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► **To cite this version:**

Richard S Blumberg, David Lillicrap, Steven W Pipe, Sébastien Lacroix-Desmazes, Michal Pyzik, et al.. Tolerogenic properties of the Fc portion of IgG and its relevance to the treatment and management of hemophilia. *Blood*, 2018, 131 (20), pp.2205-2214. <10.1182/blood-2017-12-822908>. <hal-02328264>

HAL Id: hal-02328264

<https://hal.science/hal-02328264v1>

Submitted on 26 Oct 2019

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Tolerogenic Properties of Fc portion of IgG and its relevance to the treatment and management of hemophilia

Short title: Tolerogenicity of Fc fusion proteins in hemophilia

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Abstract Word Count: 160

Introduction/Discussion/Conclusion Word Count: 4307

Number of Figures: 1

Number of Tables: 1

Number of References: 120

Abstract

Hemophilia, or inherited genetic deficiencies in coagulation factors result in uncontrolled bleeding requiring replacement therapy with recombinant proteins given preventively or on-demand. However, a major problem with these approaches is the potential for development of immune responses to the administered proteins due to the underlying genetic deficiency of the factor(s) throughout life. As such, there is great interest in developing strategies that avoid immunogenicity and induce immune tolerance. Recently, recombinant Factor VIII and Factor IX fused to the Fc domain of IgG have been developed as therapeutic agents for hemophilia A and B, respectively. Although it is well known that the possession of an Fc domain confers IgG's longer-lasting circulating half-life, it is not generally appreciated that the Fc domain also confers immunoregulatory properties that are associated with the induction of tolerance. Here, we review some of the latest advances in our understanding of the tolerogenic abilities of IgG Fc and the impact of rFVIII-Fc on the treatment of hemophilia.

Introduction

As a class of therapeutic moieties, crystallizable fragment (Fc)-fusion proteins have a long history of clinical use, dating back to 1998 when the first Fc-fusion protein product was approved for therapy.¹ The rationale for such an approach stems from the ability of Fc fusion proteins to confer the characteristics of both the IgG Fc-domain and the chimerized protein or peptide. An important property of IgG is its long serum half-life due to interactions between the IgG Fc-domain and neonatal crystallizable fragment receptor (FcRn) conferring an extended half-life on the chimerized cargo drug.²⁻⁶ An underappreciated quality of Fc-fusion proteins is their ability to produce limited immunogenicity to the attached molecule. Indeed, several Fc fusion drugs have been approved by FDA. While there are no direct comparisons between the immunogenicity of the coupled (Fc-cargo) and uncoupled (cargo) therapies, it has been noted that the immunogenicity of such fusion proteins is low.¹ The latter finding is consistent with observations dating back to more than 40 years ago that IgG is endowed with tolerance inducing functions which are conferred through the Fc domain.⁷⁻¹³

This is potentially important to recombinant replacement therapies whereby recurring supplementation of these compounds can trigger an immune-mediated reaction, as is the case for long-term treatment with recombinant Factor VIII (rFVIII) and Factor IX (rFIX) in humans with hemophilia A and hemophilia B, respectively, who are genetically or functionally deficient in these factors. Hence, administration of therapeutic FVIII and FIX can result in the development of neutralizing anti-FVIII or anti-FIX IgG antibodies that can reduce the therapeutic effects of these proteins.¹⁴⁻¹⁸ Fc-fusion proteins of rFVIII (rFVIII-Fc) and rFIX (rFIX-Fc) represent a new class of therapeutic proteins in which the Fc domain of human IgG1 is genetically fused to one molecule of rFVIII or rFIX, respectively, creating so-called monomeric Fc-fusion proteins that are produced in a human cell line which enables a human glycosylation pattern.¹⁹⁻²³ As a consequence of these attributes, there is burgeoning evidence that FVIII-Fc and FIX-Fc may be capable of being uniquely more effective in inducing antigen-specific tolerance to these recombinant coagulation factors. Here we summarize current evidence in support of this proposal, the potential mechanisms involved and how these concepts may be used in current treatment regimens of hemophilia A and B for tolerance induction.

The relationship between IgG Fc and immune tolerance

In the late 1960's, Weigle and his colleagues built on the newly discovered collaboration between T and B cells to examine mechanisms and targets for tolerance using ultracentrifuged human gamma globulin (HGG) as a model antigen.^{24,25} They found that ultracentrifuged and deaggregated HGG was tolerogenic in mice, whereas aggregated HGG was immunogenic, suggesting tolerance was associated with monomeric IgG but not IgG as a complex. Further, both T and B cells could be rendered unresponsive, but with different dose requirements and kinetics for tolerance induction and duration.

Yves Borel and co-workers subsequently expanded on these observations by demonstrating direct coupling of immunogenic haptens (such as chemicals or nucleic acids) to murine IgG isotypes led to both T- and B-cell tolerance to the coupled epitopes and that IgG subclasses worked best as tolerogenic carriers relative to other proteins such as albumin or IgM.^{7-9,26-28} Baxevanis *et al.* extended this work by examining the effect of coupling an antigen directly with human Fc (hFc).²⁹ They found that hFc could induce tolerance in mice, while a truncated Fc variant containing only the C_H3 domain could not. In addition, Waldschmidt and colleagues demonstrated *in vitro* that although intact IgG was a tolerogenic carrier, F(ab)₂ fragments were not, indicating the unique importance of the Fc domain of IgG for tolerance induction.¹⁰ Further studies by Scott's group validated the use of IgG carriers and showed that potential

immunogenic peptide epitopes could be rendered tolerogenic in an antigen specific manner by genetically embedding them into an IgG framework.³⁰⁻³³

Although the mechanisms by which the IgG Fc domain can induce tolerance are poorly characterized, it has been suggested to involve Fc receptor dependent and independent interactions. In humans, two main classes of Fc receptors have been described and include the classical Fc γ receptors (Fc γ R: Fc γ RI, Fc γ RIIa/b/c, Fc γ RIIIa/b) which are expressed primarily on the surface of hematopoietic cells and non-classical Fc γ R (FcRn, DC-SIGN, CD22, CD23, TRIM21, FcRL1-6, FCRLA, FCRLB) which have a broader cellular localization and cell expression pattern (**Table 1**).^{34,35} Among the classical Fc γ Rs, Fc γ RIIb is the sole receptor that possesses inhibitory function. It is also the only Fc γ R in mice and humans that is expressed on B cells although it is widely expressed on innate immune effector cells including monocytes, macrophages and dendritic cells and also on liver sinusoidal endothelium.^{36,37} In Fc γ RIIb-deficient mice, antibody production is strongly enhanced and less specific, resulting in autoantibody production and a systemic lupus erythematosus-like disease in susceptible mouse strains. Thus, IgG-Fc binding to Fc γ RIIb on B cells provides an important checkpoint for maintaining humoral tolerance and limiting self-reactive immune responses.^{38,39} Furthermore, antigen-antibody complexes (immune complexes, IC) may induce B cell apoptosis by triggering Fc γ RIIb in the absence of B cell receptor signaling which may be an important mechanism to limit the survival of autoantibody producing plasma cells in the bone marrow (**Figure 1a**).⁴⁰⁻⁴³

The immune-modulating property of IgG is also dependent on glycosylation status. The Fc portion of IgG has a single carbohydrate modification site at an Asparagine 297 residue that can produce at least 30 potential IgG glycoforms (**Figure 1b**) which have important consequences for the biologic activities and effector functions of antibodies.⁴⁴ Ravetch and colleagues have shown that sialylated IgG glycoforms can bind DC-SIGN (or its mouse homolog SIGN-R1) and induce the expression of Fc γ RIIb by professional antigen presenting cells (APC), such as macrophages or dendritic cells (DC).⁴⁵ These cells may promote tolerance presumably through suppression of APC function or promotion of antigen presentation of the internalized antigen in a tolerogenic fashion (**Figure 1c**).⁴⁶ Furthermore, sialylated IgG glycovariants were demonstrated to upregulate the inhibitory Fc γ RIIb variant on human B cells in vitro and murine cells in vivo via binding to CD23, which limits antibody responses (**Figure 1a**).⁴⁷ Thus, select IgG Fc-glycoforms may be involved in limiting immune activation in both the adaptive humoral immune response and its downstream effector functions.

Among other non-classical Fc γ R, FcRn is thought to mediate some of the tolerogenic properties of IgG. FcRn normally binds IgG through the C_H2-C_H3 domain of Fc at acidic pH as in an endosome of an APC, and protects it from degradation by diverting the IgG and its associated molecules away from lysosomes to the cell surface (**Figure 1e**).⁴⁸ Thus, FcRn is both responsible for the long serum half-life of IgG but also a potential vehicle for preventing immunogenicity by diverting associated cargo, such as Fc fusion proteins away from antigen presentation compartments when the IgG is monomeric (**Figure 1d**).⁴⁹⁻⁵⁵ In addition, neonatal murine models of tolerance have demonstrated that maternally transferred IgG IC can engage FcRn in mucosal DC and induce FOXP3⁺ T regulatory (T_{Reg}) cells, thus linking FcRn to generation of tolerance pathways in certain settings.⁵⁶

Finally, Fc receptor independent mechanisms include the observation that promiscuous tolerogenic epitopes may also exist in the C_H2 domain of Fc; so-called "Tregitopes" proposed by DeGroot and colleagues.⁴⁴ They have suggested that the Fc portion of IgG upon degradation is processed and presented by major histocompatibility complex class II molecules that promote the activation of T_{Reg} cells (**Figure 1e**).⁵⁷⁻⁵⁹ Importantly, some of these Tregitopes overlap with

regions critical for binding to Fc γ R and/or FcRn.⁶⁰⁻⁶² On the other hand, additional studies have shown that some Tregitopes possess limited T_{Reg} cell triggering capacities consistent with the notion that the Fc portion of IgG engages multiple mechanisms of tolerance induction.⁶³ Amongst the other potential mechanisms, it has been suggested that monomeric IgGs might negatively affect Ag uptake, processing or loading onto MHC-class II molecules by APC rendering T cell stimulation less efficient.⁶⁴⁻⁶⁶ Whether these mechanisms promote bystander tolerance to non-IgG epitopes attached to Fc remains to be determined.

Together, multiple mechanisms, both Fc γ R-dependent and independent, potentially underlie the tolerance inducing activities of IgG through its Fc domain and account in part for the anti-inflammatory activities of intravenous immunoglobulin (IVIG).⁶⁷

The relationship between IgG Fc and immune tolerance in models of hemophilia

Such concepts have direct potential relationship to the immunogenicity of, and immune tolerance to, FVIII and FIX. Building on these historical observations, pioneering studies of Lei & Scott have shown that insertion of the immunogenic A2 and C2 FVIII domains into the Fc-domain of IgG, creating chimeric IgG molecules, can preventatively induce FVIII-specific tolerance and actively induce tolerance in - FVIII immunized rodents.⁶⁸ Notably, the latter observations represent more closely the clinical setting in that the inhibitors are present before the start of the therapy in most hemophilia A patients. Similarly, hemophilia A mice exposed to rFVIII-Fc at therapeutically relevant doses (50 IU/kg and 100 IU/kg), but not higher doses (250 IU/kg), exhibit reduced antibody responses relative to that observed in response to rFVIII without an Fc-domain.¹¹ Moreover, pre-treatment of hemophilia A mice with therapeutic doses of rFVIII-Fc, but not an irrelevant protein, can prevent the induction of anti-FVIII antibodies including those with neutralizing potential. The mechanistic basis of the reduced immunogenicity of rFVIII-Fc was found to involve a combination of immunomodulatory influences which are consistent with the induction of antigen-specific tolerance. Examination of splenocytes from rFVIII-Fc-treated mice showed increased numbers of CD4⁺CD25⁺FOXP3⁺ T_{Reg} cells as well as an increase in T cells expressing the tolerogenic CD279 (PD-1) molecule.¹¹ Further analysis of these splenic T cells revealed reduced expression of the proinflammatory protein TNF α and examination of their transcriptome confirmed an increased expression of immunomodulatory molecules such as FOXP3, CTLA-4, IL-10 and TGF- β . Furthermore, the levels of transcripts for proinflammatory molecules such as CCL3 and STAT3 were reduced in the spleens of rFVIII-Fc-treated mice. Lastly, rFVIII-Fc mutant molecules were generated that lacked the ability to bind to either Fc γ R or FcRn. In mice, the immunomodulatory influences of the two mutant forms of rFVIII-Fc were maintained, although with a less evident immune regulatory profile as seen with the original rFVIII-Fc protein. Overall, this murine study suggests that the immunomodulatory effect of rFVIII-Fc is the combined result of increased numbers of T_{Reg} cells and the generation of a non-inflammatory splenic microenvironment. There is also evidence that interaction with both FcRn and Fc γ R contributes to this outcome.

Among the Fc γ R to be considered in the context of tolerance responses potentially associated with rFVIII-Fc is the inhibitory Fc γ RIIb. Fc γ RIIb is a low-affinity IgG Fc receptor that binds to IC rather than monomeric IgG.^{69,70} As a consequence, rFVIII-Fc is unlikely to bind Fc γ RIIb at therapeutic concentrations which typically achieve the levels of FVIII that normally exist in the circulation.^{20,22} As an IC, on the other hand, rFVIII-Fc would be able to engage Fc γ RIIb and activating Fc γ R.⁷¹ It is thus interesting to consider the possibility that the presence of anti-FVIII or anti-rFVIII-Fc antibodies might allow for formation of IC capable of binding to and triggering Fc γ RIIb function which might deliver inhibitory signals to B and other hematopoietic cells.⁴³ However, Fc γ RIIb plays a complex role in regulating antibody-mediated tolerogenic pathways. This is illustrated by observations in a FVIII^{-/-} mouse model where the

presence of Fc γ RIIb was shown to be potentially detrimental in this regard through its ability to ensure survival of memory B cells during re-stimulation with FVIII.^{72,73} Therefore, in some instances Fc γ RIIb may be necessary to protect memory B cells from over-stimulation during FVIII re-encounter and allow them to survive.

rFVIII-Fc's interaction with FcRn suggests that the molecule's immunomodulatory effects might be transferred across the placenta as the FcRn receptor is expressed by the syncytiotrophoblast and is involved in the transplacental transfer of IgG.^{74,75} This proposal is supported by evidence that an Fc fusion version of β -glucuronidase has been found to cross to the murine fetus.⁷⁶ To date, preliminary evidence obtained in hemophilia A mice has also shown that when rFVIII-Fc is administered at high doses to late stage pregnant mothers there is FVIII activity detectable in the fetus.⁷⁷ This is not found in fetal mice treated with rFVIII only. Consistent with this, Gupta and colleagues have taken advantage of these concepts to further demonstrate the vital role played by FcRn in the transplacental transfer of IgG during gestation in relation to hemophilia.^{12,78} They have shown that the antenatal transfer of Fc containing the A2 and C2 domains of FVIII can induce FVIII-specific T_{Reg} cells in the progeny animals and prevent immune responses to rFVIII upon subsequent exposure during post-natal life.¹² This is due to FVIII-specific tolerance induction as resistance to FVIII-associated immune responses can be transferred to previously naïve animals. What is not known presently is how the transplacental transport of FVIII is influenced by its interaction with von Willebrand factor⁷⁷. Nevertheless, if this potential was realized it might be possible to induce prenatal tolerance to FVIII, a significant step towards mitigating this treatment's complication.

Mechanisms of immunogenicity of replacement clotting factors VIII and IX

As previously stated, the intravenous administration of therapeutic FVIII and FIX results in the development of neutralizing anti-FVIII or anti-FIX IgG, that are referred to as "inhibitors", in up to 40% and 4%, respectively, of the patients with the severe forms of these diseases.¹⁶⁻¹⁸ Immune responses to FVIII and FIX are believed to be classical responses to foreign antigens: the proteins are endocytosed by professional APC, processed and presented to naïve CD4⁺ T cells (**Figure 1d**); the naïve T cells are activated, proliferate and provide help to naïve antigen-specific B cells that differentiate into plasmocytes or memory B cells. In the case of FVIII, the dependence on T-cell help was initially suggested in inhibitor-positive patients who became responsive to FVIII therapy following infection by human immunodeficiency virus and loss of CD4⁺ T cells, as well as by the isotype-switched nature of anti-FVIII IgG (predominantly IgG1 or IgG4) and by the presence of affinity maturation.⁷⁹⁻⁸¹ More directly, FVIII-specific CD4⁺ T cell lines or clones have been isolated from inhibitor-positive patients.⁸²⁻⁸⁴ Several factors have been proposed to predispose patients to FVIII inhibitor development. These include genetic risk factors, such as the type of hemophilia A-causing FVIII mutation, and more precisely, the presence of FVIII antigen, HLA-DR and DQ haplotypes, and polymorphisms in different immuno-inflammatory genes (*TNFA*, *IL10*, *HMOX1*, *FCGR*).⁸⁵⁻⁸⁸ Other non-genetic risk factors have also been identified such as the type of FVIII product used, vaccination schedules or the intensity of treatment in the first months of life.^{18,89}

The nature of the immune regulation of the anti-FVIII response is poorly understood. Healthy donors can produce FVIII-reactive IgG and T cells, albeit under homeostatic conditions, suggesting that tolerance to FVIII relies on dynamic and controlled immune recognition rather than on the mere elimination of FVIII-specific T cells and B cells in primary lymphoid organs.⁹⁰⁻⁹² Experiments in mice have suggested that induced tolerance to exogenous FVIII relies on the generation of both central (thymic) and peripheral (induced) T_{Reg} cells.¹² Besides, the development of FVIII inhibitors was suggested to depend on an impaired capacity of the patients' DCs to trigger indoleamine 2,3-dioxygenase 1 (IDO1)-dependent tolerance

mechanisms.⁹³ Yet, the facts that i) healthy donors without previous abnormalities may develop pathogenic anti-FVIII autoimmunity (i.e., acquired hemophilia), and ii) patients with mild/moderate forms of the disease, who express mutated forms of the FVIII molecule, are at a lesser, but life-long risk of developing FVIII inhibitors, illustrate the tenuous and complex nature of FVIII-specific regulatory mechanisms.⁹⁴ Although less well understood, it is likely that similar mechanisms may underlie the hypersensitivity to FIX observed in patients with hemophilia B.⁹⁵

Current treatment approaches and success rate for management of inhibitors

In some individuals with hemophilia who have low titer inhibitors (<5 Bethesda units[BU]/ml) to FVIII or FIX, higher doses of factor concentrate may be able to achieve hemostasis or even allow continued prophylactic therapy. However, for most patients with inhibitors, particularly, those with high titers (>5 BU/ml), this precludes continued use of standard FVIII or FIX replacement therapy, making acute management of bleeding and prophylaxis more challenging. Thus “bypassing agents” have been the only available strategy to treat or prevent bleeding. The approved bypassing agents are an activated prothrombin complex concentrate (aPCC) or recombinant factor VIIa (rFVIIa).⁹⁶ A recombinant porcine FVIII is approved for treatment of acute bleeding in patients with acquired hemophilia A, but is still being investigated in clinical trials in patients with congenital hemophilia A with inhibitors.⁹⁷ Most recently, a humanized bispecific antibody, Emicizumab, that partially mimics the scaffolding function of FVIII has shown significant hemostatic activity in FVIII inhibitor patients and its properties were recently reviewed.^{98,99} This therapy has now been licensed for prophylactic management of bleeding in this patient population.

aPCC is a plasma-derived concentrate that contains both zymogen and active forms of vitamin K-dependent clotting factors, with its most important hemostatic components believed to be prothrombin and activated factor X (FX).⁹⁸ The mechanism of action of rFVIIa is not entirely clear, however, evidence supports the notion that the therapeutic effect of high doses of rFVIIa in hemophilia stems from FVIIa-catalyzed activation of FX, requiring phospholipids exposed on activated platelets, but independent of tissue factor.⁹⁶ Even though a scarce amount of information is available on their mode of action, both bypassing agents have demonstrated efficacy in achieving hemostasis with acute bleeding episodes of about 80%, with no clear evidence of superiority of either agent, although there is considerable inter-patient and intra-patient variability.⁸⁶ Thus, both agents may be used concomitantly. Clinical trials support the use of both bypassing agents for prophylaxis in hemophilia patients with inhibitors in association with reduction in the number of bleeding episodes and improvement in quality of life measures. However, overall efficacy in preventing bleeding episodes is inferior compared to prophylaxis in hemophilia patients without inhibitors and remains a substantial treatment burden that adds considerably to the overall costs of therapy. Thus, eradication of the inhibitor remains a high priority.

The standard of care for inhibitor eradication is thus immune tolerance induction (ITI). ITI therapy involves the frequent and regular infusion of FVIII or FIX, typically at high doses over months to years to induce tolerance to the infused factor and allow factor infusions alone to control acute bleeding and resumption of prophylaxis. The proposed mechanisms by which tolerance is induced have included T cell exhaustion through overstimulation leading to T cell anergy, inhibition of FVIII-specific memory B-cell differentiation and the formation of anti-idiotypic antibodies.¹⁰⁰⁻¹⁰²

ITI is effective in about two-thirds of patients. However, observational studies have identified good and poor risk features that affect successful outcome. Poor risk features include age at start of ITI of >8 years old, a historical peak titer of >200 BU/ml, pre-ITI titer of >10 BU/ml, and

time to titer decline to <10 BU/ml before ITI of >24 months, with tolerance success rates that are less than 50%. The International Immune Tolerance Study demonstrated an overall success rate of approximately 70% in subjects with good risk features.¹⁰³ This study was a randomized, controlled study comparing low-dose (50 IU/kg three times per week) to high-dose FVIII (200 IU/kg daily) and did not show a significant difference between the dosing regimens in overall tolerance induction success rate. However, high-dose subjects achieved a negative titer and recovered significantly more rapidly than low-dose subjects (4.2 months vs 9.2 months). In addition, there was a significantly greater number of bleeding episodes in the low-dose subjects. ITI has significant financial implications, with costs of approximately \$50,000 to \$75,000 per month not including the high cost associated with the chronic use of bypassing agents. Economic modeling has suggested that low-dose ITI combined with aPCC prophylaxis could be a cost-saving strategy with the potential to reduce the morbidity by lowering the risk of breakthrough bleeding during ITI.¹⁰⁴ These observations highlight the critical need for additional approaches to prevent and manage the complication of inhibitor formation.

Potential immunomodulatory properties of rFVIII-Fc and rFIX-Fc in the management of inhibitors

The immunomodulatory properties of rFVIII-Fc have suggested that it may be beneficial to hemophilia patients in preventing inhibitor formation or in those in whom inhibitors have already developed. There are now several pieces of clinical evidence that support this proposal.

rFVIII-Fc and rFIX-Fc display extended stability and availability in the circulation, through interaction of the IgG-Fc domain with FcRn, diverting the chimeric proteins away from intracellular degradation; although this half-life extension is greater with FIX than FVIII due to the latter's interaction with von Willebrand factor.¹⁰⁵⁻¹⁰⁷ Importantly, passage of rFVIII-Fc through intracellular recycling routes doesn't affect its overall function and studies involving FVIII (rFVIII-SQ) stability at different pH levels have shown that its activity is minimally lost at pH 6.^{20,22,108,109} It was only below this pH level that FVIII activity was increasingly absent.¹⁰⁸ Further, the endocytic recycling pathway where FcRn operates to salvage IgG from lysosomal degradation involves mildly acidic environments characteristic of an early endosome, sorting endosome and recycling endosome where the lowest pH is between ~5.8-6.5.^{49,110-113} In this mildly acidic environment the activity of FVIII would thus be expected to be preserved. Consequently, both rFVIII-Fc and rFIX-Fc have demonstrated efficacy in managing acute bleeding episodes and in preventing bleeding through prophylaxis.^{114,115} In addition, to date no inhibitors have been reported within previously treated patient populations with either Fc fusion product. There is thus good biological rationale for reduced immunogenicity of these fusion proteins as well as improved efficacy in ITI based upon the aforementioned comments; recognizing however that this requires additional studies in controlled ITI trials and in previously untreated patient populations. Moreover, recent clinical data support this notion.^{13,116} However, definitive confirmation in this regard await clinical data from previously untreated patients and in prospective ITI studies.

In a case report, Ragni and colleagues for example noted that in comparison to a child in an inhibitor-prone family who developed a high titer inhibitor in response to conventional rFVIII treatment, a cousin with severe hemophilia A was observed to develop a low titer inhibitors when treated with rFVIII-Fc.¹¹⁶ Further, the child who received rFVIII-Fc was able to continue prophylactic dosing with rFVIII-Fc with subsequent resolution of the inhibitor, while the rFVIII only family member went on to require placement of a port central venous catheter and high dose ITI to eradicate the inhibitor.¹¹⁶ In addition, two case series have described the successful induction of FVIII tolerance in four children with severe hemophilia A and high titer inhibitors using doses of rFVIII-Fc ranging from 50 IU/kg three times per week up to 200 IU/kg every other day.^{13,117} In

the report from Malec and colleagues, the time to disappearance of anti-FVIII antibodies was 4-12 weeks which was shorter than that reported with rFVIII ITI. More recently, a non-interventional, retrospective chart review of males with severe hemophilia A and high-titer inhibitors treated with rFVIII-Fc for ITI was conducted at 10 sites in the United States and Canada.^{117,118} Nineteen patients were treated: 7 first-time ITI and 12 who had previously failed ITI with other products (rescue ITI). Although this retrospective study included a patient population with poor risk features for ITI success, rFVIII-Fc use demonstrated a rapid decrease in BU titers and rapid tolerization in first-time ITI patients, as well as showing therapeutic benefit in patients undergoing rescue ITI. Furthermore, a trend toward rapid BU titer decline was observed with higher rFVIII-Fc dosing (>130 IU/kg) administered daily. These preliminary results will be evaluated further in two prospective clinical trials using rFVIII-Fc for ITI in patients with hemophilia A and inhibitors (NCT03093480 and NCT03103542) to determine if an immunomodulatory influence of rFVIII-Fc may be more prompt and efficient than current ITI protocols. In addition, a phase 2 clinical study has been organized to assess the influence of rFVIII-Fc on inhibitor incidence in previously untreated patients (the INHIBIT study – ClinicalTrials.gov Identifier NCT02196207).¹¹⁹ Confirmation of the immunomodulatory influence of rFVIII-Fc in enhancing the efficiency of current ITI protocols will require the design of appropriate clinical trials that are now ongoing. Similar studies should be considered for patients with hemophilia B in light of a case report describing the successful use of rFIX-Fc in an extended infusion protocol to treat a patient with a history of hypersensitivity to plasma-derived and other rFIX products.¹²⁰ Notwithstanding this initial report, more clinical data needs to be collected to confirm the immunomodulatory potential of rFIX-Fc.

Concluding Remarks

FVIII and FIX are highly immunogenic proteins when used as long-term replacement therapy in patients with hemophilia A and B, respectively. This fact significantly complicates the management of these diseases. These immune responses represent a major burden on patients and the health care system, necessitating a better understanding of the pathways involved in the pathogenic immune responses, their regulation and novel means to mitigate the complication through the induction of immune tolerance. The development of recombinant FVIII and FIX as fusion proteins with the Fc domain of IgG1 for the treatment of these patients is increasingly recognized to provide a unique opportunity for confronting this problem. The possession of an IgG Fc domain not only endows FVIII and FIX with extended pharmacokinetic survival due to interactions with FcRn, but also potentially takes advantage of the less appreciated but equally important property of the Fc domain as a factor involved in tolerance induction as reviewed here. Indeed, the recent application of rFVIII-Fc and rFIX-Fc to humans with hemophilia A and B has revealed encouraging evidence that coupling these proteins to Fc may, at present mainly with rFVIII-Fc, alter the host immune response in a manner that is associated with enhanced tolerance induction. These timely observations raise the possibility that such fusion proteins may be less immunogenic and/or allow for enhanced induction of factor specific tolerance relative to their native counterparts which will require ongoing and newly established protocols focused on addressing the major clinical challenges associated with coagulation factor immunogenicity. It is hoped that this review article will stimulate such preclinical and clinical studies and the opportunities that they provide.

Acknowledgments

D.L. is supported by a Canada Research Chair in Molecular Hemostasis and by a Canadian Institutes of Health Research (CIHR) Foundation Grant FDN-154285. S.W.P is supported by research grants from Shire and the Goerlich Foundation. S.L-D. was supported by Institut National de la Santé et de la Recherche Médicale (INSERM), Centre National de la Recherche Scientifique (CNRS), Université Pierre et Marie Curie (UPMC) Paris 6, and a grant from Agence Nationale de la Recherche (ANR-10-BLAN-1118). M.P. is supported by CIHR. F.N. is supported by grants from the German Research Foundation (CRC1181-A7, GK1660, TRR130-P13), the IZKF Erlangen (A68) and the Emerging Fields Initiative. D.W.S. is supported by National Institutes of Health (NIH) grants HL126727 and HL127495. R.S.B. is supported by NIH Grant DK053056.

Authorship

Contributions: D.L., S.W.P., S.L-D., M.P., F.N., D.W.S., and R.S.B prepared, edited and approved the manuscript.

Conflict of Interest disclosure:

D.L. receives research support from Bioverativ, Bayer, CSL-Behring and Octapharma. S.W.P. serves as a consultant to Bioverativ, Shire, Novo Nordisk, Pfizer, and CSL Behring. S.L-D. serves as a consultant for SOBI. F.N. served as a consultant to SOBI. R.S.B. serves as a consultant to Bioverativ.

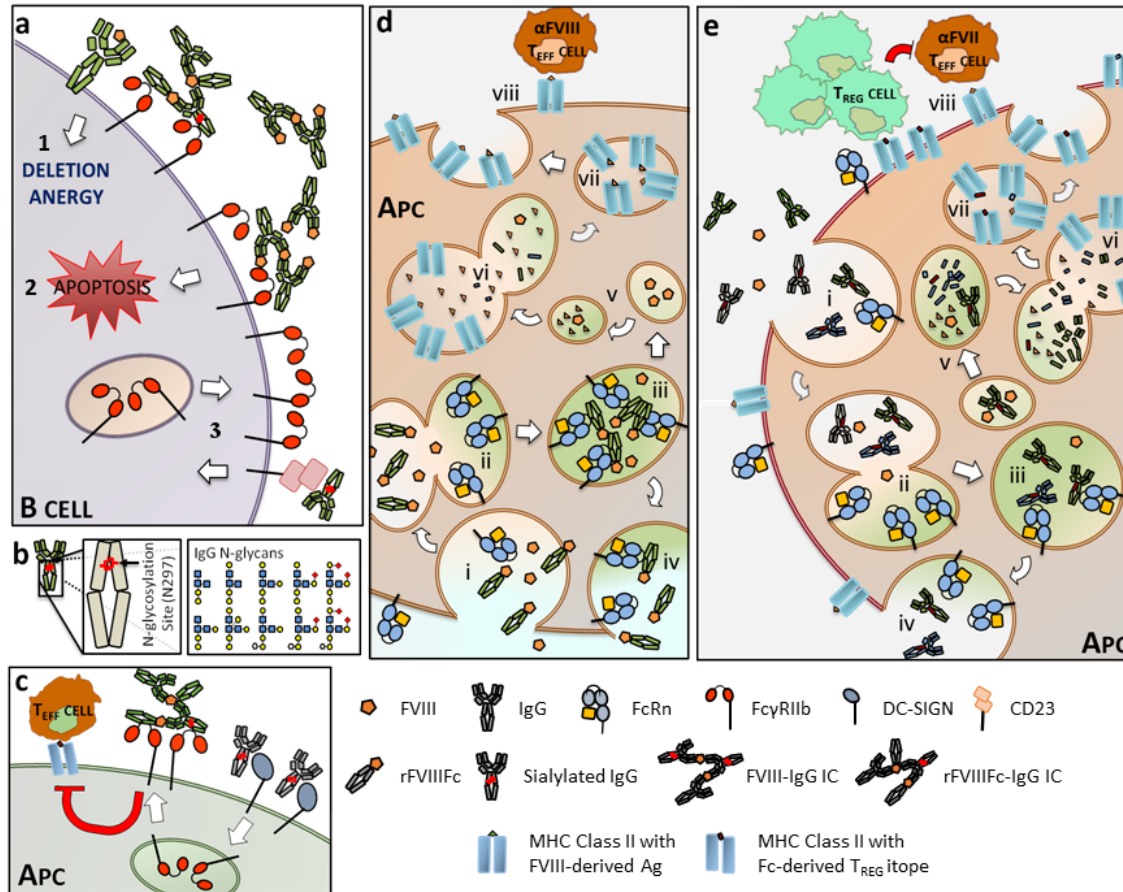


Figure 1: A schematic representation of the potential mechanisms of tolerance induction by Fc portion of IgG. (a) The ligation of the inhibitory receptor Fc γ RIIb by IgG IC (potentially composed of FVIII-anti-FVIII IgG or rFVIII Fc-anti-FVIII IgG) on B cells has different consequences depending on B cell maturity and has been shown to (1) prevent B cells with a higher-affinity self-reactive receptor from becoming IgG positive plasma cells and (2) induce apoptosis. When sialylated IgG engages CD23, (3) B cells upregulate Fc γ RIIb expression. (b) In the C_H2 domain of the IgG Fc region a single conserved glycosylation site is located (asparagine, N297). This site hosts two sugar moieties per IgG with extensive heterogeneity due to the variable addition of fucose, galactose, bisecting N-acetylglucosamine, or sialic acid. These differences result in altered IgG binding to Fc γ Rs, among others, which ultimately influence the effector functions of the Fc domain. For instance, (c) ligation of sialylated IgGs to DC-SIGN is involved in upregulation of inhibitory Fc γ RIIb on the surface of the APC which modulates downstream APC functions. (d-e) Although APC express FcRn on the surface, FcRn does not bind IgG at neutral pH. Thus, monomeric IgG or rFVIII Fc is internalized by i) fluid-phase endocytosis and binds to FcRn in ii-iii) an acidic endosomal compartment, the pH at which FcRn binds IgG. FcRn then recycles iv) IgG or rFVIII Fc back into the neutral pH milieu of the circulation. FcRn unbound IgG or other internalized soluble proteins (FVIII) will be subsequently degraded in v) lysosomes and routed to vii) Ag processing compartments where loading onto MHC class II molecules takes place. Therefore, FcRn diverts IgG or recombinant protein fused to Fc from Ag presentation. e) IgG not bound to FcRn due to levels that exceed FcRn capacity will also be degraded and peptides derived from IgG can be presented in the

context of MHC class II molecules. Within the C_H2 domain of Fc, tolerogenic epitopes are present and promote tolerance via T_{REG} cell activation (T_{reg.itope}). As tolerance can be imposed upon proteins attached to Fc, these regulatory effects are likely to be transmissible.

References

1. Rath, T., Baker, K., Dumont, J.A., Peters, R.T., Jiang, H., Qiao, S.W., Lencer, W.I., Pierce, G.F. & Blumberg, R.S. Fc-fusion proteins and FcRn: structural insights for longer-lasting and more effective therapeutics. *Crit Rev Biotechnol* 2015;**35**(2):235-54.
2. Vaughn, D.E., Milburn, C.M., Penny, D.M., Martin, W.L., Johnson, J.L. & Bjorkman, P.J. Identification of critical IgG binding epitopes on the neonatal Fc receptor. *J Mol Biol* 1997;**274**(4):597-607.
3. Vaccaro, C., Zhou, J., Ober, R.J. & Ward, E.S. Engineering the Fc region of immunoglobulin G to modulate in vivo antibody levels. *Nat Biotechnol* 2005;**23**(10):1283-1288.
4. Petkova, S.B., Akilesh, S., Sproule, T.J., Christianson, G.J., Presta, L.G., Meng, Y.G. & Roopenian, D.C. Enhanced half-life of genetically engineered human IgG1 antibodies in a humanized FcRn mouse model: potential application in humorally mediated autoimmune disease. *Int Immunol* 2006;**18**(12):1759-1769.
5. Dall'Acqua, W.F., Kiener, P.A. & Wu, H. Properties of human IgG1s engineered for enhanced binding to the neonatal Fc receptor (FcRn). *J Biol Chem* 2006;**281**(33):23514-23524.
6. Hinton, P.R., Xiong, J.M., Johlfs, M.G., Tang, M.T., Keller, S. & Tsurushita, N. An engineered human IgG1 antibody with longer serum half-life. *J Immunol* 2006;**176**(1):346-356.
7. Borel, Y. Induction of immunological tolerance by a hapten (DNP) bound to a non-immunogenic protein carrier. *Nat New Biol* 1971;**230**(14):180-182.
8. Borel, Y., Kilham, L. & Schwartz, R.S. Carrier-determined tolerance in various strains of mice: the role of isogenic IgG in the induction of hapten specific tolerance. *Proc Soc Exp Biol Med* 1974;**145**(2):470-474.
9. Borel, Y., Golan, D.T., Kilham, L. & Borel, H. Carrier determined tolerance with various subclasses of murine myeloma IgG. *J Immunol* 1976;**116**(3):854-858.
10. Waldschmidt, T.J., Borel, Y. & Vitetta, E.S. The use of haptened immunoglobulins to induce B cell tolerance in vitro. The roles of hapten density and the Fc portion of the immunoglobulin carrier. *J Immunol* 1983;**131**(5):2204-2209.
11. Krishnamoorthy, S., Liu, T., Drager, D., Patarroyo-White, S., Chhabra, E.S., Peters, R., Josephson, N., Lillicrap, D., Blumberg, R.S., Pierce, G.F. & Jiang, H. Recombinant factor VIII Fc (rFVIII-Fc) fusion protein reduces immunogenicity and induces tolerance in hemophilia A mice. *Cell Immunol* 2016;**301**:30-39.

12. Gupta, N., Culina, S., Meslier, Y., Dimitrov, J., Arnoult, C., Delignat, S., Gangadharan, B., Lecerf, M., Justesen, S., Gouilleux-Gruart, V., Salomon, B.L., Scott, D.W., Kaveri, S.V., Mallone, R. & Lacroix-Desmazes, S. Regulation of immune responses to protein therapeutics by transplacental induction of T cell tolerance. *Sci Transl Med* 2015;**7**(275):275ra221.
13. Groomes, C.L., Gianferante, D.M., Crouch, G.D., Parekh, D.S., Scott, D.W. & Lieuw, K. Reduction of Factor VIII Inhibitor Titers During Immune Tolerance Induction With Recombinant Factor VIII-Fc Fusion Protein. *Pediatr Blood Cancer* 2016;**63**(5):922-924.
14. Wight, J. & Paisley, S. The epidemiology of inhibitors in haemophilia A: a systematic review. *Haemophilia* 2003;**9**(4):418-435.
15. Mannucci, P.M. & Franchini, M. Present and future challenges in the treatment of haemophilia: a clinician's perspective. *Blood Transfus* 2013;**11 Suppl 4**:s77-81.
16. DiMichele, D.M. Immune tolerance in haemophilia: the long journey to the fork in the road. *Br J Haematol* 2012;**159**(2):123-134.
17. Gouw, S.C., van der Bom, J.G., Ljung, R., Escuriola, C., Cid, A.R., Claeysens-Donadel, S., van Geet, C., Kenet, G., Mäkipernaa, A., Molinari, A.C., Muntean, W., Kobelt, R., Rivard, G., Santagostino, E., Thomas, A., van den Berg, H.M. & Group, P.a.R.S. Factor VIII products and inhibitor development in severe hemophilia A. *N Engl J Med* 2013;**368**(3):231-239.
18. Peyvandi, F., Mannucci, P.M., Garagiola, I., El-Beshlawy, A., Elalfy, M., Ramanan, V., Eshghi, P., Hanagavadi, S., Varadarajan, R., Karimi, M., Manglani, M.V., Ross, C., Young, G., Seth, T., Apte, S., Nayak, D.M., Santagostino, E., Mancuso, M.E., Sandoval Gonzalez, A.C., Mahlangu, J.N., Bonanad Boix, S., Cerqueira, M., Ewing, N.P., Male, C., Owaidah, T., Soto Arellano, V., Kobrinsky, N.L., Majumdar, S., Perez Garrido, R., Sachdeva, A., Simpson, M., Thomas, M., Zanon, E., Antmen, B., Kavakli, K., Manco-Johnson, M.J., Martinez, M., Marzouka, E., Mazzucconi, M.G., Neme, D., Palomo Bravo, A., Paredes Aguilera, R., Prezotti, A., Schmitt, K., Wicklund, B.M., Zulfikar, B. & Rosendaal, F.R. A Randomized Trial of Factor VIII and Neutralizing Antibodies in Hemophilia A. *N Engl J Med* 2016;**374**(21):2054-2064.
19. Powell, J.S., Josephson, N.C., Quon, D., Ragni, M.V., Cheng, G., Li, E., Jiang, H., Li, L., Dumont, J.A., Goyal, J., Zhang, X., Sommer, J., McCue, J., Barbetti, M., Luk, A. & Pierce, G.F. Safety and prolonged activity of recombinant factor VIII Fc fusion protein in hemophilia A patients. *Blood* 2012;**119**(13):3031-3037.
20. Mahlangu, J., Powell, J.S., Ragni, M.V., Chowdary, P., Josephson, N.C., Pabinger, I., Hanabusa, H., Gupta, N., Kulkarni, R., Fogarty, P., Perry, D., Shapiro, A., Pasi, K.J., Apte, S., Nestorov, I., Jiang, H., Li, S., Neelakantan, S., Cristiano, L.M., Goyal, J., Sommer, J.M., Dumont, J.A., Dodd, N.,

- Nugent, K., Vigliani, G., Luk, A., Brennan, A., Pierce, G.F. & Investigators, A.-L. Phase 3 study of recombinant factor VIII Fc fusion protein in severe hemophilia A. *Blood* 2014;**123**(3):317-325.
21. Shapiro, A.D., Ragni, M.V., Valentino, L.A., Key, N.S., Josephson, N.C., Powell, J.S., Cheng, G., Thompson, A.R., Goyal, J., Tubridy, K.L., Peters, R.T., Dumont, J.A., Ewart, D., Li, L., Hallén, B., Gozzi, P., Bitonti, A.J., Jiang, H., Luk, A. & Pierce, G.F. Recombinant factor IX-Fc fusion protein (rFIXFc) demonstrates safety and prolonged activity in a phase 1/2a study in hemophilia B patients. *Blood* 2012;**119**(3):666-672.
 22. Dumont, J.A., Liu, T., Low, S.C., Zhang, X., Kamphaus, G., Sakorafas, P., Fraley, C., Drager, D., Reidy, T., McCue, J., Franck, H.W., Merricks, E.P., Nichols, T.C., Bitonti, A.J., Pierce, G.F. & Jiang, H. Prolonged activity of a recombinant factor VIII-Fc fusion protein in hemophilia A mice and dogs. *Blood* 2012;**119**(13):3024-3030.
 23. Georgescu, M.T., Lai, J.D., Hough, C. & Lillicrap, D. War and peace: Factor VIII and the adaptive immune response. *Cell Immunol* 2016;**301**:2-7.
 24. Chiller, J.M., Habicht, G.S. & Weigle, W.O. Kinetic differences in unresponsiveness of thymus and bone marrow cells. *Science* 1971;**171**(3973):813-815.
 25. Chiller, J.M., Habicht, G.S. & Weigle, W.O. Cellular sites of immunologic unresponsiveness. *Proc Natl Acad Sci U S A* 1970;**65**(3):551-556 (1970).
 26. Borel, Y. Isologous IgG-induced immunologic tolerance to haptens: a model of self versus non-self recognition. *Transplant Rev* 1976;**31**:3-22.
 27. Golan, D.T. & Borel, Y. Nonantigenicity and immunologic tolerance: the role of the carrier in the induction of tolerance to the hapten. *J Exp Med* 1971;**134**(4):1046-1061.
 28. Borel, Y., Lewis, R.M. & Stollar, B.D. Prevention of murine lupus nephritis by carrier-dependent induction of immunologic tolerance to denatured DNA. *Science* 1973;**182**(4107):76-78.
 29. Baxevasis, C.N., Ioannides, C.D., Reclos, G.J. & Papamichail, M. Evidence for distinct epitopes on human IgG with T cell proliferative and suppressor function. *Eur J Immunol* 1986;**16**(8):1013-1016.
 30. Zambidis, E.T. & Scott, D.W. Epitope-specific tolerance induction with an engineered immunoglobulin. *Proc Natl Acad Sci U S A* 1996;**93**(10):5019-5024.

31. Agarwal, R.K., Kang, Y., Zambidis, E., Scott, D.W., Chan, C.C. & Caspi, R.R. Retroviral gene therapy with an immunoglobulin-antigen fusion construct protects from experimental autoimmune uveitis. *J Clin Invest* 2000;**106**(2):245-252.
32. el-Amine, M., Hinshaw, J.A. & Scott, D.W. In vivo induction of tolerance by an Ig peptide is not affected by the deletion of FcR or a mutated IgG Fc fragment. *Int Immunol* 2002;**14**(7):761-766.
33. Lei, T.C., Su, Y. & Scott, D.W. Tolerance induction via a B-cell delivered gene therapy-based protocol: optimization and role of the Ig scaffold. *Cell Immunol* 2005;**235**(1):12-20.
34. Nimmerjahn, F., Gordan, S. & Lux, A. FcγR dependent mechanisms of cytotoxic, agonistic, and neutralizing antibody activities. *Trends Immunol* 2015;**36**(6):325-336.
35. Batsuli, G., Meeks, S.L., Herzog, R.W. & Lacroix-Desmazes, S. Innovating immune tolerance induction for haemophilia. *Haemophilia* 2016;**22 Suppl 5**:31-35.
36. Bruhns, P. & Jonsson, F. Mouse and human FcR effector functions. *Immunol Rev* 2015;**268**(1):25-51.
37. Ganesan, L.P., Kim, J., Wu, Y., Mohanty, S., Phillips, G.S., Birmingham, D.J., Robinson, J.M. & Anderson, C.L. FcγRIIb on liver sinusoidal endothelium clears small immune complexes. *J Immunol* 2012;**189**(10):4981-4988.
38. Takai, T., Ono, M., Hikida, M., Ohmori, H. & Ravetch, J.V. Augmented humoral and anaphylactic responses in Fc gamma RII-deficient mice. *Nature* 1996;**379**(6563):346-349.
39. Bolland, S. & Ravetch, J.V. Spontaneous autoimmune disease in Fc(γ)RIIB-deficient mice results from strain-specific epistasis. *Immunity* 2000;**13**(2):277-285.
40. Pearse, R.N., Kawabe, T., Bolland, S., Guinamard, R., Kurosaki, T. & Ravetch, J.V. SHIP recruitment attenuates Fc gamma RIIb-induced B cell apoptosis. *Immunity* 1999;**10**(6):753-760.
41. Xiang, Z., Cutler, A.J., Brownlie, R.J., Fairfax, K., Lawlor, K.E., Severinson, E., Walker, E.U., Manz, R.A., Tarlinton, D.M. & Smith, K.G. FcγRIIb controls bone marrow plasma cell persistence and apoptosis. *Nat Immunol* 2007;**8**(4):419-429.
42. Samuelsson, A., Towers, T.L. & Ravetch, J.V. Anti-inflammatory activity of IVIG mediated through the inhibitory Fc receptor. *Science* 2001;**291**(5503):484-486.
43. Smith, K.G. & Clatworthy, M.R. FcγRIIB in autoimmunity and infection: evolutionary and therapeutic implications. *Nat Rev Immunol* 2010;**10**(5):328-343.

44. Arnold, J.N., Wormald, M.R., Sim, R.B., Rudd, P.M. & Dwek, R.A. The impact of glycosylation on the biological function and structure of human immunoglobulins. *Annu Rev Immunol* 2007;**25**:21-50.
45. Anthony, R.M., Kobayashi, T., Wermeling, F. & Ravetch, J.V. Intravenous gammaglobulin suppresses inflammation through a novel T(H)2 pathway. *Nature* 2011;**475**(7354):110-113.
46. Bournazos, S., Wang, T.T., Dahan, R., Maamary, J. & Ravetch, J.V. Signaling by Antibodies: Recent Progress. *Annu Rev Immunol* 2017;**35**:285-311.
47. Wang, T.T., Maamary, J., Tan, G.S., Bournazos, S., Davis, C.W., Krammer, F., Schlesinger, S.J., Palese, P., Ahmed, R. & Ravetch, J.V. Anti-HA Glycoforms Drive B Cell Affinity Selection and Determine Influenza Vaccine Efficacy. *Cell* 2015;**162**(1):160-169.
48. Kim, J.K., Tsen, M.F., Ghetie, V. & Ward, E.S. Catabolism of the murine IgG1 molecule: evidence that both CH2-CH3 domain interfaces are required for persistence of IgG1 in the circulation of mice. *Scand J Immunol* 1994;**40**(4):457-465.
49. Ober, R.J., Martinez, C., Lai, X., Zhou, J. & Ward, E.S. Exocytosis of IgG as mediated by the receptor, FcRn: an analysis at the single-molecule level. *Proc Natl Acad Sci U S A* 2004;**101**(30):11076-11081.
50. Ober, R.J., Martinez, C., Vaccaro, C., Zhou, J. & Ward, E.S. Visualizing the site and dynamics of IgG salvage by the MHC class I-related receptor, FcRn. *J Immunol* 2004;**172**(4):2021-2029.
51. Akilesh, S., Christianson, G.J., Roopenian, D.C. & Shaw, A.S. Neonatal FcR expression in bone marrow-derived cells functions to protect serum IgG from catabolism. *J Immunol* 2007;**179**(7):4580-4588.
52. Prabhat, P., Gan, Z., Chao, J., Ram, S., Vaccaro, C., Gibbons, S., Ober, R.J. & Ward, E.S. Elucidation of intracellular recycling pathways leading to exocytosis of the Fc receptor, FcRn, by using multifocal plane microscopy. *Proc Natl Acad Sci U S A* 2007;**104**(14):5889-5894.
53. Montoyo, H.P., Vaccaro, C., Hafner, M., Ober, R.J., Mueller, W. & Ward, E.S. Conditional deletion of the MHC class I-related receptor FcRn reveals the sites of IgG homeostasis in mice. *Proc Natl Acad Sci U S A* 2009;**106**(8):2788-2793.
54. Baker, K., Rath, T., Flak, M.B., Arthur, J.C., Chen, Z., Glickman, J.N., Zlobec, I., Karamitopoulou, E., Stachler, M.D., Odze, R.D., Lencer, W.I., Jobin, C. & Blumberg, R.S. Neonatal Fc receptor expression in dendritic cells mediates protective immunity against colorectal cancer. *Immunity* 2013;**39**(6):1095-1107.

55. Challa, D.K., Mi, W., Lo, S.T., Ober, R.J. & Ward, E.S. Antigen dynamics govern the induction of CD4(+) T cell tolerance during autoimmunity. *J Autoimmun* 2016;**72**:84-94.
56. Ohsaki, A., Venturelli, N., Buccigrosso, T.M., Osganian, S.K., Lee, J., Blumberg, R.S. & Oyoshi, M.K. Maternal IgG immune complexes induce food allergen-specific tolerance in offspring. *J Exp Med* 2018;**215**(1):91-113.
57. De Groot, A.S., Moise, L., McMurry, J.A., Wambre, E., Van Overtvelt, L., Moingeon, P., Scott, D.W. & Martin, W. Activation of natural regulatory T cells by IgG Fc-derived peptide "Tregitopes". *Blood* 2008;**112**(8):3303-3311.
58. Su, Y., Rossi, R., De Groot, A.S. & Scott, D.W. Regulatory T cell epitopes (Tregitopes) in IgG induce tolerance in vivo and lack immunogenicity per se. *J Leukoc Biol* 2013;**94**(2):377-383.
59. De Groot, A.S., Cousens, L., Mingozzi, F. & Martin, W. Tregitope peptides: the active pharmaceutical ingredient of IVIG? *Clin Dev Immunol* 2013;**2013**:493138.
60. Baker, K., Qiao, S.W., Kuo, T.T., Aveson, V.G., Platzer, B., Andersen, J.T., Sandlie, I., Chen, Z., de Haar, C., Lencer, W.I., Fiebiger, E. & Blumberg, R.S. Neonatal Fc receptor for IgG (FcRn) regulates cross-presentation of IgG immune complexes by CD8-CD11b+ dendritic cells. *Proc Natl Acad Sci U S A* 2011;**108**(24):9927-9932.
61. Rath, T., Kuo, T.T., Baker, K., Qiao, S.W., Kobayashi, K., Yoshida, M., Roopenian, D., Fiebiger, E., Lencer, W.I. & Blumberg, R.S. The Immunologic Functions of the Neonatal Fc Receptor for IgG. *J Clin Immunol* 2013;**33 Suppl 1**:S9-S17.
62. Mi, W., Wanjie, S., Lo, S.T., Gan, Z., Pickl-Herk, B., Ober, R.J. & Ward, E.S. Targeting the neonatal fc receptor for antigen delivery using engineered fc fragments. *J Immunol* 2008;**181**(11):7550-7561.
63. Sorde, L., Spindeldreher, S., Palmer, E. & Karle, A. Tregitopes and impaired antigen presentation: Drivers of the immunomodulatory effects of IVIg? *Immun Inflamm Dis* 2017;**5**(4):400-415.
64. Aubin, E., Lemieux, R. & Bazin, R. Indirect inhibition of in vivo and in vitro T-cell responses by intravenous immunoglobulins due to impaired antigen presentation. *Blood* 2010;**115**(9):1727-1734.
65. Othy, S., Bruneval, P., Topçu, S., Dugail, I., Delers, F., Lacroix-Desmazes, S., Bayry, J. & Kaveri, S.V. Effect of IVIg on human dendritic cell-mediated antigen uptake and presentation: role of lipid accumulation. *J Autoimmun* 2012;**39**(3):168-172.

66. Nagelkerke, S.Q., Dekkers, G., Kustiawan, I., van de Bovenkamp, F.S., Geissler, J., Plomp, R., Wuhler, M., Vidarsson, G., Rispens, T., van den Berg, T.K. & Kuijpers, T.W. Inhibition of Fc γ R-mediated phagocytosis by IVIg is independent of IgG-Fc sialylation and Fc γ RIIb in human macrophages. *Blood* 2014;**124**(25):3709-3718.
67. Nimmerjahn, F. & Ravetch, J.V. The antiinflammatory activity of IgG: the intravenous IgG paradox. *J Exp Med* 2007;**204**(1):11-15.
68. Lei, T.C. & Scott, D.W. Induction of tolerance to factor VIII inhibitors by gene therapy with immunodominant A2 and C2 domains presented by B cells as Ig fusion proteins. *Blood* 2005;**105**(12):4865-4870.
69. Maenaka, K., van der Merwe, P.A., Stuart, D.I., Jones, E.Y. & Sondermann, P. The human low affinity Fc γ receptors IIa, IIb, and III bind IgG with fast kinetics and distinct thermodynamic properties. *J Biol Chem* 2001;**276**(48):44898-44904.
70. Bruhns, P., Iannascoli, B., England, P., Mancardi, D.A., Fernandez, N., Jorieux, S. & Daeron, M. Specificity and affinity of human Fc γ receptors and their polymorphic variants for human IgG subclasses. *Blood* 2009;**113**(16):3716-3725.
71. Hartholt, R.B., Wroblewska, A., Herczenik, E., Peyron, I., Ten Brinke, A., Rispens, T., Nolte, M.A., Slot, E., Claassens, J.W., Nimmerjahn, F., Verbeek, J.S. & Voorberg, J. Enhanced uptake of blood coagulation factor VIII containing immune complexes by antigen presenting cells. *J Thromb Haemost* 2017;**15**(2):329-340.
72. Werwitzke, S., Vollack, N., von Hornung, M., Kalippke, K., Kutzschbach, J., Trummer, A., Ganser, A. & Tiede, A. Deletion or inhibition of Fc γ receptor 2B (CD32) prevents FVIII-specific activation of memory B cells in vitro. *Thromb Haemost* 2015;**114**(6):1127-1135.
73. Vollack, N., Friese, J., Bergmann, S., Tiede, A. & Werwitzke, S. CD32 inhibition and high dose of rhFVIII suppress murine FVIII-specific recall response by distinct mechanisms in vitro. *Thromb Haemost* 2017;**117**(9):1679-1687.
74. Simister, N.E., Story, C.M., Chen, H.L. & Hunt, J.S. An IgG-transporting Fc receptor expressed in the syncytiotrophoblast of human placenta. *Eur J Immunol* 1996;**26**(7):1527-1531.
75. Ellinger, I., Schwab, M., Stefanescu, A., Hunziker, W. & Fuchs, R. IgG transport across trophoblast-derived BeWo cells: a model system to study IgG transport in the placenta. *Eur J Immunol* 1999;**29**(3):733-744.

76. Grubb, J.H., Vogler, C., Tan, Y., Shah, G.N., MacRae, A.F. & Sly, W.S. Infused Fc-tagged beta-glucuronidase crosses the placenta and produces clearance of storage in utero in mucopolysaccharidosis VII mice. *Proc Natl Acad Sci U S A* 2008;**105**(24):8375-8380.
77. Georgescu M, L.T., Sponagle K, Hebert K, Drager D, & Patarroyo-White S, H.C., Jiang H and Lillicrap D. Abstracts of the XXV Congress of the International Society on Thrombosis and Haemostasis, June 20-25, 2015. AS192: Factor VIII tolerance induction in haemophilia A mice via transplacental transfer of recombinant factor VIII Fc. *J Thromb Haemost* 2015;**13 Suppl 2**:1-997.
78. Simister, N.E. Placental transport of immunoglobulin G. *Vaccine* 2003;**21**(24):3365-3369.
79. Bray, G.L., Kroner, B.L., Arkin, S., Aledort, L.W., Hilgartner, M.W., Eyster, M.E., Ragni, M.V. & Goedert, J.J. Loss of high-responder inhibitors in patients with severe hemophilia A and human immunodeficiency virus type 1 infection: a report from the Multi-Center Hemophilia Cohort Study. *Am J Hematol* 1993;**42**(4):375-379.
80. Whelan, S.F., Hofbauer, C.J., Horling, F.M., Allacher, P., Wolfsegger, M.J., Oldenburg, J., Male, C., Windyga, J., Tiede, A., Schwarz, H.P., Scheiflinger, F. & Reipert, B.M. Distinct characteristics of antibody responses against factor VIII in healthy individuals and in different cohorts of hemophilia A patients. *Blood* 2013;**121**(6):1039-1048.
81. Jacquemin, M.G., Desqueper, B.G., Benhida, A., Vander Elst, L., Hoylaerts, M.F., Bakkus, M., Thielemans, K., Arnout, J., Peerlinck, K., Gilles, J.G., Vermynen, J. & Saint-Remy, J.M. Mechanism and kinetics of factor VIII inactivation: study with an IgG4 monoclonal antibody derived from a hemophilia A patient with inhibitor. *Blood* 1998;**92**(2):496-506.
82. Jacquemin, M., Vantomme, V., Buhot, C., Lavend'homme, R., Burny, W., Demotte, N., Chaux, P., Peerlinck, K., Vermynen, J., Maillere, B., van der Bruggen, P. & Saint-Remy, J.M. CD4+ T-cell clones specific for wild-type factor VIII: a molecular mechanism responsible for a higher incidence of inhibitor formation in mild/moderate hemophilia A. *Blood* 2003;**101**(4):1351-1358.
83. Ettinger, R.A., James, E.A., Kwok, W.W., Thompson, A.R. & Pratt, K.P. Lineages of human T-cell clones, including T helper 17/T helper 1 cells, isolated at different stages of anti-factor VIII immune responses. *Blood* 2009;**114**(7):1423-1428.
84. Ettinger, R.A., Paz, P., James, E.A., Gunasekera, D., Aswad, F., Thompson, A.R., Matthews, D.C. & Pratt, K.P. T cells from hemophilia A subjects recognize the same HLA-restricted FVIII epitope with a narrow TCR repertoire. *Blood* 2016;**128**(16):2043-2054.
85. Astermark, J., Oldenburg, J., Pavlova, A., Berntorp, E., Lefvert, A.K. & Group, M.S. Polymorphisms in the IL10 but not in the IL1beta and IL4 genes are associated with inhibitor development in patients with hemophilia A. *Blood* 2006;**107**(8):3167-3172.

86. Astermark, J., Donfield, S.M., DiMichele, D.M., Gringeri, A., Gilbert, S.A., Waters, J., Berntorp, E. & Group, F.S. A randomized comparison of bypassing agents in hemophilia complicated by an inhibitor: the FEIBA NovoSeven Comparative (FENOC) Study. *Blood* 2007;**109**(2):546-551.
87. Eckhardt, C.L., Astermark, J., Nagelkerke, S.Q., Geissler, J., Tanck, M.W., Peters, M., Fijnvandraat, K. & Kuijpers, T.W. The Fc gamma receptor IIa R131H polymorphism is associated with inhibitor development in severe hemophilia A. *J Thromb Haemost* 2014;**12**(8):1294-1301.
88. Repesse, Y., Peyron, I., Dimitrov, J.D., Dasgupta, S., Moshaj, E.F., Costa, C., Borel-Derlon, A., Guillet, B., D'Oiron, R., Aouba, A., Rothschild, C., Oldenburg, J., Pavlova, A., Kaveri, S.V., Lacroix-Desmazes, S. & consortium, A. Development of inhibitory antibodies to therapeutic factor VIII in severe hemophilia A is associated with microsatellite polymorphisms in the HMOX1 promoter. *Haematologica* 2013;**98**(10):1650-1655.
89. Gouw, S.C., van den Berg, H.M., Fischer, K., Auerswald, G., Carcao, M., Chalmers, E., Chambost, H., Kurnik, K., Liesner, R., Petrini, P., Platokouki, H., Altisent, C., Oldenburg, J., Nolan, B., Garrido, R.P., Mancuso, M.E., Rafowicz, A., Williams, M., Clausen, N., Middelburg, R.A., Ljung, R., van der Bom, J.G. & Group, P.a.R.o.D.o.l.d.R.S. Intensity of factor VIII treatment and inhibitor development in children with severe hemophilia A: the RODIN study. *Blood* 2013;**121**(20):4046-4055.
90. Algiman, M., Dietrich, G., Nydegger, U.E., Boieldieu, D., Sultan, Y. & Kazatchkine, M.D. Natural antibodies to factor VIII (anti-hemophilic factor) in healthy individuals. *Proc Natl Acad Sci U S A* 1992;**89**(9):3795-3799.
91. Hu, G.L., Okita, D.K. & Conti-Fine, B.M. T cell recognition of the A2 domain of coagulation factor VIII in hemophilia patients and healthy subjects. *J Thromb Haemost* 2004;**2**(11):1908-1917.
92. Meunier, S., Menier, C., Marcon, E., Lacroix-Desmazes, S., Maillère, B. CD4 T cells specific for factor VIII are present at high frequency in healthy donors and comprise naïve and memory cells. *Blood Advances* 2017;**1**(21):1842-1847.
93. Martino, D., Gargaro, M., Santagostino, E., Di Minno, M.N., Castaman, G., Morfini, M., Rocino, A., Mancuso, M.E., Di Minno, G., Coppola, A., Talesa, V.N., Volpi, C., Vacca, C., Orabona, C., Iannitti, R., Mazzucconi, M.G., Santoro, C., Tosti, A., Chiappalupi, S., Sorci, G., Tagariello, G., Belvini, D., Radossi, P., Landolfi, R., Fuchs, D., Boon, L., Pirro, M., Marchesini, E., Grohmann, U., Puccetti, P., Iorio, A. & Fallarino, F. IDO1 suppresses inhibitor development in hemophilia A treated with factor VIII. *J Clin Invest* 2015;**125**(10):3766-3781.
94. Eckhardt, C.L., van Velzen, A.S., Peters, M., Astermark, J., Brons, P.P., Castaman, G., Cnossen, M.H., Dors, N., Escuriola-Ettingshausen, C., Hamulyak, K., Hart, D.P., Hay, C.R., Haya, S., van Heerde, W.L., Hermans, C., Holmstrom, M., Jimenez-Yuste, V., Keenan, R.D., Klamroth, R., Laros-

- van Gorkom, B.A., Leebeek, F.W., Liesner, R., Makipernaa, A., Male, C., Mauser-Bunschoten, E., Mazzucconi, M.G., McRae, S., Meijer, K., Mitchell, M., Morfini, M., Nijziel, M., Oldenburg, J., Peerlinck, K., Petrini, P., Platokouki, H., Reitter-Pfoertner, S.E., Santagostino, E., Schinco, P., Smiers, F.J., Siegmund, B., Tagliaferri, A., Yee, T.T., Kamphuisen, P.W., van der Bom, J.G., Fijnvandraat, K. & Group, I.S. Factor VIII gene (F8) mutation and risk of inhibitor development in nonsevere hemophilia A. *Blood* 2013;**122**(11):1954-1962.
95. Franchini, M. Current management of hemophilia B: recommendations, complications and emerging issues. *Expert Rev Hematol* 2014;**7**(5):573-581.
96. Giansily-Blaizot, M. & Schved, J.F. Recombinant human factor VIIIa (rFVIIIa) in hemophilia: mode of action and evidence to date. *Ther Adv Hematol* 2017;**8**(12):345-352.
97. Lillicrap, D., Schiviz, A., Apostol, C., Wojciechowski, P., Horling, F., Lai, C.K., Piskernik, C., Hoellriegel, W. & Lollar, P. Porcine recombinant factor VIII (Obizur; OBI-1; BAX801): product characteristics and preclinical profile. *Haemophilia* 2015. doi: 10.1111/hae.12784. [Epub ahead of print]
98. Turecek, P.L., Varadi, K., Gritsch, H. & Schwarz, H.P. FEIBA: mode of action. *Haemophilia* 2004;**10** Suppl 2:3-9.
99. Lenting, P.J., Denis, C.V. & Christophe, O.D. Eficizumab, a bispecific antibody recognizing coagulation factors IX and X: how does it actually compare to factor VIII? *Blood* 2017;**130**(23):2463-2468.
100. Gilles, J.G., Grailly, S.C., De Maeyer, M., Jacquemin, M.G., VanderElst, L.P. & Saint-Remy, J.M. In vivo neutralization of a C2 domain-specific human anti-Factor VIII inhibitor by an anti-idiotypic antibody. *Blood* 2004;**103**(7):2617-2623.
101. Hausl, C., Ahmad, R.U., Sasgary, M., Doering, C.B., Lollar, P., Richter, G., Schwarz, H.P., Turecek, P.L. & Reipert, B.M. High-dose factor VIII inhibits factor VIII-specific memory B cells in hemophilia A with factor VIII inhibitors. *Blood* 2005;**106**(10):3415-3422.
102. Waters, B., Qadura, M., Burnett, E., Chegeni, R., Labelle, A., Thompson, P., Hough, C. & Lillicrap, D. Anti-CD3 prevents factor VIII inhibitor development in hemophilia A mice by a regulatory CD4+CD25+-dependent mechanism and by shifting cytokine production to favor a Th1 response. *Blood* 2009;**113**(1):193-203.
103. Hay, C.R., DiMichele, D.M. & Study, I.I.T. The principal results of the International Immune Tolerance Study: a randomized dose comparison. *Blood* 2012;**119**(6):1335-1344.

104. Kenet, G., Oladapo, A., Epstein, J.D., Thompson, C., Novack, A. & Nugent, D.J. Estimating the potential cost of a high dose immune tolerance induction (ITI) therapy relative to the cost of a combined therapy of a low dose ITI therapy with bypassing agent prophylaxis. *Haemophilia* 2017;**23**(5):e394-e402.
105. Roopenian, D.C. & Akilesh, S. FcRn: the neonatal Fc receptor comes of age. *Nat Rev Immunol* 2007;**7**(9):715-725.
106. Bitonti, A.J., Dumont, J.A., Low, S.C., Peters, R.T., Kropp, K.E., Palombella, V.J., Stattel, J.M., Lu, Y., Tan, C.A., Song, J.J., Garcia, A.M., Simister, N.E., Spiekermann, G.M., Lencer, W.I. & Blumberg, R.S. Pulmonary delivery of an erythropoietin Fc fusion protein in non-human primates through an immunoglobulin transport pathway. *Proc Natl Acad Sci U S A* 2004;**101**(26):9763-9768.
107. Peters, R.T., Toby, G., Lu, Q., Liu, T., Kulman, J.D., Low, S.C., Bitonti, A.J. & Pierce, G.F. Biochemical and functional characterization of a recombinant monomeric Factor VIII-Fc fusion protein. *J Thromb Haemost* 2013;**11**(1):132-141.
108. Osterberg, T., Fatouros, A. & Mikaelsson, M. Development of freeze-dried albumin-free formulation of recombinant factor VIII SQ. *Pharm Res* 1997;**14**(7):892-898.
109. Fatouros, A. & Sjostrom, B. Recombinant factor VIII SQ--the influence of formulation parameters on structure and surface adsorption. *Int J Pharm* 2000;**194**(1):69-79.
110. Wang, X., Kumar, R., Navarre, J., Casanova, J.E. & Goldenring, J.R. Regulation of vesicle trafficking in madin-darby canine kidney cells by Rab11a and Rab25. *J Biol Chem* 2000;**275**(37):29138-29146.
111. Gan, Z., Ram, S., Vaccaro, C., Ober, R.J. & Ward, E.S. Analyses of the recycling receptor, FcRn, in live cells reveal novel pathways for lysosomal delivery. *Traffic* 2009;**10**(5):600-614.
112. Grant, B.D. & Donaldson, J.G. Pathways and mechanisms of endocytic recycling. *Nat Rev Mol Cell Biol* 2009;**10**(9):597-608.
113. Weflen, A.W., Baier, N., Tang, Q.J., Van den Hof, M., Blumberg, R.S., Lencer, W.I. & Massol, R.H. Multivalent immune complexes divert FcRn to lysosomes by exclusion from recycling sorting tubules. *Mol Biol Cell* 2013;**24**(15):2398-2405.
114. Young, G., Mahlangu, J., Kulkarni, R., Nolan, B., Liesner, R., Pasi, J., Barnes, C., Neelakantan, S., Gambino, G., Cristiano, L.M., Pierce, G.F. & Allen, G. Recombinant factor VIII Fc fusion protein for the prevention and treatment of bleeding in children with severe hemophilia A. *J Thromb Haemost* 2015;**13**(6):967-977.

115. Fischer, R., Turnquist, H.R., Taner, T. & Thomson, A.W. Use of rapamycin in the induction of tolerogenic dendritic cells. *Handb Exp Pharmacol* 2009;(188):215-232.
116. Ragni, M.V., Alabek, M. & Malec, L.M. Inhibitor development in two cousins receiving full-length factor VIII (FVIII) and FVIII-Fc fusion protein. *Haemophilia* **22**, e462-464 (2016).
117. Malec, L.M.R., M.V.; Journeycake, J.M.; Alabek, M. . Immune Tolerance Induction Using RfviiiFc (Eloctate) *American Society of Hematology*. Orlando, FL; 2015.
118. Carcao, M. Abstracts. *Research and Practice in Thrombosis and Haemostasis* **1**, 1-1451 (2017).
119. Ragni, M.V. & Malec, L.M. Design of the INHIBIT trial: preventing inhibitors by avoiding 'danger', prolonging half-life and promoting tolerance. *Expert Rev Hematol* 2014;**7**(6):747-755.
120. Clough, A.M., Gilreath, J.A., McPherson, J.P., Link, N.C., Rodgers, G.M. & Nance, D. Implementation of a recombinant factor IX Fc fusion protein extended-infusion desensitization protocol. *Haemophilia* 2017;**23**(3):e227-e230.

Table 1: Human Fc Receptors															
	Classical FcγR						Non-Classical FcR								
	FcγRI	FcγRIIa	FcγRIIb	FcγRIIc	FcγRIIIa	FcγRIIIb	FcRn	DC-SIGN	CD22	CD23	TRIM21	FCRL1-6	FCRLA	FCRLB	
Other name	CD64	CD32A	CD32B	CD32C	CD16A	CD16B	Brambell Receptor	CD209; CLEC4L	SIGLEC2	FcεRII	Ro52	CD307a-f			
Cellular distribution	Surface plasma membrane						Surface and Endosomes	Surface plasma membrane		Surface	Cytoplasmic	Surface	Intracellular Compartments		
Functional outcome	Activation		Inhibition	Activation			IgG recycling; CIC responses	Ag presentation	Inhibition	Activation	Activation; viral degradation	Inhibition/Activation?	IgG retention during affinity maturation		
Cellular Expression	Hematopoietic						Most nucleated cells	Myeloid	B cells	Hematopoietic; epithelia	Most nucleated cells	Lymphocytes; Mainly B cells	Germinal center B cells		
Ig binding affinity	IgG, High	IgG, Low/Medium					IgG, High; pH dependent	sialylated IgG, Medium	Sialylated glycans, sIgM, CD45	IgE Low	IgG, IgM and IgA, Medium	IgG aggregates Low/Medium	IgG Low		

Ag, antigen; s, surface;

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Prepublished online March 27, 2018;
doi:10.1182/blood-2017-12-822908

Tolerogenic properties of Fc portion of IgG and its relevance to the treatment and management of hemophilia

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