Comparative evaluation of bolus and fractionated administration modalities for two antibody-cytokine fusions in immunocompetent tumor-bearing mice

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Abstract

Antibody-cytokine fusion proteins are being considered as biopharmaceuticals for cancer immunotherapy. Tumor-homing cytokine fusions typically display an improved therapeutic activity compared to the corresponding unmodified cytokine products, but toxicity profiles at equivalent doses are similar, since side effects are mainly driven by the cytokine concentration in blood. In order to explore avenues to harness the therapeutic potential of antibody-cytokine fusions while decreasing potential toxicity, we compared bolus and fractionated administration modalities for two tumor-targeting antibody-cytokine fusion proteins based on interleukin-2 (IL2) and tumor necrosis factor (TNF) (i.e., L19-IL2 and L19-TNF) in two murine immunocompetent mouse models of cancer (F9 and C51). A comparative quantitative biodistribution analysis with radio-labeled protein preparations revealed that a fractionated administration of L19-IL2 could deliver comparable product doses to the tumor with decreased product concentration in blood and normal organs, compared to bolus injection. By contrast, L19-TNF (a product that causes a selective vascular shutdown in the tumor) accumulated most efficiently after bolus injection. Fractionated schedules allowed the safe administration of a cumulative dose of L19-TNF, which was 2.5-times higher than the lethal dose for bolus injection. Dose fractionation led to a prolonged tumor growth inhibition for F9 teratocarcinomas, but not for C51 colorectal tumors, which responded best to bolus injection. Thus, dose fractionation may have different outcomes for the same antibody-cytokine product in different biological contexts.

Introduction

The successful treatment of a growing number of tumor types with immune checkpoint inhibitors [1–9] has stimulated the interest in the exploration of alternative and complementary approaches for the selective boosting of T cell and NK cell activity against cancer. For many years, pro-inflammatory cytokines have been considered as a promising class of biopharmaceuticals for immunotherapy applications, but the practical applicability of cytokine therapies has been limited by severe toxicity at low doses, preventing escalation to therapeutically active regimens [10,11]. In spite of these limitations, some products have gained marketing authorization and have provided a therapeutic benefit for a small proportion of patients. Recombinant IL2 (aldesleukin, Proleukin®) obtained marketing authorization for the treatment of metastatic melanoma and for renal cell carcinoma [12]. Treatment with aldesleukin induced a prolonged overall survival only in a relatively small proportion of cancer patients, however substantial toxicities (e.g. vascular leak syndrome, nausea and fever) are frequently observed [13–15]. Recombinant TNF (Beromun®) has been approved for the treatment of soft-tissue sarcoma patients only for isolated limb perfusion procedures [16–19], whereas recombinant interferons have received marketing authorization for the treatment of various types of malignancies [20,21].

A number of strategies have been considered for the increase of the therapeutic index of pro-inflammatory cytokine payloads, including modification with cleavable polymers (*de facto* generating pro-drugs which regain activity upon hydrolytic loss of the polymer chains) [22] and antibody-cytokine fusions [23,24]. We and others have previously shown that antibody-cytokine fusions, capable of selective localization at the tumor site, can substantially increase therapeutic activity compared to the non-modified cytokine counterparts, when administered at equimolar doses [25–27]. L19-IL2 and L19-TNF are two products, which target the alternatively-spliced EDB domain of fibronectin (a marker of tumor angiogenesis) and which are currently being investigated in Phase III clinical trials for the treatment of Stage III B,C melanoma (EudraCT number: 2015-002549-72 and NCT03567889) and of metastatic soft-tissue sarcoma (EudraCT number: 2016-003239-38 and NCT03420014) [28–33].

While antibody-cytokine fusions can increase the therapeutic index of their payload, toxicities at equimolar doses are often comparable. This feature, which may initially appear

as paradoxical, is easy to understand considering the fact that only a small amount of product (in absolute terms) reaches the tumor mass (approximately 5-20 percent injected dose per gram in mice and 0.01-0.1 percent injected dose per gram in patient) [34,35]. Exposure of blood and normal organs to pro-inflammatory cytokines may cause hypotension, flu-like symptoms, nausea and vomiting [13–21]. Intense research activities are devoted to the search for methods which preserve the therapeutic activity of engineered cytokine products, while decreasing systemic toxicity [24]. Experimental strategies may include the allosteric activation of cytokine activity upon antigen binding [36], the design of split-cytokine fusions [37], the generation of dual-cytokine fusions [38–44], the selective depotentiation of cytokines by mutagenesis [39,45–47] and the use of masking antibodies to cover portions of the cytokine surface [48].

The toxicity of cytokine therapeutics is often manifested only at concentrations above a certain critical threshold and follows a non-linear profile [22]. It has been argued that a transient inhibition of cytokine activity at early time points after intravenous administration may represent a viable strategy for the generation of better tolerated products [24]. Here, we describe an experimental approach for the administration of high doses of antibody-cytokine fusion proteins, which would be lethal upon bolus injection. We reasoned that a fractionated administration in mice (or a slow infusion in patients) rather than a bolus injection should deliver comparable amounts of cytokine activity to the tumor site and keep blood concentrations below a critical threshold. We used L19-IL2 [26] and L19-TNF (featuring a murine cytokine moiety) [25] since these two products act by different mechanisms of action and since their full-human counterparts are being investigated in pivotal clinical trials. Quantitative biodistribution studies with radio-iodinated protein preparations and therapy experiments in tumor-bearing mice provided insights on the usefulness of administering fractionated product doses.

Materials and Methods

Tumor cell lines and reagents

All cell lines were obtained from the ATCC with the exception of C51 colon carcinoma (kindly provided by M.P. Colombo, Istituto Nazionale Tumori, Milan, Italy). Cell lines were received between 2015 and 2017, expanded, and stored as cryopreserved aliquots in liquid nitrogen. Cells were grown according the supplier's protocol and kept in culture for no longer than 14 passages. Authentication of the cell lines also including check of postfreeze viability, growth properties, and morphology, test for mycoplasma contamination, isoenzyme assay, and sterility test were performed by the cell bank before shipment.

The clinical stage L19-IL2 was kindly provided by Philogen S.p.A (Siena, Italy). The production and purification of the murine surrogate L19-TNF was performed as described before [25].

Biochemical characterization

Purified proteins were analyzed by size-exclusion chromatography on a Superdex 200 increase 10/300 GL column on an ÄKTA FPLC (GE Healthcare, Amersham Biosciences). SDS-PAGE was performed with 10% gels (Invitrogen) under reducing and non-reducing conditions.

Immunofluorescence studies

Antigen expression was confirmed on ice-cold acetone fixed 8 µm cryostat sections of C51 and F9 tumors stained with IgG (L19)-FITC (final concentration 2 µg/mL) and detected with a Rabbit anti-FITC (Bio-Rad; 4510-7804) and Donkey anti-Rabbit AlexaFluor 488 (Invitrogen; A11008). For vascular staining Goat anti-CD31 (R&D System; AF3628) and Donkey anti-Goat AlexaFluor 594 (Invitrogen + A21209) antibodies were used. Slides were mounted with fluorescent mounting medium and analysed with fluorescent mounting medium (Dako Agilent).

Animal and tumor models

Six to eight-week-old female BALB/c mice and 129/SvEv mice were obtained from Janvier Labs. Tumor cells were implanted subcutaneously in the flank using $1.5x10^7$ cells (F9), $1x10^6$ cells (C51). Experiments were performed under a project license (license number 04/2018)

granted by the Veterinaramt des Kantons Zurich, Switzerland, in compliance with the Swiss Animal Protection Act (TSchG) and the Swiss Animal Protection Ordinance (TSchV).

Biodistribution studies

The capability of targeting EDB *in vivo* was assessed by quantitative biodistribution analysis. Purified protein samples (50-100 µg) were radio-iodinated with ^{125}I and Chloramine T hydrate and purified on a PD10 column. Radio-labeled proteins were injected into the lateral tail vein of 129SvEv mice bearing subcutaneously implanted F9 lesions. Injected dose per mouse varied between 4 and 10 μg. For the bolus treatment group mice were sacrificed 24 hours after the bolus injection. For the fractionated treatment group mice were injected every 24 hours and sacrificed 24 hours after the last injection. Organ samples were weighed and radioactivity was counted using a gamma counter. The protein uptake in the different organs was calculated and expressed as the percentage of the injected dose per gram of tissue (%ID/g ± SEM n = 5 mice/group). Data were corrected for tumor growth correction.

Therapy studies

Mice were monitored daily and tumor volume was measured with a caliper (volume = length × width^2 × 0.5). When tumors reached a suitable volume (approx. 70–100 mm^3), mice were injected into the lateral tail vein with the pharmacological agents.

L19-IL2 was administered at 100 µg and 400 µg once. L19-TNF was dissolved in PBS, also used as negative control, and administered either as a single 10 µg bolus injection or as a 5 µg fractionated dose, which was repeated three times every 24 hours for a first experiment in F9 tumor bearing mice. In a second experiment in F9 tumors the single bolus injection was reduced at a dose of 5 µg, whereas the fractionated dose (5 µg) was extended to 5 cycles every 24 hours. In the C51 tumor model L19-TNF was administered either as a single 3 µg bolus injection or as a 1 µg or 1.5 µg fractionated dose, which was repeated three times every 24 hours. Results are expressed as tumor volume in mm^3 ± SEM and % mean body weight change ± SEM. For therapy experiments n = 4-5 mice/group.

Plasma cytokine quantification

F9 tumor bearing mice were injected with either PBS, 3 µg L19-TNF once or 5 µg L19-TNF three times every 24 hours. Mice were sacrificed 24 hours after the last injection and blood was collected in Microtainer^{TM} Tubes with Lithium Heparin (BD 365965). Tubes were

centrifuged for 3 minutes at 2000g at 4°C. Plasma was collected and frozen at -80°C until cytokine level's quantification was performed (Cytolab, Regensdorf, Switzerland).

Results and Discussion

Figure 1A presents a schematic representation of possible patterns of fibronectin splice variant expression in subluminal aspects of tumor blood vessels. EDB-containing fibronectin can, in principle, be found in the basement membrane of tumor blood vessels and/or in the tumor interstitium and stroma. These two distinct features can indeed be found in patient specimens [49–52], as well as in F9 teratocarcinomas and C51 colorectal tumors: two murine models of cancer that were used in this study. A predominantly vascular pattern of EDB expression was observed in F9 tumors, while a diffuse staining of the interstitium was seen in C51 tumors [**Figure 1B**]. We used L19-IL2 [26] and L19-TNF [25] as representative immunostimulatory fusion proteins, in order to test the impact of dose fractionation in different models of cancer [**Figure 1C,D**].

Figure 1E depicts a biodistribution rationale for using fractionated administration of antibody-cytokine fusions, rather than bolus injection. Biodistribution results may be displayed in terms of product concentration in tumor masses, blood or normal organs over time. Following bolus injection, blood values typically decrease in a mono- or bi-exponential manner [53]. Adverse events (e.g., flu-like symptoms, hypotension) are typically manifested when blood concentrations are above a critical threshold and disappear at later time points [30,31]. In parallel, the concentration of product in the solid tumor mass increases over time, in a process that slows down with the progressive disappearance of antibody-cytokine fusion from circulation. Products targeting stable antigens (e.g., components of the modified tumor extracellular matrix) exhibit long residence times within the neoplastic mass [54,55]. It is therefore conceivable that *fractionated* administration of antibody-cytokine fusions may allow the *progressive* build-up of product concentration within the solid tumor mass, while keeping blood levels below a critical threshold.

We tested fractionated administration strategies in quantitative biodistribution studies with radio-labeled preparations of L19-IL2 and of L19-TNF in immunocompetent mice, bearing murine F9 teratocarcinomas, according to the experimental scheme of **Figure 2A**. The percent injected dose per gram of tissue or body fluid (%ID/g) for L19-IL2, obtained by bolus injection 24 hour prior to sacrifice or by fractionated administration over time, are displayed in **Figure 2B**. As expected, comparable doses in the tumor were observed for

single or fractionated (2- or 3-times) injection modalities. Increased tumor:organ ratios were observed when product injection was divided in three steps over a period of 72 hours [**Figure 2B**]. A different profile was observed for L19-TNF. In that case, a progressive decrease in the cumulative %ID/g value in the tumor mass was observed [**Figure 2C**]. The targeted delivery of TNF to the tumor blood vessels may cause a rapid and selective shutdown of the vasculature, leading to hemorrhagic necrosis [25,39,56,57]. The conversion of a tumor mass into a necrotic scab within the first few hours is likely to prevent product accumulation for subsequent injections.

We tested the antitumor-activity for L19-IL2 in immunocompetent mice, bearing F9 teratocarcinomas [**Figure 3A**]. Unlike the human situation, IL2 shows minimal toxicity in mice. No body weight loss could be observed upon bolus administration of 100 µg and 400 µg L19-IL2. The higher dose was efficacious in controlling tumor size for a long time period, but the lack of toxicity prevented a comparative evaluation of bolus vs. fractionated administration strategies.

We then tested L19-TNF in F9 teratocarcinomas in 129/SvEv mice and in C51 colorectal tumors in BALB/c mice. Different immunocompetent mouse strains exhibit different sensitivity to cytokine therapeutics. Dose fractionation allowed the safe administration of a cumulative dose of 15 µg in the F9 model, while 10 µg of L19-TNF were lethal when administered as a bolus injection [**Figure 3B**]. Motivated by these encouraging results, we further extended dose fractionation to five consecutive injections, leading to the administration of a cumulative dose of 25 µg of product and to the prolonged inhibition of tumor growth [**Figure 3C**]. Analysis of cytokine concentrations in plasma for the different treatment groups did not explain differences in toxicity, as similar plasma concentrations of IL4, IL2, IL10, IL4, IL17. MIG cytokine and TGF-ß1 were observed after bolus injection (5 µg) or fractionated administration (3x3 µg) of L19-TNF [**Figure 4**].

Dose fractionation of L19-TNF in C51 tumors led to an opposite outcome compared to what had been observed in F9 teratocarcinomas. The product was administered either as a single 3 µg bolus injection or as 1 µg or 1.5 µg fractionated doses [**Figure 5**]. In this setting, a bolus administration of L19-TNF showed a better anti-cancer activity compared to saline and to both fractionated treatment groups.

Metronomic administration procedures have been extensively studied for many types of chemotherapeutic drugs, but are less characterized for cytokine-based biopharmaceuticals [58–60]. The therapeutic activity of NKTR-214 (a PEGylated derivative of IL2) in mice [22] and in patients [61] has been attributed to its ability to release free IL2 in a controlled fashion. The product is administered intravenously, the PEG chains are slowly hydrolyzed and as a consequence the drug becomes active. This strategy reduces systemic toxicities by providing minimal exposure of the free IL2, while achieving, over a period of 5 days, a 380-fold increased tumor exposure of the active cytokine, compared to the unmodified IL2 (i.e., adesleukin).

Certain immunotherapeutics work better when given by continuous infusion. Blinatumomab (a bispecific antibody product in BiTE™ format) has received marketing authorization for the treatment of adult and pediatric patients with B-cell precursor acute lymphoblastic leukemia (ALL). The product is administered as 30-day continuous infusion thanks to the use of an infusion pump [62]. The same agent was found to be substantially inefficacious when administered as bolus injection [63,64].

Subcutaneous injections may lead to a sustained release of immunotherapeutics. Recombinant human IL2 has shown comparable activity (but different tolerability) when given as subcutaneous administration or as bolus injection [65]. An engineered version of human interleukin-15 ALT-803) has recently shown superior biodistribution and activity profiles when administered as subcutaneous injections, while a rapid disappearance from circulation and elevated toxicity was reported for bolus intravenous administration [66].

From a theoretical viewpoint, we would expect dose fractionation to be associated with a better tolerability profile and, indeed, this feature was observed for L19-TNF in murine models of cancer. However, the different tolerability and therapeutic performance of this product in F9 and C51 tumors, upon bolus and fractionated administration [**Figures 3 and 5**], suggests that dose and schedule may ultimately require an optimization for individual products and indications at the clinical level.

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Conflict of interest

Dario Neri is co-founder, shareholder and member of the board of Philogen, a company working on antibody therapeutics. The authors declare no additional conflict of interest.

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Figure Captions

All figures are colored.

Figure 1: Tumor models, reagents and biodistribution rationale for using fractionated administration of antibody-cytokine fusions, rather than bolus injection. [**A**] Illustration of possible patterns of EDB in mouse models of cancer. EDB can be expressed in the basement membrane of tumor blood vessels and/or in the tumor interstitium and stroma. [**B**] Fluorescence analysis of EDB expression on C51 [**B, left panel**] and F9 [**B, right panel**] tumor sections. Cryosections were stained with L19-IgG FITC (green, AlexaFluor 488) and anti-CD31 (red, AlexaFluor 594). 10x magnification, scale bars = 100 µm. [**C, D**] Starting from left: schematic representation of the domain assembly, SDS-PAGE analysis (MW: molecular weight, NR: non-reducing conditions, R: reducing conditions) and size exclusion chromatography profile of L19-IL2 and L19-TNF, respectively. [**E**] Schematic representation of the analysis reported in this study.

Figure 2: Biodistribution experiments of fractionated administration of antibody-cytokine fusions versus bolus injection. [**A**] Experimental scheme of the study. Comparative quantitative biodistrubution analysis of radio-iodinated L19-IL2 [**B**] and L19-TNF [**C**] in immunocompetent mice bearing F9 teratocarcinoma tumors. For the bolus treatment group mice were sacrificed 24 hours after the bolus injection. For the fractionated treatment group mice were injected every 24 hours and sacrificed 24 hours after the last injection. Results are expressed as percentage of injected dose per gram of tissue (%ID/g ± SEM), (n = 5 mice per group). For L19-IL2 data were corrected for tumor growth correction.

Figure 3: Tumor therapy experiments in 129/SvEv mice bearing F9 teratocarcinomas. [**A**] Therapy with L19-IL2, the fusion protein was administered at 100 µg and 400 µg once. [**B**] First therapy with L19-TNF, the fusion protein was administered either as a single 10 µg bolus injection or as a 5 µg fractionated dose, which was repeated three times every 24 hours. * 5/5 mice died after the injection of 10 µg of L19-TNF. [**C**] Second therapy with L19-TNF, the fusion protein was administered either as a single 5 µg bolus injection or as a 5 µg fractionated dose, which was repeated five times every 24 hours. Data represent mean tumor volume ± SEM (left) and % mean body weight change ± SEM (right).

Figure 4: Plasma concentration of cytokines in F9 tumor bearing mice injected with either PBS, 3 µg L19-TNF once or 5 µg L19-TNF three times every 24 hours. Blood samples were collected 24h after the last injection.

Figure 5: Tumor therapy experiments in BALB/c mice bearing C51 lesions. L19-TNF was administered either as a single 3 µg bolus injection or as a 1 µg or 1.5 µg fractionated dose, which was repeated three times every 24 hours. Data represent mean tumor volume ± SEM (left) and % mean body weight change ± SEM (right).

Figure 1

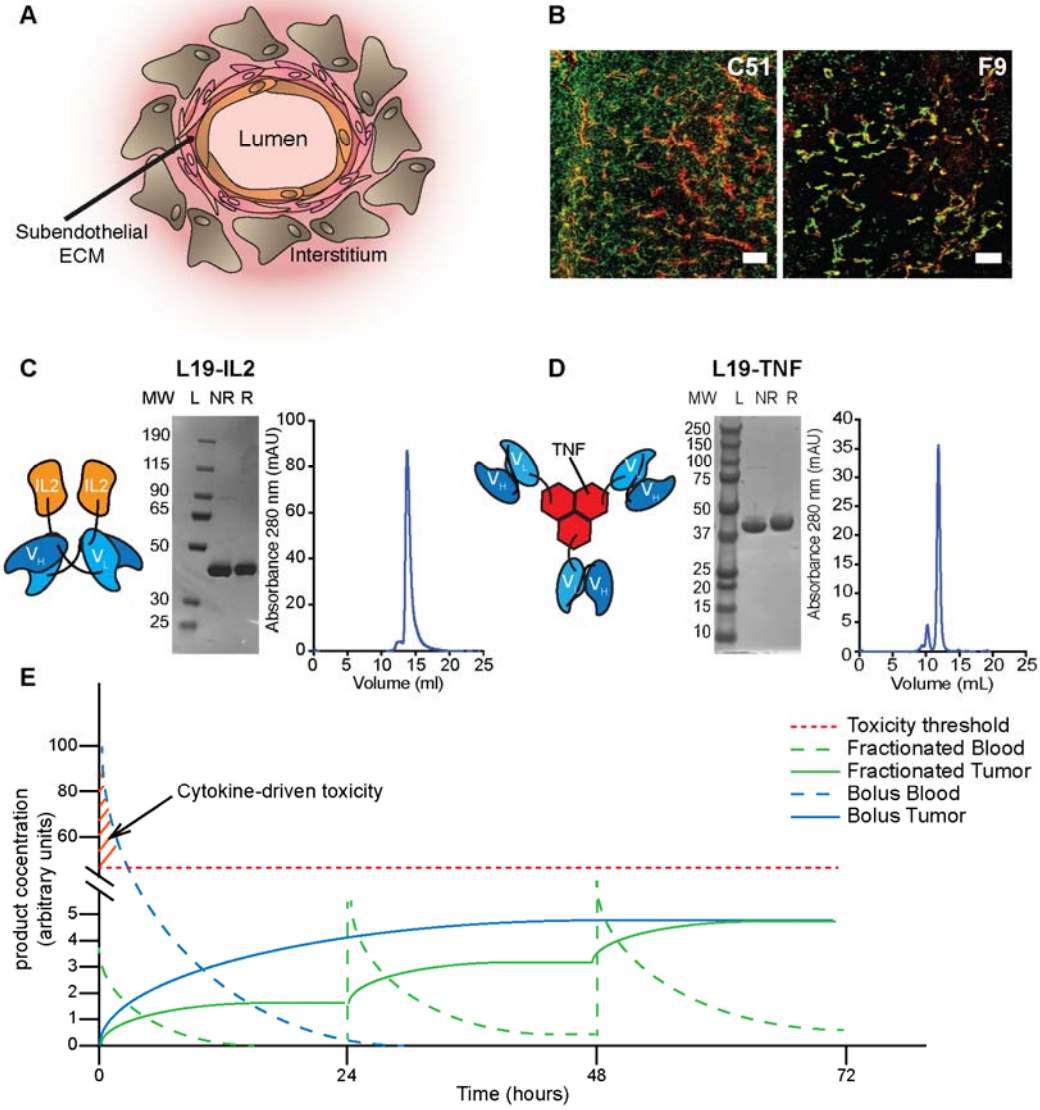
A
Lumen
Subendothelial ECM
Interstitium
B
C51
F9
C
L19-IL2
MW L NR R
190
115
90
65
50
30
25
IL2
IL2
Absorbance 280 nm (mAU)
Volume (ml)
D
L19-TNF
MW L NR R
250
150
100
75
50
37
25
20
15
10
TNF
Absorbance 280 nm (mAU)
Volume (mL)
E
Toxicity threshold
Fractionated Blood
Fractionated Tumor
Bolus Blood
Bolus Tumor
Cytokine-driven toxicity
product cocentration (arbitrary units)
Time (hours)

Figure 2

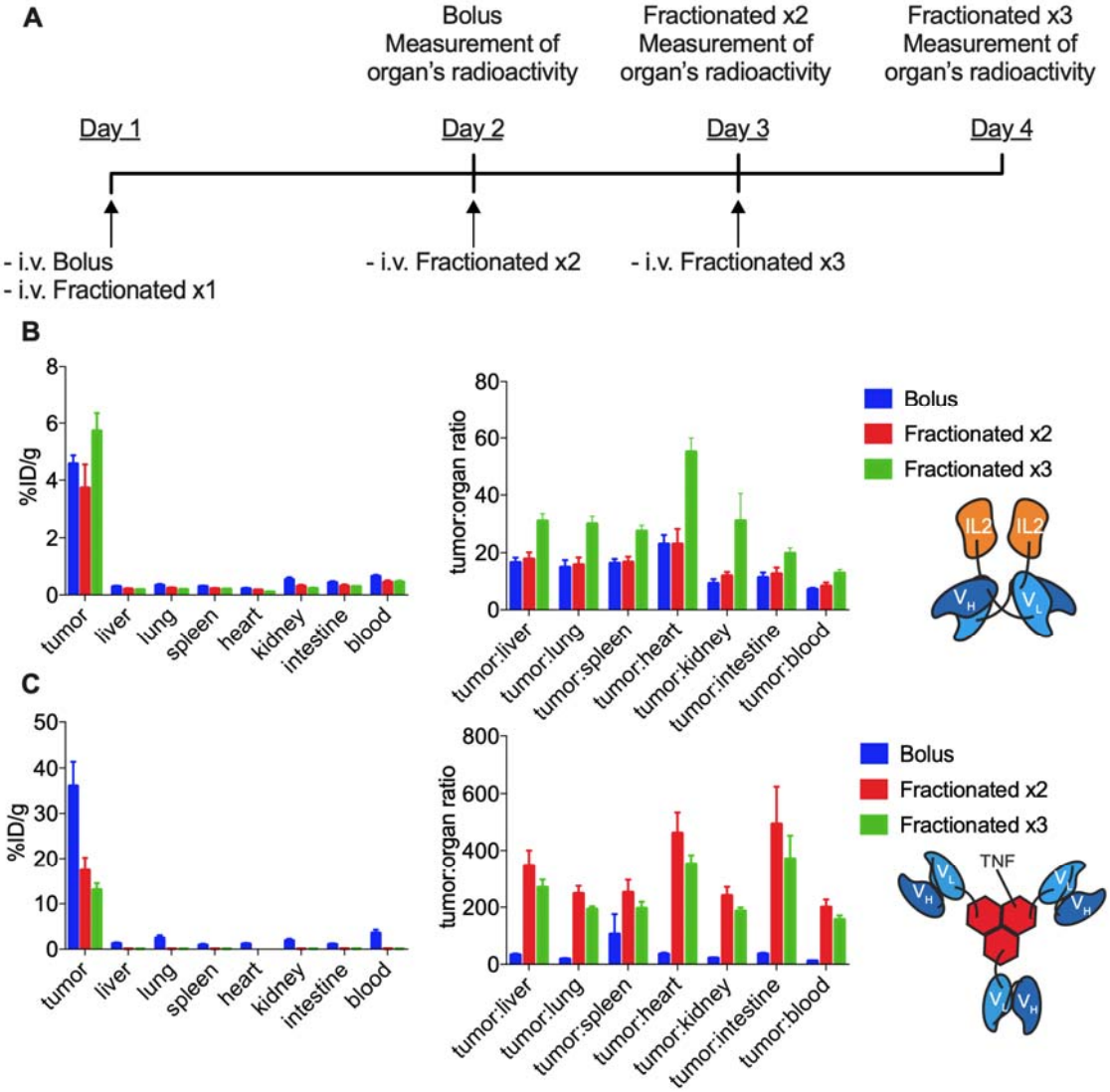
A
Bolus
Measurement of
organ's radioactivity
Fractionated x2
Measurement of
organ's radioactivity
Fractionated x3
Measurement of
organ's radioactivity
Day 1
Day 2
Day 3
Day 4
- i.v. Bolus
- i.v. Fractionated x1
- i.v. Fractionated x2
- i.v. Fractionated x3
B
%ID/g
tumor
liver
lung
spleen
heart
kidney
intestine
blood
tumor:organ ratio
tumor:liver
tumor:lung
tumor:spleen
tumor:heart
tumor:kidney
tumor:intestine
tumor:blood
Bolus
Fractionated x2
Fractionated x3
IL2
IL2
C
TNF

Figure 3

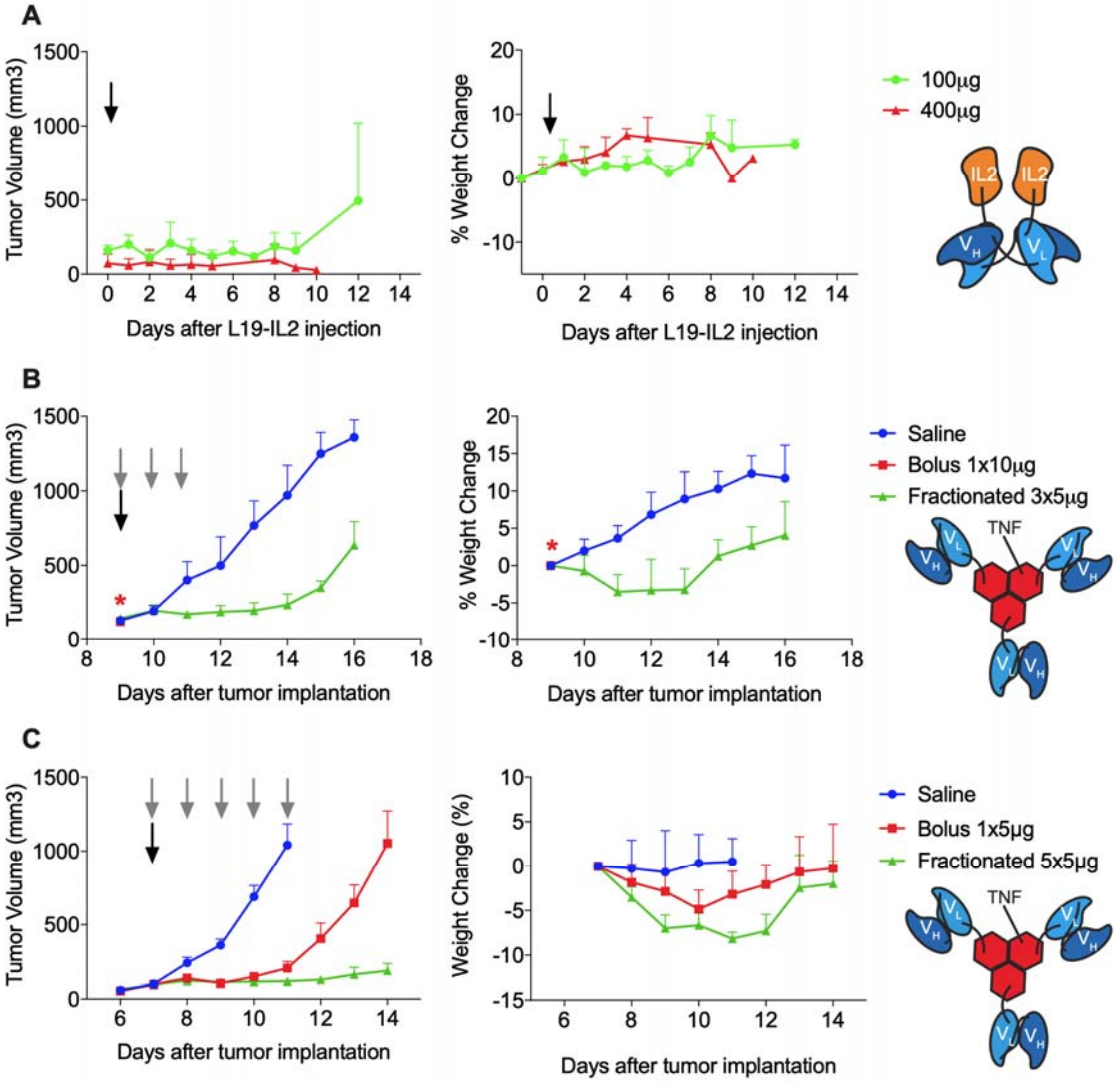
A
Tumor Volume (mm3)
Days after L19-IL2 injection
% Weight Change
Days after L19-IL2 injection
100µg
400µg
IL2
IL2
B
Tumor Volume (mm3)
Days after tumor implantation
% Weight Change
Days after tumor implantation
Saline
Bolus 1x10µg
Fractionated 3x5µg
TNF
C
Tumor Volume (mm3)
Days after tumor implantation
Weight Change (%)
Days after tumor implantation
Saline
Bolus 1x5µg
Fractionated 5x5µg
TNF

Figure 4

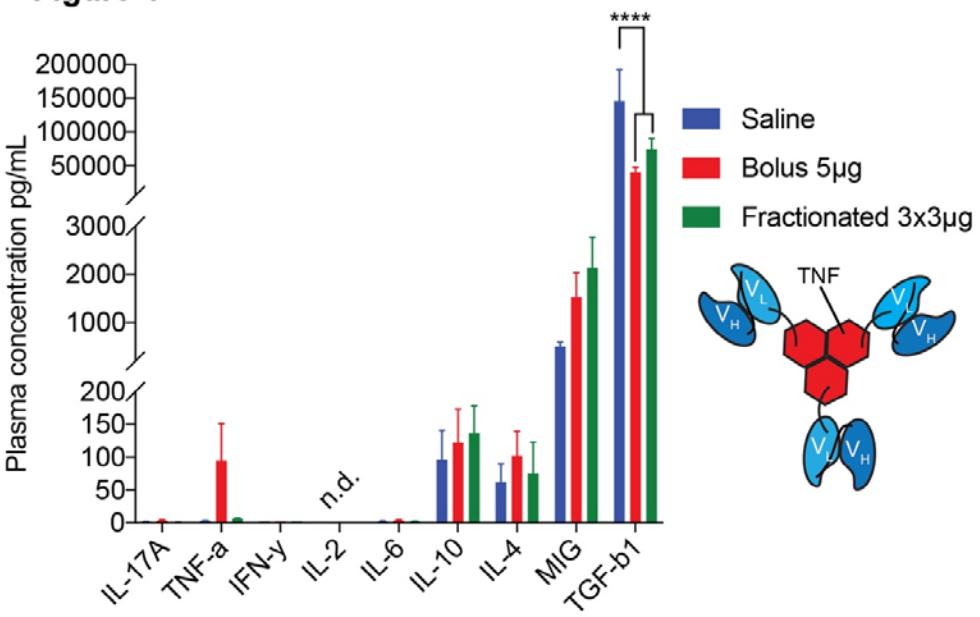
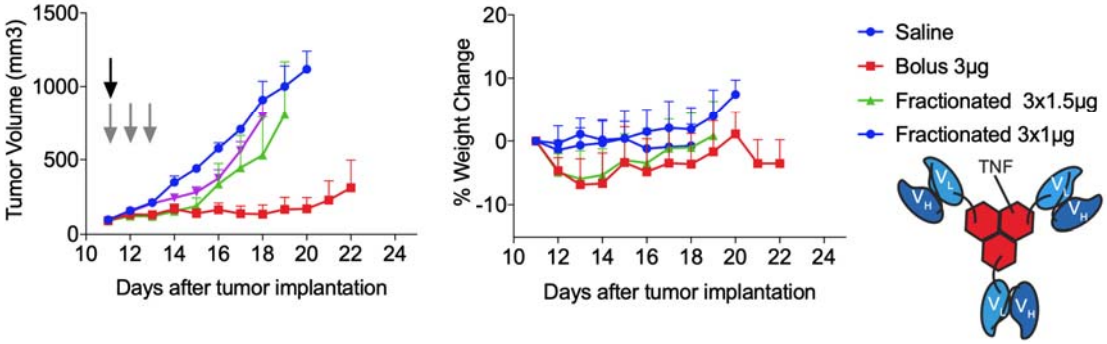
Figure 5