of selective enrichment and/or depletion of defined donor DC subsets in allogeneic transplantation.

## 5. ANTITUMOR ACTIVITY OF IL-12

In murine models, IL-12 has been shown to induce regression of established primary tumors, inhibit the formation of tumor metastases, and prolong the survival of tumor-bearing mice. Tumor regression after IL-12 administration in mice has been correlated with IFN- $\gamma$  production and increased T-cell and NK-cell infiltration into tumors. There have been a number of suggested mechanisms by which IL-12 can induce tumor regression. These include activated T-cells and NK-cells directly killing tumor cells, alterations in the tumor micro-circulation, and the IFN- $\gamma$ -dependent inhibition of tumor angiogenesis (42). IL-12 may also enhance T cell survival by suppressing the anti-apoptotic signaling molecule Akt that normally induces the pro-apoptotic mediators Fas/FasL, TNF receptor, and TRAIL (43). In addition, the antitumor effects of IL-12 may have an anti-angiogenic component, which can be abrogated by the addition of IFN- $\gamma$ -neutralizing antibodies (44-47). Besides an increase in intratumoral T-cells and NK-cells, a very high number of peritumoral B cells around the primary tumor has been described in IL-12-treated patients (48). After intratumoral rhIL-12 administration in head and neck squamous cell carcinoma patients, van Herpen *et al* detected an increased in B cell activation as determined by IgG subclass switch and an increase in IFN- $\gamma$  mRNA expression. The broader outer region of the mantle zone could be seen in the lymph nodes of patients treated with IL-12, and these patients had a higher number of interfollicular B-blasts, which is indicative of B cell activation. Moreover, peritumoral B cell infiltration was a positive prognostic sign in head and neck squamous cell carcinoma patients (49).

### 5.1. The combination of IL-12 and other costimulatory cytokines

On basis of the provocative results of IL-12 administration in murine cancer models, several Phase I and Phase II studies in various cancer types (50-59) have been performed to apply these findings to clinical practice, but with modest clinical results. The immunomodulatory activity of IL-12 is considerably dependent on the presence of other costimulatory cytokines. Based on the data from

the animal models, a variety of clinical trials have been conducted using rhIL-12 combined with another cytokines.

Another potent antitumor cytokine, IL-2, can interact synergistically with IL-12 to enhance T and NK cell proliferation, IFN- $\gamma$  production, and cytolytic activity, meanwhile augmenting the antitumor activity (60-63). Post-transplant peripheral blood mononuclear cells produced IFN- $\gamma$  *in vitro* when stimulated by IL-12 plus IL-2 (64). In a murine study by Siapati *et al* (65), the combination of IL-12 and IL-2 had the greatest antitumor effect and eradicated or inhibited tumors in 91% of mice vaccinated with the neuroblastoma cell line compared with only 63% of mice vaccinated the cell line and treated with IL-12 alone. As IL-2 alone had little effect on tumor growth, the authors concluded that IL-2 potentiates the effect of IL-12 on stimulating the expansion of the T-cells. When the ability of IL-12 to activate unmanipulated peripheral blood NK cells and CD8+ T cells in humans was examined, it was found that these lymphocyte subsets only responded to IL-12 when co-stimulated with IL-2 (66). Recombinant human IL-2 has been shown to synergistically enhance NK cell activity when added to rhIL-12-treated lymphocyte cultures of normal controls. Moreover, IL-2 appears to potentially up-regulate IL-12 receptor expression on lymphocytes in short-term cultures (67). Gollob *et al* also found that the down-regulation of IFN- $\gamma$  induction during chronic therapy with twice-weekly intravenous rhIL-12 was associated with a diminished capacity for IL-12 to stimulate lymphocyte IFN- $\gamma$  production *in vitro*; however, this acquired defect could be overcome if lymphocytes from rhIL-12-treated patients were stimulated *in vitro* with both IL-2 and IL-12 (50). Following these *in vitro* experiments, a phase I clinical trial was initiated to test whether the addition of IL-2 to rhIL-12 could reverse the *in vivo* down-regulation of IFN- $\gamma$  induction and thereby increase tumor response rates (68). Treatment with rhIL-12 plus low-dose IL-2 resulted in increased IFN- $\gamma$  plasma levels, and the up-regulation of IFN- $\gamma$ -inducible protein-10, dramatically enhanced NK cell expansion, and modestly augmented the synthesis of tumor necrosis factor- $\alpha$  (TNF- $\alpha$ ) and IL-10. The net result was a significant antitumor effect observed in some patients receiving rhIL-12 plus IL-2.

Both IL-15 and IL-18 are also key costimulatory cytokines, which, when combined with IL-12, induce IFN- $\gamma$  production by T and NK cells (69, 70). In a study by Inuma *et al*, IL-12 was combined with IL-18 via a DC/neuroblastoma cell fusion vaccine (71). The vaccine alone had a modest effect on increasing IFN- $\gamma$  production, but the cotransfection of IL-12 and IL-18 led to a robust IFN- $\gamma$  response. The authors also showed that both NK cells and CD8+ T-cells are activated by the fusion vaccine. IL-18 potentiated the impact of IL-12 and increased the survival of mice injected with neuroblastoma tumor cells. None of the mice injected with both IL-18 and IL-12 exhibited liver metastases, whereas 50% of mice injected with IL-12 alone had metastases. Mice inoculated with the combination vaccine also had significantly increased survival. In another study of mice treated with IL-12, the neutralization of endogenous IL-18 significantly blunted IFN- $\gamma$

production (72), further emphasizing the model that the biological activity of IL-12 *in vivo* is dependent on the presence and/or induction of endogenous costimulatory cytokines. In a Phase I trial of twice-weekly intravenous rhIL-12 administration in patients with metastatic renal cell cancer or malignant melanoma, rhIL-12 induced both IL-15 and IL-18 production *in vivo* (50). Since IL-15 and IL-18 are synthesized by activated monocytes and DC (73,74), it is possible that the direct activation of these antigen-presenting cells by rhIL-12 (75) *in vivo* is responsible for the induction of these costimulatory cytokines.

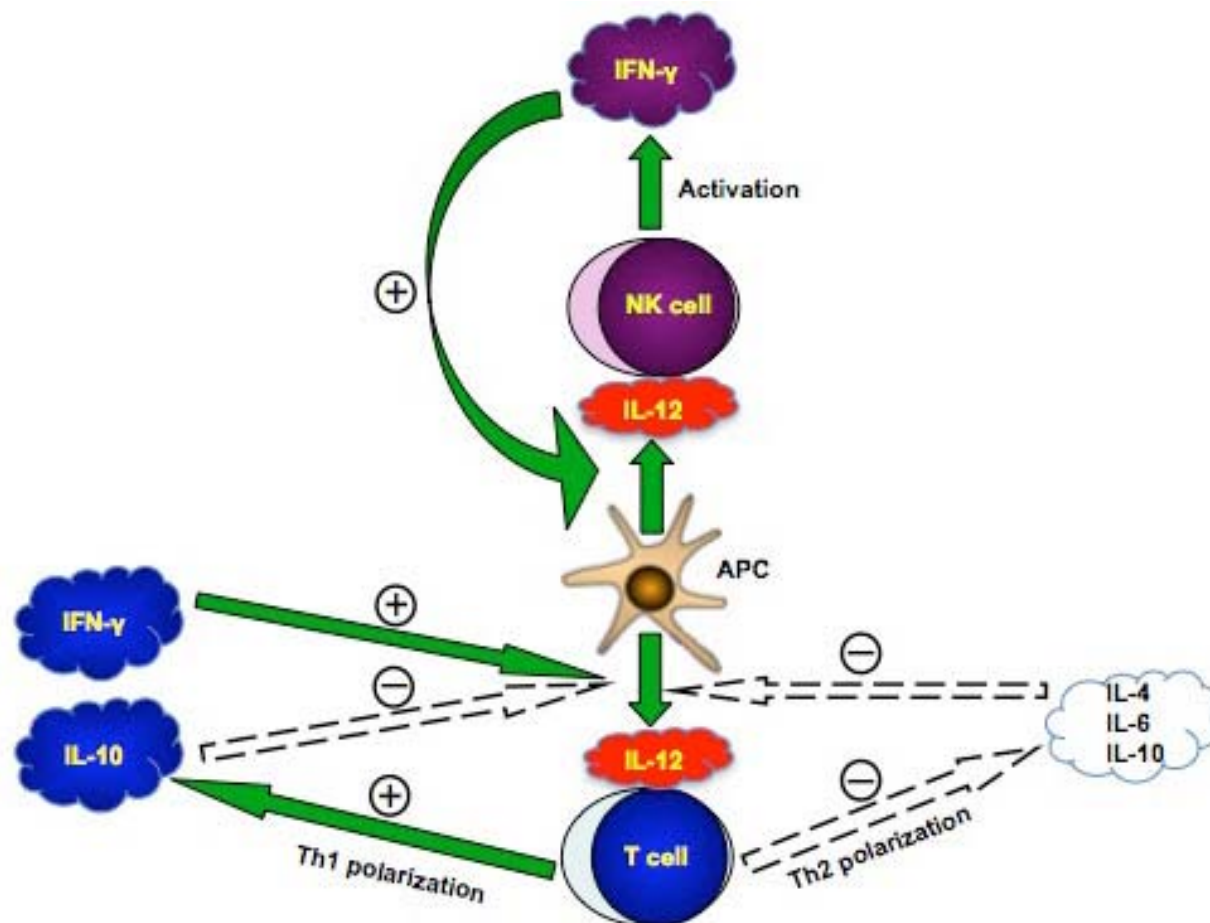
Lesinski *et al* showed that IFN- $\gamma$  produced in response to IL-12 can up-regulate the level of JAK-STAT signaling intermediates in both tumor and immune effector cells. Importantly, the up-regulation of these critical signaling intermediates sensitized host immune cells to lower doses of IFN- $\alpha$ , leading to significantly enhanced survival of tumor-bearing mice (76). In a phase I clinical trial, a regimen of IL-12 plus IFN- $\alpha$  was well tolerated in patients with advanced malignancy, and IL-12 pretreatment effectively modulated IFN- $\alpha$ -induced Jak-STAT signal transduction in peripheral-blood mononuclear cells (77).

### 5.2. The combination of IL-12 and other treatments

Besides its use in combination with other cytokines, IL-12 has been used as an adjunct to other cancer therapies. Pelloso *et al* examined the efficacy of rhIL-12 administration after autologous stem cell transplantation. rhIL-12, when given after a median of 66 days post-transplant, resulted in a marked dose-dependent expansion of major lymphocyte subsets including CD4 T cells, B cells and NK cells *in vivo* during rhIL-12 treatment (78). Furthermore, significantly increased levels of serum IFN- $\gamma$  were observed following both a single dose (64) and multiple doses (78) of IL-12.

Previously, it was shown that co-administration of IL-12 with peripheral blood mononuclear cells loaded with tumor antigen peptides induced specific cytolytic T-lymphocyte responses and tumor protection in mice, circumventing the need to generate DC (79). On that basis, Gajewski *et al.* conducted a Phase I clinical study to determine the optimal dose of rhIL-12 necessary to induce T-cell responses in combination with antigen-loaded peripheral blood mononuclear cells (80). In a follow-up phase II clinical study of immunization with Melan-A/MART-1 (81) peptide-pulsed autologous peripheral blood mononuclear cells and rhIL-12 in HLA-A2-positive patients with advanced melanoma, researchers observed a significant increase in Melan-A-specific IFN- $\gamma$ -producing CD8+ T cells after immunization. In this trial, 10% of patients had a complete response, 20% of patients had a mixed response and 20% of patients achieved a stable disease state, with a median overall survival of 12 months. Furthermore, there was a statistical association between clinical response in individual patients and the increase in numbers of antigen-specific T-cells in their blood (82).

In a mouse brain tumor model, systemic administration of rhIL-12 enhanced the antitumor response to a fusion cell vaccine (83). The results of a Phase I



**Figure 1.** The positive and negative feedback in the production of IL-12. IL-12 secreted by APC activate NK cells and induce Th1 polarization to produce IFN- $\gamma$  which enhance the production of IL-12 by a positive feedback mechanism. On the other hand, IL-12 secreted by APC block Th2 polarization to down-regulate Th2 cytokines which inhibit IL-12 production by a negative feedback mechanism. Th1 cells are not only involved in the positive feedback, but also the negative feedback because Th1 cells can produce IL-10 which is usually produced by Th2 cells.

clinical trial of fusion cells prepared with DCs and cultured autologous glioma cells indicate that this treatment safely induces anti-tumor immune responses (84). Based on the data from the phase I trial and an animal model, a phase II clinical trial of vaccine therapy using fusion cells and rhIL-12 has been performed (85). The efficacy of the combination of rhIL-12 administration with the fusion cell vaccine was greater than that of fusion cells alone, and administration of fusion cells and rhIL-12 safely induced partial antitumor responses in 4/15 patients with malignant glioma.

## 6. ANTIVIRAL ACTIVITY OF IL-12

A Th1 coordinated immune response is favorable for host control of infection with intracellular organisms, such as viruses and intracellular parasites, as well as one of the central actions of IL-12 is to shift the immune system from a Th2 response to a Th1 response, and its prime function is to promote cytotoxic functions of T and NK cells and to stimulate Th1-type of effector mechanisms to

combat microbial infections (1). Several investigators have suggested that one potential reason the immune system is unable to eradicate some viruses is that there is a shift of the human immune system away from a predominant Th1 phenotypic response to a Th2 response (86-89). On basis of these properties, IL-12 has been tested in several mouse models for human infectious diseases in which induction of Th1-type responses is critical for protective immunity. Recombinant murine IL-12 (rmIL-12) demonstrates potent activity against a variety of chronic viral infection, including herpesvirus, hepatitis B virus (HBV), hepatitis C virus (HCV), cytomegalovirus (CMV), lymphocytic choriomeningitis virus, encephalomyocarditis virus, vesicular stomatitis virus, influenza and murine acquired immunodeficiency syndrome. In animal models, administration of rmIL-12 reduced viral titers or improved survival (90-97). Based off the results in these animal models, rhIL-12 has been administrated in clinical trials in different patients with a variety of viral infections. *In vitro* studies showed rhIL-12 can increase anti-human immunodeficiency virus (HIV)-specific cytolytic activity of

peripheral blood mononuclear cells of HIV-infected patients (98), with less potential than does rhIL-2 for upregulating HIV replication (99). In contrast to IL-2, IL-12 inhibited programmed cell death via apoptosis of Th1 CD4<sup>+</sup> T cells which is a phenomenon implicated in the progressive loss of CD4<sup>+</sup> T cells in advanced HIV disease (100). Jacobson *et al* conducted a phase I trial of a single dose of rhIL-12 in HIV-infected patients with 100-500 CD4 cells/ $\mu$ l, and found increases in NK and CD8<sup>+</sup> T cells without observed changes in the absolute CD4<sup>+</sup> T cell counts or plasma HIV viral loads (101). After single dose rhIL-12 administration showed biologic activity, they used multi-dose rhIL-12 administration and observed strikingly less increase in serum IFN- $\gamma$  compared with the IFN- $\gamma$  response to single dose IL-12 (102), but increases in serum neopterin possibly represented increases of IFN- $\gamma$  because neopterin was produced by macrophages under control of IFN- $\gamma$  (103). Moreover, no significant changes in plasma HIV viral load, lymphocyte subsets, or lymphocyte proliferative were observed. The difference between results of multi-dose rhIL-12 and single dose rhIL-12 may be due to tolerance to rhIL-12 that developed following repeated rhIL-12 dosing. Although multi-dose rhIL-12 administration did not show significant effect on patients with HIV infection, Van der Meide *et al* found that IL-12 enhanced not only cellular but also humoral immune responses to HIV-1 subunit vaccine protein gp120 in non-human primates when coadministered as a potent adjuvant (104). They suggested that lower doses of various subunit vaccines administered in conjunction with IL-12 may provide a much broader level of protection than in the absence of this cytokine. Therefore IL-12 administration as an adjuvant may be a promising strategy for improving antibody and T cell immune responses to a CMV vaccine. Jacobson *et al* showed coadministration adjuvant rhIL-12 with Towne CMV vaccine resulted in rhIL-12 dose-related increases in peak anti-CMV gB IgG titers and CMV viral lysate-specific CD4<sup>+</sup> T cell proliferation responses induced by vaccine alone. Furthermore, more patients with rhIL-12 administration developed a positive CD8<sup>+</sup> T cell IFN- $\gamma$  response to pp65 peptide after Towne vaccination compared with the placebo group (105). In contrast to the effects on HIV viral load, rhIL-12 can suppress HCV plasma viral load to undetectable levels, although relapse occurred when treatment was stopped (106).

### 7. TOXICITY OF rhIL-12

Toxicities associated with intravenous rhIL-12 use are similar to those of other cytokines and frequently include fever, chills, headache, nausea, fatigue, liver transaminitis, and myelotoxicity. After rhIL-12 administration, serum levels of IFN- $\gamma$  are markedly elevated because of NK and T cell activation. IFN- $\gamma$  powerfully enhances the ability of phagocytic cells to produce IL-12 (107). This strong positive feedback mechanism likely promotes positive activity but may exacerbate the development of toxicity with exogenous administration. To test the role of IFN- $\gamma$  in the toxicology

of IL-12, IFN- $\gamma$  receptor-deficient (IFN- $\gamma$  R<sup>-/-</sup>) 129/Sv and wild-type 129/Sv mice were dosed with rmIL-12 for 4 days. In contrast to wild-type 129/sv mice, hematopoietic toxicity was not observed in IFN- $\gamma$  R<sup>-/-</sup> mice. Higher levels of committed bone marrow hematopoietic progenitor cells were present in IFN- $\gamma$  R<sup>-/-</sup> mice compared with IL-12 treated wild-type mice, suggesting that the hematopoietic toxicity of IL-12 in mice results directly from IFN- $\gamma$  (108,109).

### 8. CONCLUSION

IL-12 is a unique heterodimeric cytokine with important immunoregulatory activities in both innate and adaptive immunity, antitumor activity and antiviral activity. The production of IL-12 is regulated by both positive and negative feedback mechanisms. A variety of Phase I and Phase II clinical trials have examined the use of rhIL-12 in patients with viral infections or cancer. rhIL-12 administration was generally safe and well tolerated, and rhIL-12 induced clinical antitumor effects in some tumor patients. rhIL-12 may also be a promising adjuvant to some virus vaccines. As a potent immunostimulatory cytokine, IL-12 paradoxically limited GvHD and promoted the GvL effects of allogeneic BMT in murine BMT models. Thus, the use of IL-12 to modulate early post-transplant immune polarization of donor T cells may enhance the GvL activity of the graft while limiting GvHD for patients undergoing BMT. However, given the clear differences in transplant immunology between mice and human, preclinical studies using the most relevant large animal model to test the safety of IL-12 administration in allogeneic HSCT should be undertaken prior to testing IL-12 in a human phase I clinical trial of patients undergoing allogeneic HSCT.

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**Key Words:** IL-12, Cancer vaccine, HSCT, Graft-versus-Host Disease, Graft-versus-Leukemia, Antitumor, Antiviral, Toxicity, Clinical trial, Review

## **The regulation and activity of interleukin-12**

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