



PEGylation improves pharmacokinetic profile, liver uptake and efficacy of Interferon gamma in liver fibrosis

Ruchi Bansal, Eduard Post, Johannes H. Proost, Alie de Jager-Krikken, Klaas Poelstra, Jai Prakash*

Department of Pharmacokinetics, Toxicology and Targeting, Graduate School for Drug Exploration (GUIDE), University of Groningen, Antonius Deusinglaan 1, 9713AV, Groningen, The Netherlands

ARTICLE INFO

Article history:

Received 14 March 2011

Accepted 29 May 2011

Available online 12 June 2011

Keywords:

PEGylation

Interferon gamma

Fibrosis

Stellate cells

ABSTRACT

Interferon gamma (IFN γ) is a potent cytokine that displays a variety of anti-viral, anti-proliferative, immunomodulatory, apoptotic and anti-fibrotic functions. However, its clinical use is limited to the treatment of few diseases due to the rapid clearance from the body. PEGylated IFN- α formulations are shown to be beneficial in viral hepatitis, but PEGylation of IFN γ to enhance its therapeutic effects in liver fibrosis is not yet explored. Liver fibrosis is characterized by the extensive accumulation of an abnormal extracellular matrix and is the major cause of liver-related morbidity and mortality worldwide. To date, there is no pharmacotherapy available for this disease. We modified IFN γ with different-sized linear PEG molecules (5, 10 and 20 kDa) and assessed the biological activity *in vitro* and *in vivo*. All PEGylated IFN γ constructs were biologically active and activated IFN γ signaling *in vitro* as determined with a nitric oxide release assay and a pGAS-Luc reporter plasmid assay, respectively. Similar to IFN γ , all PEGylated IFN γ induced a significant reduction of fibrotic parameters in mouse NIH3T3 fibroblasts as shown with immunohistochemical staining and quantitative PCR analyses. *In vivo*, the pharmacokinetic profile of radiolabeled ¹²⁵I-IFN γ -PEG conjugates revealed a decreased renal clearance and an increased plasma half-life with an increase of PEG size. Moreover, the liver accumulation of PEGylated IFN γ constructs was significantly higher than the unmodified IFN γ , which was also confirmed by increased MHC-II expression in the livers. Furthermore, in a CCl₄-induced acute liver injury model in mice, PEGylated constructs reduced the early fibrotic parameters more drastically than unmodified IFN γ . Of note, these effects were stronger with higher PEG-sized IFN γ constructs. These data nicely correlated with the pharmacokinetic data. In conclusion, PEGylation significantly improved the pharmacokinetics, liver uptake and anti-fibrotic effects of IFN γ . This study opens new opportunities to exploit the therapeutic applications of PEGylated IFN γ for the treatment of liver fibrosis and other diseases.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Liver fibrosis, mainly caused by viral hepatitis, alcohol consumption and obesity, is characterized by an excessive production of extracellular matrix proteins that form hepatic scars. If untreated, this leads to cirrhosis and eventually hepatocellular carcinoma [1,2]. Following liver injury, growth factors and cytokines, produced due to hepatocyte damage, lead to the activation of hepatic stellate cells (HSC). HSC subsequently transdifferentiate into proliferative, contractile and extracellular matrix producing myofibroblasts [3,4]. Despite evolving experimental therapies for liver fibrosis in animals, to date none has

been clinically approved, leaving liver transplantation as the only therapeutic option [5]. Treatment of hepatitis B and C infections has been quite successful in recent years mainly due to the development of PEGylated IFN α molecules that have an optimal pharmacokinetic profile combined with potent antiviral activity. This illustrates the potential of using endogenous cytokines for therapeutic purposes. Interferon gamma (IFN γ) has been shown to display potent anti-fibrotic effects *in vitro* and in animal models [5,6], therefore we examined whether modified forms of IFN γ can be used as anti-fibrotic drugs.

Interferon gamma is a homodimeric Th1 proinflammatory cytokine produced by activated inflammatory cells and has been documented to be highly effective in immunodeficiency diseases, chronic inflammatory diseases, fibrosis, tumors and atypical mycobacterial infections [7–9]. Despite the potent biological therapeutic activities of IFN γ , its clinical application is limited to the treatment of chronic granulomatous disease and malignant osteopetrosis [8], due to rapid renal clearance and systemic side effects. When administered intravenously (a tolerated dose with minimal side effects), rapid plasma clearance was

Abbreviations: α -SMA, alpha smooth muscle actin; AUC_(0–∞), Area under the curve from zero to infinity; CCl₄, carbon tetrachloride; HSC, Hepatic stellate cells; IFN, Interferon; PEG, Polyethylene glycol; TGF β , Transforming growth factor beta.

* Corresponding author at: Department of Pharmacokinetics Toxicology and Targeting, Groningen University of Drug Exploration (GUIDE), University of Groningen, Antonius Deusinglaan 1, 9713AV, Groningen, The Netherlands. Tel.: +31 50 3637565; fax: +31 50 3633247.

E-mail addresses: R.Bansal@hotmail.com (R. Bansal), J.Prakash@rug.nl (J. Prakash).

observed, while higher doses or frequent doses induced severe adverse effects [10–12].

During liver injury, IFN γ is produced by inflammatory cells as a self-defensive mechanism. In rodents, disruption of IFN γ or its signaling via signal transducer and activator of transcription (STAT1) enhanced liver fibrosis while treatment with IFN γ ameliorated hepatic fibrosis induced by CCl $_4$ and dimethylnitrosamine (DMN) [13,14]. But its reduced bioavailability due to poor pharmacokinetics reduces its potency. Although a number of approaches have been developed to increase the half-life of cytokines or other protein drugs, fewer attempts have been made for IFN γ [15]. PEGylation, the covalent attachment of polyethylene glycol (PEG), has modified a variety of therapeutic drugs into effective and potent compounds compared to their unmodified parent molecules. This is one of the common approaches used to improve the pharmacokinetics, immunological and pharmacodynamics properties of therapeutic proteins [16–19]. PEGylated formulations of IFN α (PEGIntron and PEGASYS) are exemplar clinically approved drugs for the treatment of hepatitis C [20,21]. Surprisingly, knowing the potential of IFN γ , PEGylation of IFN γ has not been reported.

In the present study, we synthesized different PEGylated formulations of IFN γ using different sized PEG molecules and evaluated their biological activity *in vitro*. Subsequently, we examined their pharmacokinetics and investigated *in vivo* therapeutic efficacy in a CCl $_4$ -induced acute liver fibrosis model in mice. To our best knowledge, this is the first comprehensive study presenting the pharmacokinetics and efficacy of different PEGylated IFN γ formulations in liver fibrosis.

2. Materials and methods

2.1. Synthesis and characterization of PEGylated IFN γ conjugates

Murine IFN γ (0.32 nmol, 50 μ g/ml dissolved in PBS; Peprtech, London, UK) was reacted with 16 nmol of different sized PEG succinimidyl ester (6.4 μ l of 12.5 mg/ml mPEG-NHS5, 25 mg/ml mPEG-NHS10 and 50 mg/ml mPEG-NHS20 dissolved in PBS). mPEG-NHS of different sizes (5 kDa, 10 kDa and 20 kDa) were purchased from Creative PEG works, Winston Salem, NC. The reaction was performed at 4 $^{\circ}$ C for overnight on a slow vortex. The synthesized products were extensively dialyzed against PBS using suitable dialysis membranes. For purification of IFN γ -PEG5 and IFN γ -PEG10, 10 kDa cut-off low protein binding disodialyzers were used and for purification of IFN γ -PEG20, 25 kDa cut-off low protein binding disodialyzers (Harvard Apparatus, Holliston, Massachusetts) were used. Similar steps were followed with unmodified IFN γ , where 0.32 nmol murine IFN γ (50 μ g/ml dissolved in PBS) was mixed with 6.4 μ l of PBS, incubated overnight and dialyzed against PBS using 10 kDa cut-off disodialyzers. Since the protein concentrations used for the reactions were too low (5 μ g) to detect with quantitative assays, final concentrations were calculated based on the initial amounts added to the reaction mixtures. All the steps were kept similar for free and PEGylated IFN γ and equivalent protein concentrations were used further in *in vitro* and *in vivo* experiments.

The IFN γ conjugates were characterized by SDS-PAGE analysis followed by barium-iodide PEG staining. Briefly, 25 μ l of IFN γ conjugates (equivalent to 250 ng) were subjected to SDS-PAGE (10%) according to standard protocols. After running the gel, PEGylated IFN γ formulations were detected with PEG staining as follows. The gels were rinsed with water, followed by fixation in perchloric acid (0.1 M) for 15 min. The gels were washed again and treated with barium chloride (5%) for 10 min. Subsequently, the color was developed using tritol iodine solution (Sigma, St. Louis, MO). The gels were photographed using G-Box (Syngene, Cambridge, UK). In addition to PEG staining, western blotting was performed where the SDS-PAGE gel was run with 100 ng of protein. The separated proteins were then transferred to PVDF membrane and the membranes were blocked with TBST (20 mM Tris-HCl pH 7.6, 154 mM NaCl, 0.1% Tween 20) containing 5% skimmed milk. The blots were incubated with either rabbit polyclonal IFN γ antibody

(Abcam, Cambridge, UK) for 1 h at room temperature. After three washings with TBST, the blots were incubated with HRP-conjugated goat anti-rabbit antibody (DAKO, Glostrup, Denmark) for 1 h and were developed using western lightning-ECL reagent (Perkin-Elmer, Boston, MA) according to the manufacturer's instructions.

2.2. Cell lines

Mouse NIH3T3 fibroblasts and mouse RAW macrophages were obtained from American type culture collection (ATCC, Rockville, MD). NIH3T3 fibroblasts and RAW macrophages were cultured in Dulbecco's modified Eagle's medium (DMEM, Invitrogen, Carlsbad, CA) supplemented with 10% FBS (Invitrogen) and antibiotics (50 U/ml penicillin plus 50 ng/ml streptomycin). After attaining 80% confluency (3–4 days), cells were passaged and 1×10^6 cells were plated in fresh T75 flask. Mouse NIH3T3 fibroblasts were used from passage 160 to passage 170 and RAW macrophages were used between passage 13 and passage 19.

2.3. *In vitro* experiments

2.3.1. Nitric oxide (NO) release bioassay in mouse RAW macrophages

The bioactivity of IFN γ and IFN γ conjugates was assessed by measuring the accumulation of nitrite NO $_2$, a stable nitric oxide (NO) metabolite produced by RAW macrophages as previously described [22]. Briefly, cells (1×10^5 cells/200 μ l/well) were seeded in 96-well plates and grown overnight at 37 $^{\circ}$ C/5% CO $_2$. Then either medium alone, IFN γ or PEGylated IFN γ conjugates were added at different concentrations (5, 10, 25 and 50 ng/ml diluted from 1 μ g/ml stock solutions) with or without 100 ng/ml lipopolysaccharides (LPS from *E. coli* O55:B5, Cat. no. L-6529, Sigma) prepared from 1 mg/ml stock. After 24 h, the secreted nitrite was measured using Griess reagent (1% sulfanilamide; 0.1% naphthylethylenediamine dihydrochloride; 3% H $_3$ PO $_4$). The absorbance was determined at 550 nm using an ELISA plate reader.

2.3.2. Plasmid transfection assay in NIH3T3 fibroblasts

The signaling pathway of IFN γ and PEGylated IFN γ constructs was determined with a luciferase assay using a luciferase containing cis-reporter plasmid DNA, pGAS-Luc (Stratagene, La Jolla, CA), which contains four direct repeats of the IFN gamma-activating sequence (GAS) upstream of the TATA box and a luciferase gene. pCIS-CK was used as a control plasmid that contains luciferase reporter gene but lacks a GAS enhancer sequence. 1×10^4 cells per well were seeded in 96-well plates, and the plasmid transfection was performed after 24 h using FuGENE-6 Transfection Reagent (Roche Diagnostics, Mannheim, Germany). Cells were treated with 0.17 μ g DNA/0.5 μ l FuGENE-6 complex in 100 μ l of normal medium with 10% FCS for 24 h. Subsequently, cells were washed with serum-free medium and incubated with different concentrations (5, 25, 100, 200 and 500 ng/ml diluted from 1 μ g/ml stock solutions) of IFN γ or PEGylated IFN γ for 6 h. Thereafter, cells were washed with PBS and lysed using 20 μ l of lysis buffer and subsequently 100 μ l of luciferase substrate (Promega, Madison, WI) was added. Luciferase activity was measured by a luminometer (Lumicount; Packard, Meriden, CT) and the luminescence unit values of pGAS-Luc were neutralized by subtracting from that of pCIS-CK values.

2.3.3. Anti-fibrotic effects of PEGylated IFN γ conjugates in NIH3T3 fibroblasts

NIH3T3 cells were seeded in 24-well culture plates (3×10^4 cells per well) or 12-well plates (1×10^5 cells/well) and grown overnight. The cells were then washed twice with PBS and starved for 24 h in serum-free medium. Subsequently, cells were incubated with IFN γ or PEGylated IFN γ (equivalent 1 μ g/ml IFN γ prepared from 25 μ g/ml stock) along with 5 ng/ml of recombinant human transforming growth factor-beta (TGF β , diluted from 1 μ g/ml stock, Roche Diagnostics) for 24 h. Thereafter, cells were fixed and immunostained for collagen type I/III and α -SMA as described below. In addition, cells were lysed with

lysis buffer constituted with β -mercaptoethanol (Stratagene) to perform quantitative PCR analysis for procollagen 1 α 1, α -SMA and GAPDH (house-keeping gene) as described below.

2.4. Pharmacokinetics of radiolabeled IFN γ and PEGylated IFN γ constructs

IFN γ and IFN γ -PEG constructs were radiolabeled with ^{125}I radiolabel using N-bromosuccinimide. Briefly, an equal volume of HCl was added to the sodium salt of ^{125}I for neutralization and then 50 μl Tris/HCl buffer (1 M) was added. Subsequently, N-bromosuccinimide (3.2 nmol) was added to IFN γ and the IFN γ -PEG constructs (0.32 nmol) followed by vortex for 30 s. Labeled compounds were then purified extensively using 7 kDa zeba spin desalting columns (Thermo scientific Rockford, IL) to receive >95% purity. Mice were intravenously injected with tracer doses (5×10^5 cpm equivalent to 150 ng/mice) of ^{125}I -IFN γ , ^{125}I -IFN γ -PEG5, ^{125}I -IFN γ -PEG10 and ^{125}I -IFN γ -PEG20. At indicated time points after administration (10, 30, 60, 150 and 300 min), the animals were sacrificed and blood samples were collected by heart puncture. The organs were excised, washed in saline and weighed after which the ^{125}I -radioactivity was counted with a γ -counter. Plasma was prepared by centrifugation of blood at 2000 g for 20 min. The total radioactivity per organ was calculated and corrected for blood-derived radioactivity using correction factors. This correction factor was calculated from bio-distribution studies with albumin which remains in the circulation during the time frame of this experiment. Pharmacokinetic (PK) analysis was performed using the Multifit program (Department of Pharmacokinetics, Toxicology and Targeting, University of Groningen, The Netherlands). The plasma concentration curves were fitted from 0 to 300 min with the Marquardt algorithm and the constant relative error variance model (weighting). An iterative two-Stage Bayesian population analysis was applied to obtain the population pharmacokinetic parameters using a separate analysis for different groups. This analysis results in estimates for the mean and standard deviation of each parameter. Initial estimates were obtained from a standard two-stage analysis. It was demonstrated that the final population pharmacokinetic parameters were independent of initial estimates. Moreover, the data were fitted to a one and a two-compartment model. The goodness of fit was then assessed by Akaike Information Criterion (AIC). The goodness of fit was best for the two-compartment model. The pharmacokinetic parameters calculated from the proposed model:

$\text{AUC}_{(0-\infty)}$ area under the curve from zero to infinity

$V_{ss} = V_1 + V_2$ (V_1 and V_2 are the parameters derived from population PK analysis)

CL (total plasma clearance) = $\text{Dose}/\text{AUC}_{(0-\infty)}$

2.5. CCl $_4$ -induced acute liver fibrosis model in mice

Normal male balb/c mice (20–22 g) were obtained from Harlan (Zeist, The Netherlands). The animals were kept in cages and received *ad libitum* normal diet, at a 12 h light and 12 h dark cycle. All experimental protocols for animal studies were approved by the Animal Ethics Committee of the University of Groningen. Acute liver injury was induced in male C57BL/6 mice by a single intra-peritoneal injection of 1 ml/kg CCl $_4$ (1:5 dilution in olive oil) at day one [23,24]. At day 2 and day 3, mice intravenously received IFN γ , IFN γ -PEG5, IFN γ -PEG10, IFN γ -PEG20 (equivalent to 5 μg IFN γ /mouse/day) or PBS alone. At day 4, all mice were sacrificed; blood and different organs were collected for further analysis.

2.6. Immunohistochemistry and immunofluorescence

The cells were fixed with acetone:methanol (1:1), dried and stored until immunostaining. Livers were harvested and transferred to Tissue-Tek OCT embedding medium (Sakura Finetek, Torrance, CA), and snap-

frozen in isopentane chilled in a dry ice. Cryosections (4 μm) were cut using a Leica CM 3050 cryostat (Leica Microsystems, Nussloch, Germany). The sections were allowed to adhere to Superfrost microscopic glass slides (Menzel-Gläser, Braunschweig, Germany), air-dried and fixed with acetone for 10 min. Cells or tissue sections were rehydrated with PBS and incubated with the primary antibody in appropriate dilution (refer to Supplementary Table 1) for 1 h at room

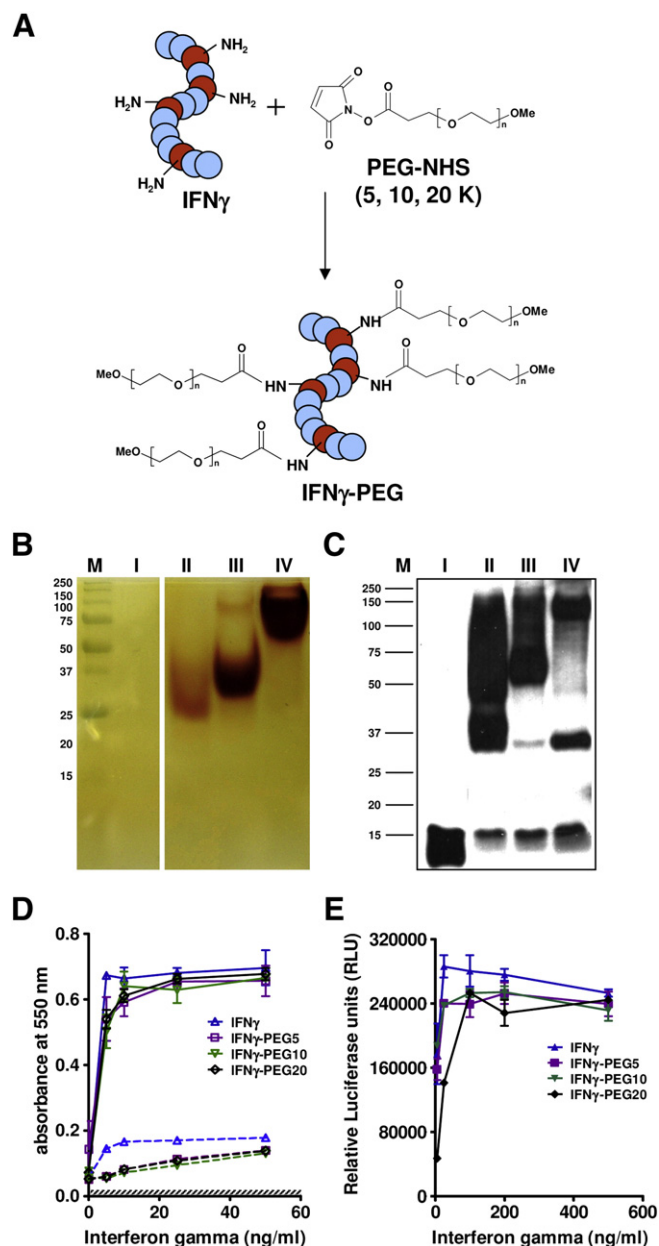


Fig. 1. Synthesis and *in vitro* functional characterization of PEGylated IFN γ . (A) Schematic synthesis of PEGylated IFN γ . (B) PEG staining illustrates the successful synthesis of PEGylated IFN γ conjugates. M denotes molecular weight markers in kDa; Lane I: unmodified IFN γ , Lane II: IFN γ -PEG5 conjugate; Lane III: IFN γ -PEG10 conjugate; Lane IV: IFN γ -PEG20 conjugate. The shift in the bands indicates successful PEG coupling of approx. 2–3 PEG moieties per IFN γ molecule. (C) Western blot analysis using anti-IFN γ antibody showing formation of PEGylated IFN γ adducts and presence of $\leq 10\%$ free IFN γ . M denotes molecular weight markers in kDa; Lane I: unmodified IFN γ , Lane II: IFN γ -PEG5 conjugate; Lane III: IFN γ -PEG10 conjugate; Lane IV: IFN γ -PEG20 conjugate. (D) Nitrogen oxide (NO x) release in mouse RAW macrophages ($n = 3$) after incubation with unmodified IFN γ and IFN γ -conjugates in absence of LPS (denoted by open symbols) and presence of LPS (denoted by closed symbols). Shaded area denotes response to LPS alone without IFN γ . (E) Relative luciferase expression measured to assess the signaling pathway of IFN γ and PEGylated IFN γ constructs using a luciferase containing cis-reporter plasmid DNA, pGAS-Luc. Data represent three independent experiments performed in triplicates.

temperature. Cells or sections were incubated with horseradish peroxidase (HRP)-conjugated secondary antibody for 30 min at room temperature. Then, cells or sections were washed with $1\times$ PBS for 15 min (5 min each). Following incubation with HRP-conjugated tertiary antibody for 30 min after which cells or sections were washed thrice with $1\times$ PBS. Thereafter, peroxidase activity was developed with 3-amino-9-ethyl carbazole (Sigma, St. Louis, MO) for 20 min and nuclei were counterstained with hematoxylin (Fluka Chemie, Buchs, Switzerland). Cells or sections were mounted with Kaiser's gelatin (Darmstadt, Germany) and visualized using a light microscope (Olympus UK Ltd., Essex, UK). α -SMA staining was performed using M.O.M kit (vector laboratories, Burlingame, CA) according to the manufacturer's instructions. For quantitation, 27 microscopic fields at $200\times$ magnification per liver section from each mouse were captured. The stained area in the digital photomicrographs was quantified using automated Cell-D imaging software (Olympus) according to standard procedures.

2.7. Quantitative real time PCR

Total RNA from cells and liver tissues was isolated using absolutely RNA microprep kit (Stratagene) and RNeasy mini kit respectively

(Qiagen, Hilden, Germany) according to manufacturer's instructions. The RNA concentration was quantitated by a UV spectrophotometer (NanoDrop Technologies, Wilmington, DE). Total RNA ($1.6\ \mu\text{g}$) was reverse transcribed in a volume of $50\ \mu\text{l}$ using cDNA synthesis kit (Promega). All the primers were purchased from Sigma-Genosys (Haverhill, UK). The sequences of primers used in the study are enlisted in Supplementary Table 2. 20 ng of cDNA was used for quantitative real time PCR analysis. The reactions were performed using SYBR green PCR master mix (Applied Biosystems) according to the manufacturer's instructions and were analyzed by ABI7900HT sequence detection system (Applied Biosystems). Finally, the threshold cycles (Ct) were calculated and relative gene expression was normalized with GAPDH (for mouse) and 18srRNA (for human) as house-keeping genes.

2.8. Statistical analyses

Data are presented as mean \pm standard error of the mean (SEM). Multiple comparisons between different groups were performed by one-way analysis of variance (ANOVA) with Bonferroni post-test.

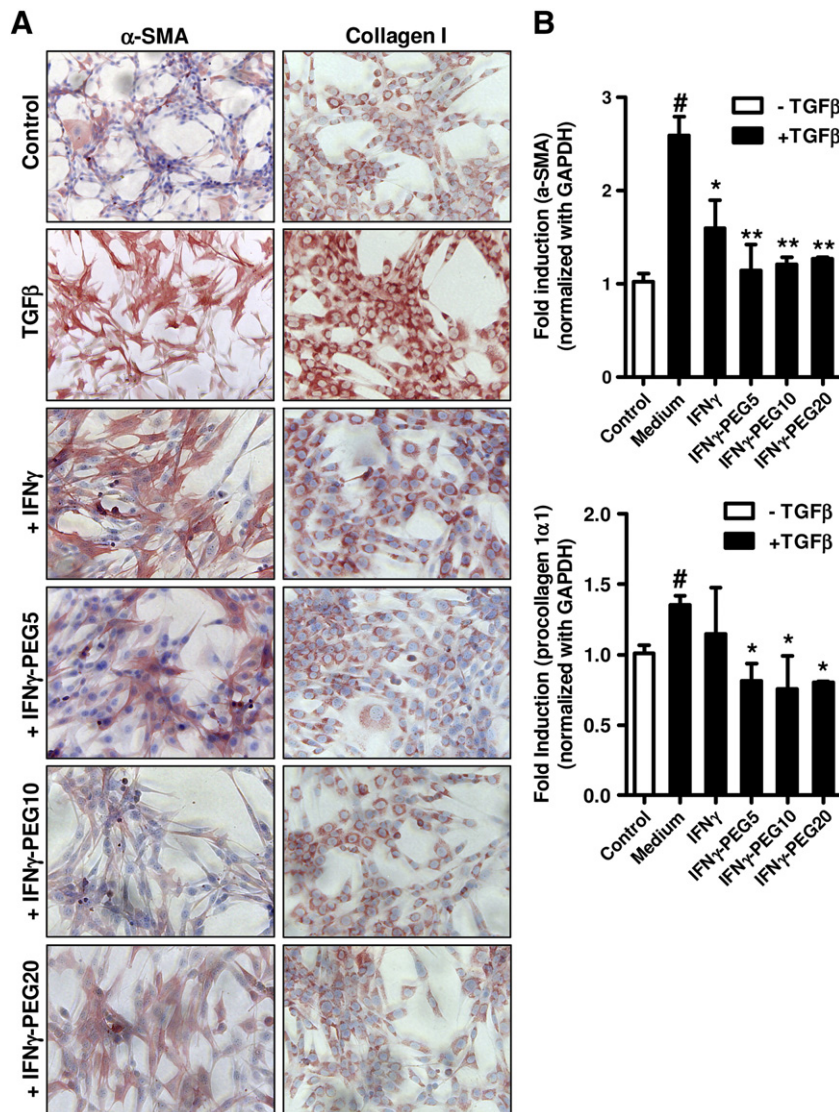


Fig. 2. Reduction of fibrotic parameters with PEGylated IFN γ constructs in NIH3T3 fibroblasts. (A) Representative pictures ($n = 3$) of collagen I/III stained NIH3T3 cells, incubated with medium alone (control) or TGF β (5 ng/ml) in combination with IFN γ or IFN γ conjugates (1 $\mu\text{g/ml}$). (B) Effects of different constructs on the gene expression of procollagen 1 α 1 and α -SMA. Data represent the mean \pm SEM for three independent experiments.

3. Results

3.1. Syntheses and characterization of PEGylated IFN γ conjugates

IFN γ was directly conjugated to different sized polyethylene glycol molecules (PEG 5, 10, 20 kDa) as depicted in a schematic representation in Fig. 1A. The successful PEGylation of IFN γ was confirmed by SDS-PAGE analysis followed by barium-iodide staining for PEG molecules and western blot analysis using anti-IFN γ antibody. Fig. 1B and C show the shift in protein bands after PEGylation. The shifts indicated the successful coupling of PEG molecules to IFN γ molecule as determined with molecular weight ladder. Western blot analysis showed formation of multiple PEGylated adducts of IFN γ during the conjugation reactions and indicated the presence of $\leq 10\%$ unconjugated free IFN γ (Fig. 1C, Supplementary Table 3).

3.2. In vitro biological effects of PEGylated IFN γ conjugates

Since chemical modification can affect the biological activity of IFN γ , we examined the bioactivity of PEGylated IFN γ conjugates versus unmodified IFN γ in mouse RAW macrophages using a standard nitric oxide (NO) release assay. IFN γ and PEGylated IFN γ constructs caused a dose-dependent increase in NO production in the absence and presence of LPS (Fig. 1D). PEGylated IFN γ constructs induced a reduction in NO production as compared to free IFN γ in absence of LPS while there was no significant difference in the dose response curves of PEGylated IFN γ constructs compared to unmodified IFN γ in presence of LPS (Fig. 1D). PEGylation might also hinder the interaction of IFN γ with its receptor thereby influencing the IFN γ signaling pathway. IFN γ –IFN γ R interaction results in the activation of the JAK–STAT pathway and activates signal transducers and activators of transcription (STAT1) that binds to unique gamma-activated sequence (GAS) regulating IFN γ -responsive genes [25,26].

We examined the signaling pathway induced by IFN γ -PEG constructs and unmodified IFN γ in mouse NIH3T3 fibroblasts using the pGAS-Luc cis-reporter plasmid assay where the luciferase gene is downstream of the GAS enhancer sequence. A dose-dependent increase in luciferase expression (luminescence) by both IFN γ and IFN γ -PEG constructs indicated that there were no significant differences between IFN γ and IFN γ -PEG constructs (Fig. 1E).

Subsequently, we investigated the anti-fibrotic effects of the PEGylated constructs in mouse NIH3T3 fibroblasts after activation with TGF β 1. We found that TGF β 1-induced fibroblast activation (α -SMA expression) and collagen expression were significantly inhibited by IFN γ and more strongly with IFN γ -PEG constructs both at protein and mRNA transcript levels (Fig. 2A and B).

3.3. Induction of IFN γ receptor expression during liver fibrosis

We compared the IFN γ receptor expression levels in fibrotic human and mouse livers versus normal livers using immunohistochemistry and mRNA analyses. PAS staining showed the liver damage in humans and mice (Fig. 3A and C). Both protein and mRNA analyses revealed that IFN γ R was significantly up-regulated in cirrhotic human livers and in acute CCl $_4$ -induced fibrotic mouse livers (Fig. 3A–D).

3.4. Pharmacokinetics of PEGylated IFN γ constructs in vivo

Since IFN γ R was highly up-regulated during liver injury, we first compared the bio-distribution of 125 I-IFN γ in normal versus fibrotic mice to determine if the high receptor expression enhances its liver uptake. We found that the plasma disappearance of 125 I-IFN γ was similar in both cases (Supplementary Fig. 1A). However, the liver levels were significantly increased in fibrotic livers ($AUC_{(0-\infty)}$, 64% $\text{dose}\cdot\text{h}$) compared to normal livers ($AUC_{(0-\infty)}$, 39.2% $\text{dose}\cdot\text{h}$) (Supplementary Fig. 1B). These data indicate that accumulation of IFN γ is dependent on

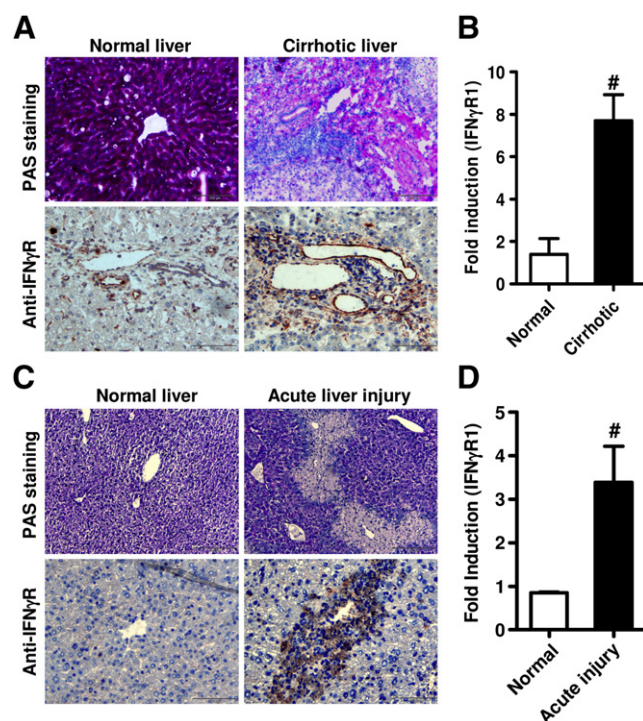


Fig. 3. IFN γ receptor expression in fibrotic versus normal livers in human (A, B) and mice (C, D). Representative photomicrographs illustrating PAS staining and IFN γ R expression in cirrhotic human livers (A) and in CCl $_4$ -induced fibrotic mouse livers (C) versus respective normal livers. Scale bars; 100 μm . IFN γ R mRNA levels in cirrhotic human livers, $n = 3$ (B) and in CCl $_4$ -induced fibrotic mouse livers, $n = 6$ (D) were higher compared to the normal livers. Bars represent mean \pm SEM. Differences versus normal are presented as $\#P < 0.05$.

the expression of IFN γ R and therefore longer circulation of IFN γ might increase liver accumulation leading to improved efficacy in fibrotic mice.

Next, we examined the pharmacokinetics of 125 I-labeled IFN γ and PEGylated IFN γ in the acute CCl $_4$ -induced liver injury model in mice. Fig. 4A shows the plasma levels of radiolabeled IFN γ and PEGylated IFN γ constructs at various time points after a single intravenous injection in fibrotic mice. The pharmacokinetic parameters derived from plasma disappearance curves are shown in Table 1. The plasma levels were significantly increased at different time points with increasing size of PEG. The liver levels of IFN γ -PEG5 and IFN γ -PEG10 were higher after intravenous injection while administration of IFN γ -PEG20 had comparatively lower levels. This was further confirmed by calculating AUC reflecting total liver uptake (Fig. 4B and Table 2). Conversely, kidney levels gradually decreased with increasing PEGylation of IFN γ (Fig. 4C and Table 2).

We also assessed major histocompatibility class II (MHC-II) expression, which is known to be up-regulated by IFN γ [27], to assess the biological activity of the conjugates in livers. PEGylated IFN γ with increasing PEG size induced a remarkable up-regulation in MHC-II expression (Fig. 5A–C) within the damaged areas.

3.5. Attenuation of liver fibrosis with PEGylated IFN γ conjugates

IFN γ and different PEGylated IFN γ constructs were subsequently examined for their anti-fibrotic effects in a CCl $_4$ -induced acute liver fibrosis model in mice. After two intravenous injections, PEGylated IFN γ constructs induced a strong inhibition in collagen I expression accompanied by substantial reduction in α -SMA- and desmin-positive hepatic stellate cells (Fig. 6A–C). The reductions of fibrotic parameters observed in stainings were paralleled by reductions in the respective transcript levels as assessed by quantitative rtPCR

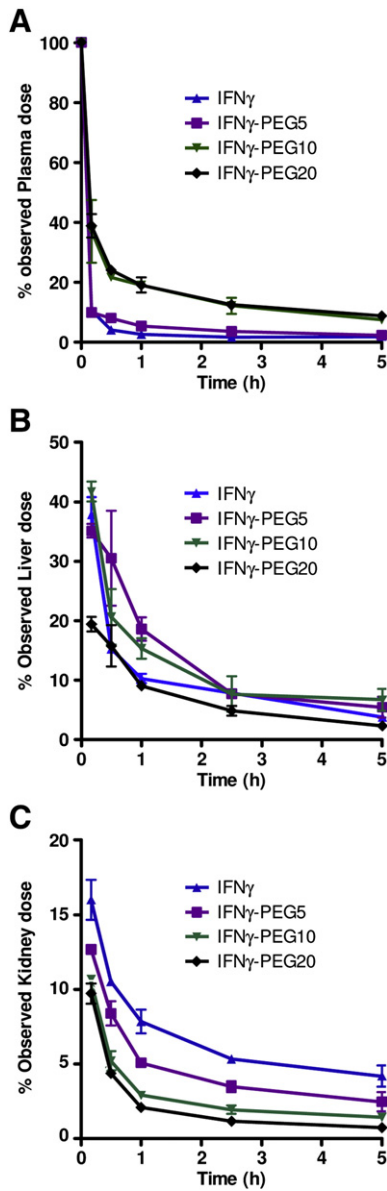


Fig. 4. Pharmacokinetic profile of IFN γ versus PEGylated IFN γ in CCl₄-induced acute liver injury model in mice. (A) Plasma disappearance curves of IFN γ and PEGylated IFN γ in fibrotic mice. (B) Liver and (C) kidney accumulation at different time points after administration of radiolabeled (¹²⁵I)-IFN γ or (¹²⁵I)-PEGylated IFN γ in fibrotic mice. n = 10 mice were used per treatment group and each time point represents the mean of two animals.

(Fig. 7). The anti-fibrotic effects with IFN γ -PEG were significantly enhanced with increasing PEG size. In contrast, treatment with IFN γ did not induce a significant reduction of any of these parameters which is most likely due to the short half-life of IFN γ .

Table 1

Pharmacokinetics parameters (two-compartment model) derived from concentration–time curves after a single intravenous dose of IFN γ and PEGylated IFN γ in fibrotic mice.

Plasma	AUC (h * %dose)	Vss (ml)	CL (ml/h)
IFN γ	27.1	18.4	3.69
IFN γ -PEG5	33.0	10.13	3.03
IFN γ -PEG10	105	3.73	0.95
IFN γ -PEG20	121	3.71	0.83

AUC_(0–∞), area under the curve from zero to infinity; Vss, steady state volume of distribution; CL, Total plasma clearance.

Table 2

Liver and kidneys AUC derived from concentration–time curves after a single intravenous dose of IFN γ and PEGylated IFN γ in fibrotic mice.

	Liver AUC _(0–∞) (h * %dose)	Kidney AUC _(0–∞) (h * %dose)
IFN γ	64.1	49.8
IFN γ -PEG5	78.2	30.7
IFN γ -PEG10	78.5	18.3
IFN γ -PEG20	40.2	12.0

AUC_(0–∞), area under the curve from zero to infinity.

4. Discussion

IFN γ is a pro-inflammatory cytokine and has been studied pre-clinically for the treatment of immunological, viral and cancer diseases due to its pleiotropic activities [28]. It has also been explored as a potential treatment for renal, idiopathic and liver fibrosis [13,29,30]. Despite the various therapeutic effects of IFN γ , its clinical use is limited to only a few diseases, due to rapid clearance from the body. Some attempts have been made to prolong the half-life or to enhance activity of IFN γ by incorporating it into hydrogels, nanoparticles, liposomes, microspheres and elastomers [31,32], but none of them have reached to clinic. PEGylation of IFN α (PEGASYS and PEGIntron) has been clinically successful but this approach has strikingly not been applied for IFN γ .

In the present study, we PEGylated IFN γ with different sized linear PEG chains of 5 kDa, 10 kDa and 20 kDa to find optimum PEGylation combined with unhindered receptor interaction. Following synthesis of PEGylated IFN γ constructs, we first evaluated their bio-distribution profiles and effects *in vitro*. Chemical modification can lead to reduced activity of IFN γ as reported by other studies [33,34], caused by a change in conformation or steric hindrance

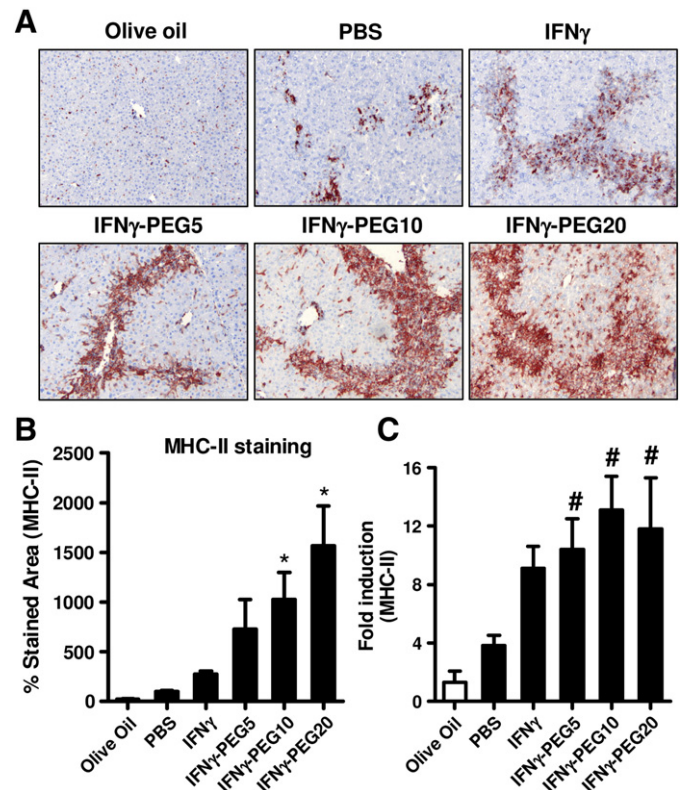


Fig. 5. Increased MHC-II expression with PEGylated IFN γ constructs *in vivo*. Representative photomicrographs (A) and quantitative analysis (B) and gene expression analysis (C) of MHC-II in liver samples. Animals were treated with either olive oil (treated with PBS as control) or CCl₄ plus PBS, IFN γ or different PEGylated IFN γ constructs. Scale bars; 100 μ m.

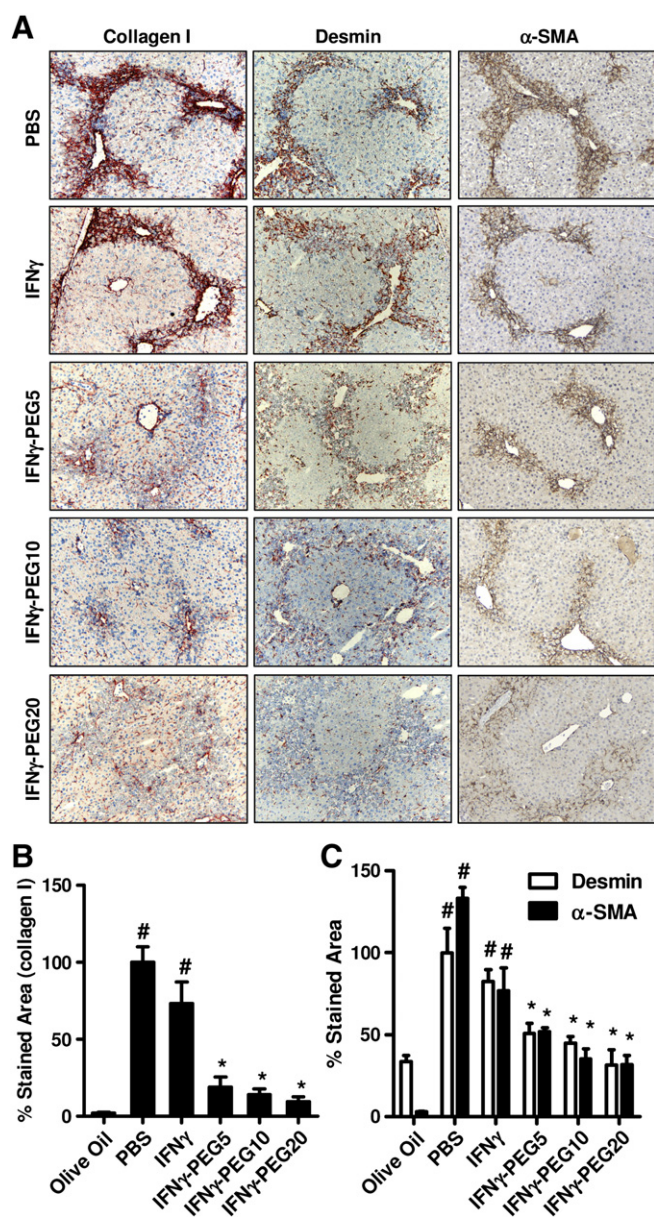


Fig. 6. Reduction in fibrotic parameters induced by PEGylated IFN γ *in vivo*. Representative photomicrographs (A) and quantitative analysis of collagen I (B), α SMA and desmin (C) positive liver sections from olive oil (CCl $_4$ vehicle as a control) and fibrotic animals treated with PBS, IFN γ and different PEGylated IFN γ constructs. Scale bars; 100 μ m. Bars represent mean \pm SEM of 4 mice per group. #P<0.05 versus olive oil and *P<0.05 versus PBS treated-CCl $_4$ mice.

influencing receptor binding. Though PEGylated constructs showed a reduced biological activity compared to IFN γ in the absence of LPS but did not show significant differences in their biological activities in presence of LPS. In addition, PEGylated IFN γ induced IFN γ R signaling similar to native IFN γ as demonstrated with a reporter plasmid assay. Furthermore, these constructs showed even stronger effects than unmodified IFN γ *in vitro* by inhibiting fibroblasts activation and collagen production in these cells. This increased effectivity *in vitro* indicates increased stability of IFN γ in biological environments due to the PEGylation.

We observed high up-regulation of IFN γ receptor expression during liver fibrosis (both in mice and human) and then we explored the uptake of radiolabeled IFN γ in fibrotic livers. We found a significant increase of IFN γ uptake in fibrotic livers compared to normal livers, but the plasma disappearance rate of IFN γ was still quite

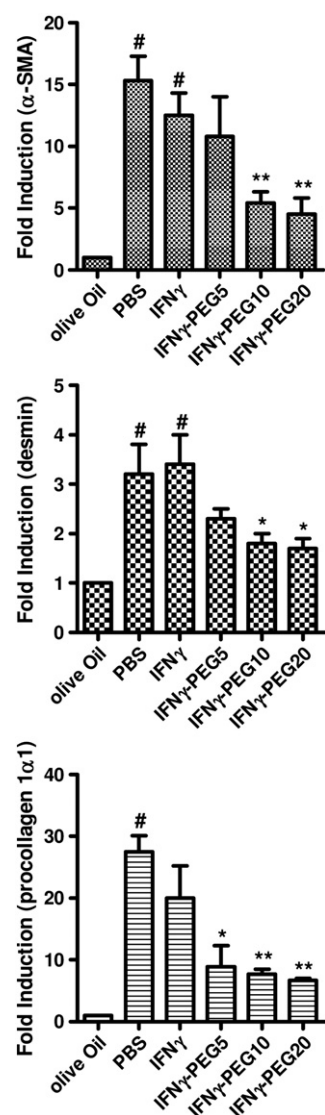


Fig. 7. Reduction in mRNA expression levels of crucial fibrotic parameters (α -SMA, desmin and procollagen 1 α 1) induced by PEGylated IFN γ *in vivo*. Effects of different constructs on the gene expression of crucial fibrotic parameters: α -SMA, desmin and procollagen 1 α 1 in CCl $_4$ -induced liver fibrosis in mice. Animals were treated with either olive oil (CCl $_4$ vehicle as a control) or CCl $_4$ plus PBS, IFN γ or different PEGylated-IFN γ constructs. Bars represent mean \pm SEM of 4 mice per group. #P<0.05 versus olive oil and *P<0.05, **P<0.01 versus PBS treated-CCl $_4$ mice.

high. Therefore, we assumed that longer circulation of IFN γ due to PEGylation might result in even higher liver accumulation and thereby enhanced anti-fibrotic effects. We therefore explored the effects of PEGylation of IFN γ in CCl $_4$ -induced acute liver fibrosis model in mice.

Using radioactive studies, we demonstrated that PEGylated IFN γ constructs had a better pharmacokinetic profile compared to IFN γ *in vivo*. PEGylation of IFN γ increased the plasma circulation time, enhanced liver levels and reduced renal accumulation of IFN γ constructs compared to free IFN γ . Only IFN γ -PEG20 displayed lower liver accumulation which, most likely, is due to its larger size that caused its longer circulation and less accumulation into the collagen-rich fibrotic liver. In addition, PEGylated IFN γ constructs induced the up-regulation of MHC-II expression, a well-known activity of IFN γ [27]. The increase in MHC-II expression was consistent with increased size of PEGylation of IFN γ , while unmodified IFN γ induced moderate MHC-II expression, most likely due to rapid renal clearance.

Since PEGylation significantly improved the pharmacokinetics of IFN γ , we furthermore investigated PEGylated constructs for their

therapeutic effectivity. All the IFN γ -PEG constructs induced significantly stronger anti-fibrotic effects *in vivo* compared to IFN γ at the similar doses in the acute CCl $_4$ -induced liver injury model in mice. The reduction of extracellular matrix deposition was accompanied with reduced activation and proliferation of hepatic stellate cells, a key pathogenic cell involved in the progression of liver fibrosis. While native IFN γ had only some effects, PEGylation of IFN γ led to the profound reductions in all the fibrotic parameters examined. The increased efficacy was already significant with IFN γ -PEG5 but was further potentiated with increased PEG size.

In the present study, the pharmacokinetic profile, *in vitro* and *in vivo* efficacies of the PEGylated IFN γ were critically evaluated. We have clearly demonstrated that PEGylation of IFN γ significantly improved its pharmacokinetic profile and therapeutic effectivity. Since the use of this potent cytokine for therapeutic purposes offers great opportunities, therefore further studies are warranted to explore further modifications of IFN γ . These long-circulating IFN γ constructs with a concomitant enhancement of the anti-fibrotic activity represent a step forward towards an effective anti-fibrotic therapy.

Acknowledgments

C. Reker-Smit and M. de Ruiter are kindly acknowledged for their technical assistance. This work was supported by VICI grant-in-aid from Netherlands Organization for Scientific Research (NWO) and the Dutch Technical foundation (STW) and the Innovative Action Grant (IAG2) from Province of Groningen.

Appendix A. Supplementary data

Supplementary data to this article can be found online at [doi:10.1016/j.jconrel.2011.05.027](https://doi.org/10.1016/j.jconrel.2011.05.027).

Reference

- [1] R. Bataller, D.A. Brenner, Liver fibrosis, *J. Clin. Invest.* 115 (2005) 209–218.
- [2] D. Schuppan, N.H. Afdhal, Liver cirrhosis, *Lancet* 371 (2008) 838–851.
- [3] S.L. Friedman, Stellate cells: a moving target in hepatic fibrogenesis, *Hepatology* 40 (2004) 1041–1043.
- [4] S.L. Friedman, Hepatic stellate cells: protean, multifunctional, and enigmatic cells of the liver, *Physiol. Rev.* 88 (2008) 125–172.
- [5] O.A. Gressner, R. Weiskirchen, A.M. Gressner, Evolving concepts of liver fibrogenesis provide new diagnostic and therapeutic options, *Comp. Hepatol.* 6 (2007) 7.
- [6] D.C. Rockey, Current and future anti-fibrotic therapies for chronic liver disease, *Clin. Liver Dis.* 12 (2008) 939–962 xi.
- [7] E.M. Bonnem, R.K. Oldham, Gamma-interferon: physiology and speculation on its role in medicine, *J. Biol. Response Mod.* 6 (1987) 275–301.
- [8] C.H. Miller, S.G. Maher, H.A. Young, Clinical use of interferon-gamma, *Ann. N. Y. Acad. Sci.* 1182 (2009) 69–79.
- [9] K. Schroder, P.J. Hertzog, T. Ravasi, D.A. Hume, Interferon-gamma: an overview of signals, mechanisms and functions, *J. Leukoc. Biol.* 75 (2004) 163–189.
- [10] P.J. Pockros, L. Jeffers, N. Afdhal, Z.D. Goodman, D. Nelson, R.G. Gish, K.R. Reddy, R. Reindollar, M. Rodriguez-Torres, S. Sullivan, L.M. Blatt, S. Faris-Young, Final results of a double-blind, placebo-controlled trial of the antifibrotic efficacy of interferon-gamma1b in chronic hepatitis C patients with advanced fibrosis or cirrhosis, *Hepatology* 45 (2007) 569–578.
- [11] I. Rutenfranz, H. Kirchner, Pharmacokinetics of recombinant murine interferon-gamma in mice, *J. Interferon Res.* 8 (1988) 573–580.
- [12] H.M. Younes, B.G. Amsden, Interferon-gamma therapy: evaluation of routes of administration and delivery systems, *J. Pharm. Sci.* 91 (2002) 2–17.
- [13] G.S. Baroni, L. D'Ambrosio, P. Curto, A. Casini, R. Mancini, A.M. Jezequel, A. Benedetti, Interferon gamma decreases hepatic stellate cell activation and extracellular matrix deposition in rat liver fibrosis, *Hepatology* 23 (1996) 1189–1199.
- [14] W.I. Jeong, O. Park, S. Radaeva, B. Gao, STAT1 inhibits liver fibrosis in mice by inhibiting stellate cell proliferation and stimulating NK cell cytotoxicity, *Hepatology* 44 (2006) 1441–1451.
- [15] M. Hamidi, A. Zarrin, M. Foroozesh, Novel delivery systems for interferons, *Crit. Rev. Biotechnol.* 27 (2007) 111–127.
- [16] G.E. Francis, D. Fisher, C. Delgado, F. Malik, A. Gardiner, D. Neale, PEGylation of cytokines and other therapeutic proteins and peptides: the importance of biological optimisation of coupling techniques, *Int. J. Hematol.* 68 (1998) 1–18.
- [17] S. Jevsevar, M. Kunstelj, V.G. Porekar, PEGylation of therapeutic proteins, *Biotechnol. J.* 5 (2010) 113–128.
- [18] J.S. Kang, P.P. Deluca, K.C. Lee, Emerging PEGylated drugs, *Expert Opin. Emerg. Drugs* 14 (2009) 363–380.
- [19] F.M. Veronese, G. Pasut, PEGylation, successful approach to drug delivery, *Drug Discov. Today* 10 (2005) 1451–1458.
- [20] T. Poynard, J. McHutchison, M. Manns, C. Trepo, K. Lindsay, Z. Goodman, M.H. Ling, J. Albrecht, Impact of pegylated interferon alfa-2b and ribavirin on liver fibrosis in patients with chronic hepatitis C, *Gastroenterology* 122 (2002) 1303–1313.
- [21] C. Camma, B.D. Di, F. Schepis, E.J. Heathcote, S. Zeuzem, P.J. Pockros, P. Marcellin, L. Balart, A. Alberti, A. Craxi, Effect of peginterferon alfa-2a on liver histology in chronic hepatitis C: a meta-analysis of individual patient data, *Hepatology* 39 (2004) 333–342.
- [22] Y.M. Kim, K. Son, A nitric oxide production bioassay for interferon-gamma, *J. Immunol. Meth.* 198 (1996) 203–209.
- [23] M.M. van Beuge, J. Prakash, M. Lacombe, E. Post, C. Reker-Smit, L. Beljaars, K. Poelstra, increased liver uptake and reduced hepatic stellate cell activation with a cell-specific conjugate of the rho-kinase inhibitor Y27632, *Pharm. Res.* (2011).
- [24] J. Wu, P.A. Norton, Animal models of liver fibrosis, *Scand. J. Gastroenterol.* 31 (1996) 1137–1143.
- [25] A.H. van Boxel-Dezaire, G.R. Stark, Cell type-specific signaling in response to interferon-gamma, *Curr. Top. Microbiol. Immunol.* 316 (119–54) (2007) 119–154.
- [26] C.M. Horvath, The Jak–STAT pathway stimulated by interferon gamma, *Sci. STKE* 2004 (2004) tr8.
- [27] A. Muhlethaler-Mottet, B.W. Di, L.A. Otten, B. Mach, Activation of the MHC class II transactivator CIITA by interferon-gamma requires cooperative interaction between Stat1 and USF-1, *Immunity* 8 (1998) 157–166.
- [28] M.A. Farrar, R.D. Schreiber, The molecular cell biology of interferon-gamma and its receptor, *Annu. Rev. Immunol.* 11 (1993) 571–611.
- [29] D. Bouros, K.M. Antoniou, A. Tzouveleki, N.M. Sifakas, Interferon-gamma 1b for the treatment of idiopathic pulmonary fibrosis, *Expert. Opin. Biol. Ther.* 6 (2006) 1051–1060.
- [30] S.D. Oldroyd, G.L. Thomas, G. Gabbiani, A.M. El Nahas, Interferon-gamma inhibits experimental renal fibrosis, *Kidney Int.* 56 (1999) 2116–2127.
- [31] J.L. Cleland, A.J. Jones, Stable formulations of recombinant human growth hormone and interferon-gamma for microencapsulation in biodegradable microspheres, *Pharm. Res.* 13 (1996) 1464–1475.
- [32] F. Gu, H.M. Younes, A.O. El-Kadi, R.J. Neufeld, B.G. Amsden, Sustained interferon-gamma delivery from a photocrosslinked biodegradable elastomer, *J. Control. Release* 102 (2005) 607–617.
- [33] B.M. Brooks, B.F. Flanagan, A.L. Thomas, J.W. Coleman, Penicillin conjugates to interferon-gamma and reduces its activity: a novel drug-cytokine interaction, *Biochem. Biophys. Res. Commun.* 288 (2001) 1175–1181.
- [34] B.M. Brooks, A.L. Thomas, J.W. Coleman, Benzylpenicillin differentially conjugates to IFN-gamma, TNF-alpha, IL-1beta, IL-4 and IL-13 but selectively reduces IFN-gamma activity, *Clin. Exp. Immunol.* 131 (2003) 268–274.