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A Meningococcal Factor H Binding Protein Mutant That Eliminates Factor H Binding Enhances Protective Antibody Responses to Vaccination

Peter T. Beernink,* Jutamas Shaughnessy,† Emily M. Braga,* Qin Liu,‡ Peter A. Rice,† Sanjay Ram,† and Dan M. Granoff*†

Certain pathogens recruit host complement inhibitors such as factor H (fH) to evade the immune system. Microbial complement inhibitor-binding molecules can be promising vaccine targets by eliciting Abs that neutralize this microbial defense mechanism. One such Ag, meningococcal factor H-binding protein (fHbp), was used in clinical trials before the protein was discovered to bind fH. The potential effect of fH binding on vaccine immunogenicity had not been assessed in experimental animals because fHbp binds human fH specifically. In this study, we developed a human fH transgenic mouse model. Transgenic mice immunized with fHbp vaccine had 4- to 8-fold lower serum bactericidal Ab responses than those of control mice whose native fH did not bind the vaccine. In contrast, Ab responses were unimpaired in transgenic mice immunized with a control meningococcal group C polysaccharide–protein conjugate vaccine. In transgenic mice, immunization with an fH nonbinding mutant of fHbp elicited Abs with higher bactericidal activity than that of fHbp vaccination itself. Abs elicited by the mutant fHbp more effectively blocked fH binding to wild-type fHbp than Abs elicited by fHbp that bound fH. Thus, a mutant fHbp vaccine that does not bind fH but that retains immunogenicity is predicted to be superior in humans to an fHbp vaccine that binds human fH. In the case of mutant fHbp vaccination, the resultant Ab responses may be directed more at epitopes in or near the fH binding site, which result in greater complement-mediated serum bactericidal activity; these epitopes may be obscured when human fH is bound to the wild-type fHbp vaccine. The Journal of Immunology, 2011, 186: 3606–3614.

Surface-exposed proteins from bacterial pathogens are potential vaccine candidates when they are targets of complement-dependent bactericidal or opsonophagocytic Abs. Bacterial surface proteins that also bind host complement inhibitors (or complement downregulators) are particularly attractive as vaccine candidates (1, 2) because Abs directed against them may also block binding of the complement inhibitors. Binding of these inhibitors allows certain bacterial species to evade a host innate immune defense that would otherwise result in death of the organism. Downregulation of complement activation occurs when the complement inhibitors are in close proximity to active complement components that are located nearby on the bacterial surface, thereby permitting the organism to disarm a key component(s) of innate host defense and cause disease. Factor H (fH) is one such important complement inhibitor. A soluble-phase inhibitor of the alternative pathway of complement, fH inhibits the assembly of an active C3 convertase by competing with factor B for C3b binding, accelerating the decay of the alternative pathway C3 convertase (C3b,Bb), while also acting as a cofactor in factor I-mediated cleavage of C3b to iC3b (3–7). Recently, genetic variation in the human fH gene cluster was found to affect susceptibility to developing meningococcal disease (8).

The vaccine potential of a number of microbial proteins that bind inhibitors of complement is an active area of investigation. These include, for example, M-protein (Streptococcus pyogenes) (9, 10), OspE (Borrelia burgdorferi) (11), PspC (Streptococcus pneumoniae) (12, 13), and GNA1870 (Neisseria meningitidis); the latter is also known as factor H-binding protein (fHbp) (14). A vaccine that elicits Abs directed at bacterial ligands for complement inhibitors, such as fH, could confer protection by dual mechanisms: 1) by binding of the Abs to the surface of the pathogen, which results in direct activation of complement, and 2) by blocking binding of the complement inhibitor (e.g., fH), thereby enhancing susceptibility of the pathogen to complement-mediated bactericidal or opsonic activity. N. meningitidis is a major cause of bacterial meningitis and sepsis worldwide. The organism binds both fH and C4BP to its surface (14–16), although maximum C4BP binding is observed only under conditions of low stringency, which may limit its physiological role (15). When fH is bound to the meningococcal cell surface, the ability of fH to downregulate complement activation enables the organism to survive in human serum or blood (16–18). Ligands for fH binding to meningococci include a surface-exposed lipoprotein referred to as fHbp and a second recently described receptor protein, Neisserial surface protein A (NspA) (19). NspA may be important for evasion of complement-mediated killing by strains with low fHbp expression.
Recombinant fHbp Ags are part of two promising group B meningococcal vaccines that are in late-stage clinical development (20). These vaccines elicited serum bactericidal Ab responses in mice (21–23) and humans (24–26). It was only after fHbp vaccine had been developed and tested in clinical trials that the Ag was discovered to bind to fH (14). Furthermore, binding of fH to fHbp was found to be specific for human fH (27). A potential undesirable consequence of targeting an Ag that binds a human complement inhibitory protein is formation of a complex between the vaccine Ag and complement protein, which might interfere with Ag presentation and protective Ab responses.

The purpose of the current study was to investigate fHbp immunogenicity under conditions where human fH was present; to accomplish this, we developed a human fH transgenic mouse model. We also investigated the immunogenicity of a newly identified mutant fHbp vaccine containing a single amino acid substitution that eliminated fH binding to mutant fHbp but that retained immunogenicity in wild-type mice. By eliminating fH binding, we hypothesized that in human fH transgenic mice, the mutant fHbp vaccine would elicit serum Abs with greater potential for protection (e.g., greater bactericidal activity) than that of Abs elicited by wild-type fHbp.

Materials and Methods

Generation of human fH transgenic mice

Full-length cDNA encoding human fH (3.9 kb) was subcloned into the EcoRI site of the expression vector pCAGGS (28). A CMV enhancer and chicken β-actin promoter sequences are located upstream of the EcoRI site in pCAGGS. A rabbit γ-globin poly(A) sequence is located downstream of the EcoRI site. The resulting plasmid, pCAGGS-human fH, was digested with SalI and PstI to isolate the transgenic cassette fragment consisting of the CMV enhancer, the chicken β-actin promoter, the human fH cDNA, and the rabbit β-globin poly(A) sequence. The isolated ~6 kb SalI and PstI fragment was purified for microinjection into mouse embryos from BALB/c mice. Mouse embryos were implanted into pseudo-pregnant female BALB/c mice (Charles River Breeding Laboratories) at the Transgenic Facility of the University of Massachusetts Medical School. Human fH transgenic mice initially were identified by PCR analysis using genomic DNA prepared from mouse tails. A region inside cDf was amplified by PCR using primers 5′-CATCTGCCTGACATCTTCCAAA-3′ and 5′-CTTCCAAA-3′ and 5′-ATCTAATGTGCTGTGGTTACCC-3′ to yield a 232-bp product. Amplified products were electrophoretically resolved in 2% TAE agarose gels and were visualized by ethidium bromide staining under UV light. Expression of human fH in sera of pups was determined immunogenicity in wild-type mice. By eliminating fH binding, we hypothesized that in human fH transgenic mice, the mutant fHbp vaccine would elicit serum Abs with greater potential for protection (e.g., greater bactericidal activity) than that of Abs elicited by wild-type fHbp.

 Serum human fH concentrations

To distinguish human from mouse fH, we used an fHbp capture ELISA that specifically binds human fH. Recombinant fHbp (2 μg/ml) in sterile PBS was adsorbed to wells of microtiter plates. After blocking with 1% BSA, dilutions of preimmune mouse (wild-type or transgenic) or human sera were added. Bound human fH was detected using sheep anti-human fH (Lifespan Biosciences, Seattle, WA). Human fH concentrations were determined in comparison with a standard human fH curve generated from human spermatozoa. Bound human fH concentration was determined by comparison with the human fH standard curve. All sera were assayed in duplicate.

Recombinant fHbp

The gene encoding fHbp ID 1 (http://pubmlst.org/Neisseria/fHbp) was subcloned into expression plasmid pET21b as described previously (22). A R41S substitution was introduced by changing the codon AGG to AGC in the fHbp gene using the QuickChange II Site-Directed Mutagenesis Kit (Agilent Technologies, Santa Clara, CA) and the manufacturer’s protocol. Recombinant fHbp and R41S mutant proteins were purified by Ni2+ affinity chromatography as previously described (22, 29). Molecular mass and purity were assessed by SDS-PAGE (NuPAGE; Invitrogen, Carlsbad, CA), and the thermal stability was monitored by differential scanning calorimetry (VP-DSC; Microcal, Northampton, MA), which was performed as previously described (30). Binding of human fH and anti-fHbp mAbs (31, 32) to recombinant fHbp was measured by ELISA as described previously (22, 29). Surface plasmon resonance experiments were performed by immobilizing purified human fH (Complement Technology; 2400 or 4000 response units) on a CM5 chip (GE Healthcare, Piscataway, NJ) via amine coupling. Binding of soluble fHbp to immobilized fH was measured at concentrations ranging from 0.016 to 5 μM using a BLIcore X/100 instrument (GE Healthcare).

Mouse immunogenicity

The immunogenicity of fHbp and R41S mutant fHbp vaccines was evaluated in 6- to 8-wk-old BALB/c wild-type or human fH transgenic mice. Three doses of fHbp vaccine containing 20 μg fHbp adsorbed with 600 μg aluminum hydroxide were administered i.p. at 3-wk intervals. Control immunization was performed using the same schedule with a meningococcal group C conjugate vaccine (Meningitec; Wyeth, Montreal, Quebec, Canada). Each dose contained 2 μg polysaccharide and 3 μg CRM197 diphtheria toxoid protein adsorbed with 100 μg aluminum phosphate.

The Institutional Animal Care and Use Committees at the University of Massachusetts Medical School and Children’s Hospital Oakland Research Institute approved the respective protocols performed at each study site.

Measurement of serum Ab responses

Serum IgG anti-fHbp Ab responses were measured by ELISA as described previously (30). IgG anti-CRM and anticapsular Ab responses were measured using diphtheria CRM197 (List Biological Laboratories, Campbell, CA) and group C meningococcal polysaccharide conjugated to adipic dihydrazide (33) as the Ags on the plate, respectively. Serum bactericidal Ab responses were measured using log-phase bacteria and human serum depleted of IgG as a complement source as previously described (34). Brieﬂy, a 1-ml aliquot of human serum was passed over a protein G column (HiTrap; GE Life Sciences, Piscataway, NJ) equilibrated with PBS, and the ﬂow-through fraction was collected. The IgG-depleted fraction exhibited a >95% decrease in IgG concentration measured by ELISA and ~30% decrease in hemolytic complement activity measured with the EZ Complement CH50 test kit (Diamedix Corp., Miami, FL), which resulted, in part, from dilution of the serum sample. To compensate for the lower CH50 activity, 12 μl of the IgG-depleted serum was added to the 40 μl (30%) bactericidal reaction instead of 8 μl (20%) of nondepleted serum. Bactericidal responses to fHbp vaccines were determined using group B strain H44/76 (B:15:P1.7,16; ST-32), which originally was a case isolate from an epidemic in Norway (35) and was obtained from Novartis Vaccines [referred to as 44/76-SL (36)]. This strain is a relatively high expresser of fHbp (37). Bactericidal responses to the group C polysaccharide protein conjugate vaccine were measured using group C strain 2423 (C:2a:PL1.5,2; ST-11) (38), which is an invasive clinical isolate from Dallas County, TX (39, 40).

Anti-fHbp Ab inhibition of human fH binding to fHbp

Inhibition of human fH binding to fHbp by serum anti-fHbp Abs was measured by ELISA (41). fHbp was affixed to microtiter wells as described above. To compare inhibition of fHbp binding to fHbp by Abs raised against fHbp (itself) or the R41S mutant vaccines, we tested individual sera from vaccinated transgenic mice (n = 11 per vaccine group) at four dilutions (1:100, 1:400, 1:1600, and 1:6400); each dilution was tested in the presence of 5% IgG-depleted human serum (pool of three individuals) as a source of exogenous human fH. After incubation for 2 h at room temperature, wells were washed, and bound human fH was detected with sheep anti-human fH (1:7000; Lifespan Biosciences, Seattle, WA) followed by donkey anti-sheep IgG conjugated to alkaline phosphatase (GE Life Sciences, Piscataway, NJ). Optical density (OD) values were used to test whether the amount of human fH bound in the absence of the mouse serum.

Statistical analyses

Two-tailed Student t tests were used to compare reciprocal geometric mean titers (GMTs) of serum Ab responses between two independent groups of mice. An exception was in Study 2, where we used a one-tailed t test to examine whether anti-fHbp Ab responses of transgenic mice immunized with the wild-type fHbp vaccine were not lower than those of immunized wild-type mice, which was justified based on the lower responses in transgenic mice observed in Study 1. General linear regression models were used to test whether the type of fHbp vaccine and human fH

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concentrations affected serum bactericidal Ab responses. In addition, we calculated the Pearson correlation coefficients between log₂ serum bactericidal titers and log₁₀ human fH concentrations of transgenic mice immunized with the fHbp that bound human fH and the mutant vaccine that did not bind human fH. The test of equality of two Pearson correlation coefficients drawn from the two different samples was performed as described (42). To meet normality assumption, both serum bactericidal Ab measurements and fH concentrations were log₁₀ transformed in regression and correlation analyses. A two-tailed p value ≤0.05 was considered statistically significant.

Results
A mutant fHbp with a single amino acid substitution, R41S, does not bind human fH

Based on a published crystal structure of fHbp bound to a fragment of fH (43), the arginine residue at position 41 forms a charged hydrogen-bond with fH (Fig. 1A, R41). We predicted that fH binding might be eliminated if the arginine were replaced by serine (Fig. 1A, S41). Because most of the important fHbp epitopes that elicit bactericidal Ab have been reported to be in the terminal domain of the protein (46), and JAR 5, which recognized by JAR 4, which involved residues 25–27 and 57–59 in the N-terminal domain (31), which was proximal to the amino acid substitution. By ELISA, the wild-type and R41S mutant fHbp vaccines elicited similar respective concentration-dependent binding responses to the mutant fHbp. The purified wild-type and R41S mutant proteins were adsorbed to the wells of the microtiter plate. Further, this control indicated that comparable amounts of the respective native fHbp Ag. The R41S mutant fHbp has preserved immunogenicity in wild-type mice

In wild-type mice whose serum fH did not bind to either vaccine Ag, the wild-type and R41S mutant fHbp vaccines elicited similar serum bactericidal Ab responses (reciprocal GMTs of 77 and 71, respectively; p = 0.32 by t test) (Fig. 3, Initial Study). In contrast, a separate mutant fHbp vaccine, E218A/E239A, which previously

FIGURE 1. A, Structural model of fHbp bound to a fragment of fH based on published atomic coordinates (43). The blue and green ribbons represent the respective N- and C-terminal domains of the fHbp molecule. The gray ribbon represents the sixth and seventh short consensus repeat domains of human fH previously shown to mediate the interaction of human fH and fHbp (43). The arginine residue at position 41 formed a charged H-bond with fH (left lower inset), which was predicted to be eliminated when arginine was replaced by serine (right lower inset). B, SDS-PAGE of fHbp. Wild-type (WT) fHbp and R41S mutant fHbp (5 μg/lane) were separated on 4–12% polyacrylamide gradient gel (NuPAGE; Invitrogen) and stained with Coomassie blue. The molecular masses (in kDa) of the protein standards (Std) are labeled on the left.
had been reported not to bind to fH (43) and to have impaired immunogenicity in wild-type mice (30), elicited significantly lower bactericidal titers (reciprocal GMT of 9 versus 77 for the wild-type fHbp, $p = 0.01$ by $t$ test) (Fig. 3, Initial Study). These results confirmed diminished Ab responses from possible loss of epitopes or minor destabilization of the C-terminal domain of the molecule that contained the E218A and E239A substitutions, which is in the region of the molecule reported to contain the majority of the epitopes responsible for generating bactericidal Abs (44). In contrast, the Ab responses of the wild-type mice to the R41S mutant fHbp vaccine indicated that substitution of serine for arginine in the N-terminal domain did not decrease immunogenicity. The similar bactericidal Ab responses to the wild-type and R41S mutant fHbp vaccines were replicated in an independent study (reciprocal GMT of 115 versus 83, $p = 0.90$) (Fig. 3, Replicate Study).

Generation of human fH transgenic mice

To test the effect of human fH on the immunogenicity of fHbp vaccines, we generated human fH transgenic mice by microinjection of embryos with a PCR product containing the human fH cDNA (Fig. 4A), which was performed as described in Materials and Methods. Transgenic mice containing human fH in their sera were identified by Western blotting (Fig. 4B). We quantified human fH in transgenic or wild-type mice using an fHbp capture ELISA (Fig. 4C). Wild-type mice had no detectable serum human fH (reciprocal GMT of 115 versus 83, $p = 0.90$). The mean fH concentration of human fH in the sera of the transgenic mice was 268 ± 128 µg/ml. The mean fH concentration ± SD in the human sera was 284 ± 75 µg/ml. The respective means were not significantly different ($p = 0.57$), but the variance of the fH concentrations of the human sera was lower than in transgenic mice ($F = 2.89; p = 0.008$).

Binding of human fH decreases the immunogenicity of fHbp vaccine

In two studies, human fH transgenic or wild-type mice were immunized with a recombinant fHbp vaccine that bound human fH. Three weeks after the third injection of vaccine, the serum IgG anti-fHbp Ab responses of the transgenic mice were lower than
those of the wild-type mice (Study 1, reciprocal GMT of 30,000 versus 97,000, \( p = 0.03 \); Study 2, reciprocal GMT of 107,000 versus 190,000, \( p = 0.025 \) (Fig. 5A)). In Study 1, the serum bactericidal Ab responses of the transgenic mice were 8-fold lower than those of the wild-type mice whose \( fH \) did not bind the vaccine (reciprocal GMT of 59 versus 453 in wild-type mice, \( p = 0.03 \)) (Fig. 5B). In Study 2, transgenic mice immunized with the \( fHbp \) vaccine that bound human \( fH \) again had lower serum bactericidal Ab responses (reciprocal GMT of 31 versus 115 in wild-type mice, \( p = 0.03 \)) (Fig. 5B). Comparing respective IgG GMTs of \( fHbp \) immunized WT and Tg mice: Study 1, \( p = 0.03 \); Study 2, \( p = 0.025 \). Comparing respective SBA GMTs of \( fHbp \) immunized WT and Tg mice: Study 1, \( p = 0.03 \); Study 2, \( p = 0.05 \).

Study 1 did not include a non-\( fHbp \) control vaccine. Therefore, we were uncertain whether the lower immunogenicity of the \( fHbp \) vaccine in the transgenic mice resulted from binding of the vaccine Ag with human \( fH \) or whether there might have been lower serum Ab responses of the transgenic animals to vaccine Ags in general. In Study 2, we included groups of transgenic and wild-type mice immunized with a control meningococcal group C polysaccharide–CRM\(_{197}\) conjugate vaccine. The respective serum IgG anti-CRM and anticapsular Ab titers and serum bactericidal Ab responses of the transgenic mice immunized with the meningococcal conjugate vaccine were not significantly different from those of the wild-type mice (Fig. 7). These results indicated that the transgenic mice responded normally to the control vaccine and that the lower responses of transgenic mice to the \( fHbp \) vaccine resulted from human \( fH \) binding to the vaccine.

A mutant \( fHbp \) that does not bind human \( fH \) has increased immunogenicity in human \( fH \) transgenic mice

In Study 2, human \( fH \) transgenic mice were immunized with the R41S mutant \( fHbp \) that did not bind \( fH \). The IgG anti-\( fHbp \) titers were not significantly different from those of control transgenic mice immunized with the wild-type \( fHbp \) that bound \( fH \) (GMT of 1:106,000 versus 1:105,000; Fig. 8A). The serum bactericidal responses to the mutant R41S \( fHbp \) vaccine were ~3-fold higher than those to the \( fHbp \) vaccine that bound \( fH \) (Fig. 8B), but the difference was not statistically significant (GMT of 96 versus 31, \( p = 0.11 \) by \( t \) test). This analysis, however, did not take into consideration a possible confounding effect of the human \( fH \) serum concentrations of the transgenic mice on serum anti-\( fHbp \) bactericidal responses. In transgenic mice immunized with the mutant \( fHbp \) that did not bind \( fH \), there was no significant cor-
relation between the serum bactericidal Ab responses and serum human fH concentrations \((r = +0.17; p = 0.58; \text{Fig. 6B})\), whereas as described above, there was an inverse correlation with the bactericidal titers elicited by the wild-type vaccine that bound fH \((r = -0.65; p = 0.02; \text{Fig. 6A})\). The respective correlation coefficients for the two vaccines were significantly different from each other \((p = 0.03)\).

By general linear regression, there was a significant interaction between the type of fHbp vaccine and the human fH concentration on the bactericidal response \((\text{likelihood ratio test}, p = 0.018)\). To determine if the type of fHbp vaccine \((\text{fHbp wild-type or R41S mutant})\) affected the serum bactericidal Ab responses of the transgenic mice, we used the regression model to estimate ratios of the reciprocal serum bactericidal GMT of transgenic mice immunized with the R41S mutant vaccine over those of transgenic mice immunized with the fHbp vaccine that bound fH at various serum human fH concentrations \((\text{Fig. 9})\). Whereas there were no significant differences in bactericidal responses when serum human fH concentrations were low \((<250 \mu g/ml)\), the bactericidal responses to the R41S mutant vaccine were significantly higher when the serum fH concentrations were higher than 250 \mu g/ml \((p < 0.05)\), or higher than 316 \mu g/ml \((p < 0.01)\). Because many humans have fH concentrations in this range \((\text{Fig. 4C})\), the results suggested that mutant fHbp molecules that do not bind fH might be superior vaccines in humans.

**Abs elicited by the R41S mutant fHbp vaccine have superior inhibition of binding of fH to the nominal vaccine, fHbp**

Binding of human fH to a fHbp vaccine may occlude epitopes on the vaccine Ag that may be necessary to interact with immune cells that influence production of anti-fHbp Abs with functional activity.

**Discussion**

In this study, we developed a human fH transgenic mouse model with the intent to investigate the role of this complement downregulator on infections unique to humans where fH has been proposed to play a role \((27, 47, 48)\). Human fH, whose amino acid sequence and structure varies from mouse fH, binds uniquely to Neisseria spp.; mouse fH does not. We carried this principle
further and investigated the effect of immunization with the \textit{N. meningitidis} outer membrane protein vaccine candidate, fHbp. To our knowledge, this study represents the first report of expression in a mouse of full-length human fH to permit fH direct binding, via short consensus repeat sequences 6 and 7 (49), to a vaccine component made from \textit{N. meningitidis}. Although the alternative pathway inhibitory action of human fH was not directly investigated in these studies, human fH is known to regulate the non-human alternative pathway of complement similar to its action on the respective human pathway (27, 47).

The respective serum Ab responses of the fH transgenic and wild-type mice to the control group C meningococcal conjugate vaccine were similar. These data indicated that the presence of the transgene and/or human fH in the transgenic mice did not impair serum IgG Ab responses to a control capsular polysaccharide or carrier protein Ag or complement-mediated bactericidal activity of the elicited anticapsular Abs. The effect of human fH on decreasing immunogenicity of the fHbp vaccine in the human fH transgenic mice, therefore, was specific for the fHbp vaccine Ag and was observed in two independent studies. Moreover, there was an inverse correlation between the serum bactericidal Ab responses in the transgenic mice immunized with the vaccine that bound human fH and the serum human fH concentrations of individual mice (Fig. 6A), which strengthened the case for a causal relationship between human fH and decreased fHbp vaccine immunogenicity. Finally, a mutant fHbp vaccine that did not bind fH but that, importantly, retained immunogenicity in wild-type mice elicited higher serum

\begin{figure}
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\caption{Serum Ab responses of human fH transgenic mice immunized in Study 2 with a mutant fHbp (R41S) vaccine that did not bind fH. A, IgG anti-fHbp responses. Titers of individual mice are represented by symbols [control fHbp wild-type (WT) vaccine, circles; R41S mutant vaccine, triangles; Al(OH)\textsubscript{3} control, filled diamonds]. The GMTs are indicated by horizontal lines. The symbols for mice immunized with negative control vaccine are from testing serum pools (each pool from three to four individual mice). Comparing respective IgG GMTs of fHbp WT and R41S mutant vaccine groups, \( p = 0.96 \). B, SBA responses measured with human complement against group B strain H44/76. Comparing respective SBA GMTs of fHbp WT and R41S mutant vaccine groups, \( p = 0.11 \). When the analysis of the SBA responses was adjusted by general linear regression for the confounding inverse effect of serum human fH concentrations on SBA responses of transgenic mice immunized with the fHbp that bound fH, the higher responses to the mutant R41S vaccine were significant (\( p = 0.018 \), see Fig. 9 and text).
}
\end{figure}

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\caption{Effect of serum human fH concentrations on ratio of bactericidal Ab responses elicited by R41S mutant fHbp vaccine versus wild-type (WT) fHbp vaccine. The respective GMT ratios (R41S mutant to fHbp WT) were estimated from the general linear regression model (see text), which showed that the effect of fHbp vaccine type differed by serum fH concentration on bactericidal titer (\( p = 0.018 \)). Based on the regression model, the ratios of the geometric mean bactericidal responses of the group immunized with R41S fHbp vaccine over that of the group immunized with WT fHbp vaccine were significantly greater than 1 (in favor of the mutant fHbp vaccine) for all human fH concentrations >250 \( \mu \)g/ml (\( p < 0.05 \)) and for >316 \( \mu \)g/ml (\( p < 0.01 \)).
}
\end{figure}
bactericidal Ab titers in transgenic mice than those of the fHbp vaccine that bound fH. Collectively, these data indicated that binding of the vaccine Ag to this complement protein, fH, impaired the development of protective Ab responses.

The possibility that a mutant fHbp molecule may be a superior vaccine candidate if it did not bind human fH had been suggested by Meri et al. (2) and Schneider et al. (43). Based on the crystal structure of fHbp binding to a fragment of fH, Schneider et al. identified two fHbp glutamate residues that were important for fH binding [at positions E218 and E239 based on the numbering of the mature fHbp beginning with the lipidated cysteine residue (22, 50)]. Factor H binding was eliminated when alanine was substituted at these two positions (43). In a subsequent study, an E218A/E229A mutant fHbp vaccine elicited lower serum bactericidal Ab responses in wild-type BALB/c and CD-1 mice compared with those of a native fHbp vaccine (30), a finding that we confirmed in this report. As noted above, residues 218 and 239 are in the region of the fHbp molecule that is also important for eliciting bactericidal Abs (44). Thus, some mutations that eliminate fH binding may occur as a result of structural changes and/or alterations of electrostatic charges of the molecule that decrease protective Ab responses.

Several lines of evidence indicate that the fHbp R41S mutant vaccine described in the current study, which does not bind human fH, may be a superior fHbp vaccine for humans. In two studies in wild-type mice, the respective serum bactericidal Ab responses elicited by the R41S mutant or the wild-type fHbp vaccines were not significantly different. These data indicated that the epitopes required for eliciting bactericidal Abs were preserved in the R41S mutant when tested in a mouse model in the absence of human fH binding to either vaccine. Second, there were no significant differences in the respective serum bactericidal Ab responses to the two fHbp vaccines in human fH transgenic mice with low human fH concentrations (Fig. 9), compared with elicitation of significantly higher serum bactericidal responses only by the mutant fHbp vaccine when serum human fH concentrations were high, but in a range present in many humans (Fig. 4C). Third, despite having elicited similar serum IgG anti-fHbp titers in transgenic mice (Fig. 8A), the R41S mutant fHbp vaccine elicited Abs with greater fH blocking activity than that of Abs elicited by the fHbp vaccine that bound fH (Fig. 10A). We propose that Abs elicited by the mutant “fHbp” vaccine that was no longer able to bind fH were directed at surface-exposed epitopes near the fH binding site, thereby inhibiting fH binding and contributing to higher serum bactericidal titers. In support of this hypothesis was a significant correlation between percentage inhibition of fH binding to fHbp and serum bactericidal titer ($r = 0.69; p = 0.004$; Fig. 10B).

Collectively, our data indicate that binding of the human complement regulatory protein, fH, to vaccine Ags can decrease protective Ab responses and that a mutant Ag freed of fH binding, in this case by replacing a large, positively charged amino acid with a smaller, more neutral one, may potentially be a superior immunogen in humans. Mutant fHbp vaccines that do not bind fH may also avoid the theoretical safety risk of exposure of the host to neoantigens, in this case in the form of an fH–fHbp immune complex, which may elicit autoreactive Abs to fH or fH bound to cell surfaces. Our findings, therefore, may have broad implications in the development of vaccines against microbes that bind other host molecules as well.

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Disclosures

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18. D.M.G. also holds a paid consultancy from Novartis. P.A.R., S.R., J.S., P.T.B., and D.M.G. are inventors on patents or patent applications in the area of meningococcal B vaccines.