Enhanced potency of a fucose-free monoclonal antibody being developed as an Ebola virus immunoprotectant

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No countermeasures currently exist for the prevention or treatment of the severe sequelae of Filovirus (such as Ebola virus; EBOV) infection. To overcome this limitation in our biodefense preparedness, we have designed monoclonal antibodies (mAbs) which could be used in humans as immunoprotectants for EBOV, starting with a murine mAb (13F6) that recognizes the heavily glycosylated mucin-like domain of the virion-attached glycoprotein (GP). Point mutations were introduced into the variable region of the murine mAb to remove predicted human T-cell epitopes, and the variable regions joined to human constant regions to generate a mAb (h-13F6) appropriate for development for human use. We have evaluated the efficacy of three variants of h-13F6 carrying different glycosylation patterns in a lethal mouse EBOV challenge model. The pattern of glycosylation of the various mAbs was found to correlate to level of protection, with aglycosylated h-13F6 providing the least potent efficacy (ED\textsubscript{50} = 33 μg). A version with typical heterogenous mammalian glycoforms (ED\textsubscript{50} = 11 μg) had similar potency to the original murine mAb. However, h-13F6 carrying complex N-glycosylation lacking core fucose exhibited superior potency (ED\textsubscript{50} = 3 μg). Binding studies using Fcγ receptors revealed enhanced binding of nonfucosylated h-13F6 to mouse and human FcγRIIa. Together the results indicate the presence of Fc N-glycans enhances the protective efficacy of h-13F6, and that mAbs manufactured with uniform glycosylation and a higher potency glycoform offer promise as biodefense therapeutics.

\textbf{Results}

Ebola viruses (EBOV; family Filoviridae) are among the most virulent infectious agents known and cause acute, and frequently fatal, hemorrhagic fever in humans and nonhuman primates. It has been reported that EBOV was weaponized by the former Soviet Union (1), and natural sporadic outbreaks occur regularly causing localized high morbidity and mortality. Due to its infectiousness and the rapidity of modern travel, the potential exists for any outbreak to become an international epidemic. Currently, there are no licensed vaccines or treatments for EBOV available. Vaccines and monoclonal antibody (mAb) antivirals have been identified as priorities by the U.S. Department of Health and Human Services for protection from EBOV used in acts of bioterrorism or war.

13F6 is a murine mAb, one of four highly protective anti-EBOV glycoprotein (GP) mAbs identified at U.S. Army Medical Research Institute of Infectious Diseases (2). 13F6 recognizes the heavily glycosylated mucin-like domain of EBOV GP and was shown to provide 100% prophylactic and therapeutic protection in a mouse challenge model (2). Murine mAbs are highly immunogenic in humans, so to make a mAb immunoprotectant more appropriate for human use, in this study we have undertaken to deimmunize (3) the 13F6 variable regions and chimerize them with human IgG\textsubscript{1} constant regions. Whereas CDR grafting/humanization of mAbs maximizes the content of amino acids derived from other human antibody sequences, deimmunization focuses on identifying and eliminating T-cell epitopes from the variable region sequences of antibodies.

The mechanism(s) by which 13F6 protects in vivo are largely unknown. 13F6 does not neutralize in vitro, as assessed by inhibition of plaque formation, even in the presence of complement (2), suggesting an important role for Fc-mediated effector functions in vivo protection. Although not required for classic neutralization of virus by steric hinderance, Fc glycosylation is required for killing of virus-infected cells by complement-dependent cytotoxicity (CDC) and by antibody-dependent cellular cytotoxicity (ADCC; refs. 4 and 5). CDC activity is initiated by the binding of complement protein C1q to the Fc regions of clusters of IgG bound to an infected cell displaying viral antigen. Similarly, ADCC activity is initiated by the binding of FcyRI (CD64) and FcyRII (CD16) on the surface of polymorphonuclear cells (PMNs) or natural killer (NK) cells to the infected cell-bound IgG Fc region. With the development of altered glycosylation pathways in yeast (6), plant (7), and mammalian cell culture (8), recent studies have begun to elucidate the role of specific glycans in enabling these effector functions. For example, elimination of core fucose has been shown to dramatically improve ADCC activity in vitro and in vivo through improved affinity for FcyRII (7–11).

Two manufacturing systems are being pursued for the EBOV immunoprotectant: traditional mammalian cell culture production in Chinese hamster ovary (CHO) cells and transient production using viral vectors (magniCON; Bayer in Nicotiana benthamiana (12, 13). By using a transgenic line of N. benthamiana (ΔXTFT) lacking plant-specific N-glycan residues (14), mAbs with highly homogenous human-like glycoforms can be generated (9, 14, 15). Comparing the efficacy of h-13F6 produced aglycosylated and glycosylated in two different production systems may help identify the mechanism(s) of action and a preferred manufacturing system for continued development of the EBOV therapeutic.

\textbf{Data deposition:} The sequences reported in this paper have been deposited in the GenBank database (accession nos. JN374688 and JN374689).

The authors declare no conflict of interest.

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generate h-13F6 (JN374688 and JN374689). The resulting deimmunized, chimeric mAb DNA (h-13F6) was expressed in two different systems. The first system, CHO cells, are currently the most common platform used to manufacture FDA-approved recombinant mAbs. A stable h-13F6 CHO line was used to produce the h-13F6 mAb that contained typical glycans commonly found on recombinant antibodies (Fig. 1). The second production method is a transient plant system (magnICON; refs. 12 and 16) in which the heavy and light chain genes are cloned into separate vectors containing different but compatible viral replicons to allow for the simultaneous expression of heavy and light chains from replicating viral segments. The heavy- and light-chain vectors were then introduced into *Agrobacterium tumefaciens* to allow for high efficiency infection of 1-mo-old *N. benthamiana* plants by vacuum infiltration.

In addition to the h-13F6 DNA used for expression in CHO cells or plants, we made an additional construct containing an alanine at N297 of the human IgG1 heavy-chain constant region (h-13F6@gly) to eliminate Fc glycosylation entirely. The h13F6agly was produced in the plant system.

To generate h-13F6 mAb with unique glycoforms, the *N. benthamiana* plants used for *Agrobacterium* infection and subsequent antibody production was in turn modified by RNAi expression to eliminate the expression of the endogenous plant-specific xylosyl and fusocyl transferase genes (14).

To determine the glycoforms of these h-13F6 variants, mAbs were purified by Protein A affinity chromatography and subjected to N-glycosylation analysis using LC-ESI-MS. Rituxan, a CHO-derived FDA-approved mAb, was included as a control. The N-glycosylation profile of the two CHO-derived mAbs (i.e., h-13F6CHO and Rituxan) exhibited 3–5 glycoforms, most of them with core α1,6 fucosylation. In both cases, nongalactosylated G0 and monogalactosylated G1 complex N-glycan structures were the major glycoforms (Fig. 1). In contrast, no fucosylated structures were detected in h-13F6@XF. This variant carried a single major complex N-glycan species, namely GnGn corresponding to the fucose-free G0 structures derived from CHO production (Fig. 1). As expected, no glycan structures were detected in h-13F6agly.

**Binding of h-13F6 Variants to Human Fcγ Receptors and Human C1q.**

Because h-13F6 is being developed for human use, we tested the ability of the variants to bind to human proteins important for IgG Fc-mediated effector functions that may contribute to the protective efficacy of the mAb.

**Affinity of mAbs for FcγRI (CD64).** Surface plasmon resonance was performed to determine the affinities of the h-13F6 mAbs for recombinant human FcγRI (Table 1), a receptor important for ADCC (4, 5). h-13F6CHO had a similar affinity to Rituxan, with the h-13F6@XF mAb showing slightly more potent binding ($P < 0.05$). Binding by h-13F6agly was significantly ($P < 0.05$) lower than all of the other mAbs tested.

**Affinity of mAbs for FcγRIII (CD16).** Surface plasmon resonance was also performed with recombinant FcγRIII (Table 1), a receptor important for induction of ADCC by NK cells (9, 10). Of the h-13F6 molecules, the aglycosylated version had the weakest affinity ($12 ± 1.0 \times 10^{-8}$ M), with CHO (7.1 ± 1.2 $\times 10^{-8}$ M) having slightly stronger affinity ($P < 0.01$), and h-13F6@XF having significantly higher affinity ($2.5 ± 0.3 \times 10^{-8}$ M; $P < 0.005$ compared with h-13F6CHO; $P < 0.001$ compared with h-13F6agly). Notably, these are all high affinities for what is traditionally considered a low- to medium-affinity receptor. In fact, the affinity of Rituxan was ∼8-fold less than h-13F6agly, 13-fold less than h-13F6CHO, and 36-fold less than h-13F6@XF ($P < 0.005$ for all comparisons).

**C1q binding.** C1q binding to the Fc region of antibodies, the first step in the classical complement cascade, is glycosylation dependent (4). The ability of the three different versions of h-13F6 to bind human C1q was compared (Fig. 2) using a standard ELISA (17). As expected, h-13F6agly did not bind C1q at the concentrations tested. In contrast, binding of both h-13F6CHO and the h-13F6@XF was observed, although h-13F6@XF was a slightly less potent binder than h-13F6CHO and Rituxan.

**Binding of mAbs to Murine FcγRs.** Because the h-13F6 mAbs were being tested in a mouse model, surface plasmon resonance was used to compare the relative binding of the mAbs to murine FcγRI, -II, and -III to support the in vivo testing (rather than to determine full kinetics for a cross-species interaction with little relevance beyond this study). With the different murine FcγRs captured on a sensor chip, a fixed concentration (5 μg/mL) of the

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### Table 1. Affinity of the h-13F6 mAbs for human FcγRI (CD64) and FcγRIII (CD16)

| mAb      | FcγRI (CD64) $K_D (\times 10^{-8} \text{ M})$ | FcγRIII (CD16) $K_D (\times 10^{-8} \text{ M})$ |
|----------|---------------------------------|---------------------------------|
| h-13F6CHO| 4.1 ± 1.2                       | 7.1 ± 1.2                        |
| h-13F6@XF| 1.6 ± 0.3                       | 2.5 ± 0.3*                      |
| h-13F6agly| 34 ± 16                         | 12 ± 1*                         |
| Rituxan  | 2.2 ± 0.7                       | 91 ± 18                         |

Surface plasmon resonance (Biacore) was performed using CMS chips coated with recombinant FcγRI and FcγRIII. Values presented are the average of 3 individual experiments with SE. *$P < 0.01$ compared with h-13F6CHO; **$P < 0.005$ compared with h-13F6CHO.

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**Fig. 1.** N-glycosylation profile of different h-13F6 glycoforms and Rituxan as determined by LS-ESI-MS. Numbers present the percentage of the different glyco-species in %. Minor glycoforms (below 5%) are not indicated. N-glycan nomenclature according to www.proglycan.com.
mAbs were bound to an NTA sensor chip. h-13F6 mAb (5 μg/ml) was subsequently flowed across the surface.

**Efficacy of mAbs Against Lethal EBOV Challenge.** To determine whether the different N-glycoforms present on the Fc region of these mAbs have an effect on efficacy in vivo, the h-13F6 variants were tested in a well established lethal EBOV challenge model. Groups of mice (n = 10) received single i.p. doses of mAb followed by a lethal challenge (1,000 pfu, ~30,000 LD<sub>50</sub>). The resulting dose–response data are shown in Fig. 4. Although a highly lethal challenge was administered, 20% of control mice survived (Fig. 5). This observation is common because of the Institutional Animal Care and Use Committee requirement that mice displaying significant morbidity be treated with a DietGel nutritional supplement. h-13F6<sub>ΔXF</sub> was more protective (ED<sub>50</sub> = 3 μg ~0.15 mg/kg) than h-13F6<sub>CHO</sub> (ED<sub>50</sub> = 11 μg ~0.55 mg/kg). For comparison, the protection reported with the original murine 13F6 mAb is also shown (2) and suggests the deimmunization and human chimerization of the murine mAb resulted in no change in efficacy. As would be expected if the protective activity of the mAb involved any Fc-mediated effector function mechanisms, the aglycosylated h-13F6<sub>agly</sub> provided less protection (ED<sub>50</sub> = 33 μg ~1.65 mg/kg). Relative potency was significantly different between h-13F6<sub>ΔXF</sub> and h-13F6<sub>CHO</sub> (relative potency: 0.26, 95% confidence interval: 0.07–0.91) and between h-13F6<sub>ΔXF</sub> and h-13F6<sub>agly</sub> (relative potency: 10.72, 95% confidence interval: 2.10–81.53).

Survival curves for the low-dose groups (3 μg, ~0.2 mg/kg) are shown in Fig. 5. Mice receiving h-13F6<sub>ΔXF</sub> were significantly protected (median survival of 18.5 d) compared with h-13F6<sub>CHO</sub> (P < 0.05; median survival of 7 d) and the negative PBS control (P < 0.05; median survival of 6 d).

**Discussion**

The h-13F6 binding results for FcγRI and c1q are consistent with previous reports demonstrating that the absence of fucose does not affect the binding of IgG1 (4, 18). Similar to other reports (8), elimination of core fucose from h-13F6 (h-13F6<sub>ΔXF</sub>) resulted in an improved affinity for FcγRIII. However, it is noteworthy that all versions of h-13F6 had superior affinity to FcγRIII than Rituxan, and in fact, displayed high affinity for what is typically considered a low-affinity receptor. A possible explanation for this may be the two-amino-acid difference between the heavy chain constant regions of h-13F6 and Rituxan (R214K, V215A) that may affect the conformation of the Fc region possibly resulting in improved affinity for FcγRIII. Alternatively, non-Fc amino acids may have a conformational affect on the Fc region. h-13F6 contains a rare Vλx light-chain variable region and the crystal structure for the murine parental mAb shows that the three light-chain complementarity-determining regions adopt unusual conformations distinct from Vκ and other Vλ light chains (19). Also noteworthy is the relatively high affinity of h-13F6<sub>agly</sub> for FcγRIII. Aglycosylated IgG is generally considered to be unable (20) or to only very weakly bind FcγRIII (21). Because 13F6 does not neutralize in vitro, the protective activity displayed by h-13F6<sub>agly</sub> may be attributable to low-level ADCC activity.

Our results suggest that Fc glycosylation of h-13F6 plays a significant role in the antiviral protection in the mouse EBOV...
model. These results are in line with a recent study that shows increased anti-lentivirus cell-mediated viral inhibition of a fucose-free anti-HIV mAb in vitro (9). Although capable of partial protection at the doses tested, h-13F6agly was less potent than h-13F6CHO with heterogenous mammalian type glycosylation. h-13F6agly, with homogenous glycans lacking a core fucose, showed increased protection by a factor greater than twofold. Elimination of core fucose dramatically improves the ADC activity of mAbs mediated by NK cells (8), but appears to have the opposite effect on the ADC activity of PMNs (22). This would suggest that the improved efficacy of h-13F6agly may be due to ADC mediated by NK cells via FcγRII. Indeed, the ED50 for the three versions of h-13F6 are comparably ranked with the K0 of the mAbs for FcγRII. A potential caveat when drawing conclusions from the mouse testing is that the in vivo data were generated from mAbs with human Fcγ regions interacting with mouse Fcγ receptors. However, the in vivo data are consistent with the in vitro binding data to the murine Fcγ receptors (Fig. 3), supporting the conclusion that the enhanced protection afforded by h-13F6agly is mediated by improved ADC activity. In addition, the observation of equivalent protection between the original hybridoma-derived murine 13F6 and h-13F6CHO (Fig. 4), combined with a previous report that a chimeric mAb with IgG1 human Fc regions can confer in vitro ADC activity and in vivo antitumor activity comparable to its fully murine parental mAb (23), suggests that the murine Fcγ receptors may have promiscuity in binding IgG from other species similar to that reported for the murine Fcγ receptor (24).

A small number of mAbs against EBOV have been found to protect in lethal mouse (2) or guinea pig challenges (25). The predictivity of these models for protection in primates is currently unknown; human mAb KZ-52 protected guinea pigs but failed to protect nonhuman primates (NHPs; ref. 26). Similarly neutralizing polyclonal antibody also failed to protect NHPs (27). However, protection with polyclonal antibody against another filovirus, Marburg, has recently been reported (John Dye et al.; Chemical and Biological Defense Science and Technology Conference, 15–19 November 2010 in Orlando, FL), suggesting that, with the right specificity, protection against EBOV should be achievable. NHP studies will help determine the potential of h-13F6 as an EBOV virus immunoprotectant for human use. In sum, we have focused on the role of glycosylation in the development of an immunoprotectant for Ebola virus. We engineered plants to produce an anti-EBOV mAb with a highly homogenous N-glycosylation profile (h-13F6agly) carrying biantennary N-glycans with terminal N-acetylgalactosamine on both branches (GnGn) and lacking potentially immunogenic plant-specific β1,2 xylose and core α1,3 fucose. The resulting glycosylation profile is considerably more uniform than typically observed in mammalian cell culture (Fig. 1). Greater homogeneity allows for more precise comparisons of the role specific glycans play in mAb functionality. Expression systems that produce recombinant mAbs from mammalian cells are typically heterogeneous mixtures of glycoforms (28). Although first described over 20 y ago in transgenic Nicotiana (29), it is only within the last 4–5 y that rapid and high-yield production of mAbs in plants has become routine (13, 30). Manufacturing in plants offers the potential for reduced cost of goods at commercial scale and very clear cost savings during early cGMP manufacturing (31, 32). A historic concern with manufacturing therapeutics in plants has centered on the potential of plant-specific sugars to be immunogenic and change drug pharmacokinetics. However, with the development of mutants of N. benthamiana with human-type glycosylation (14), these concerns have been dramatically reduced, if not eliminated. Recent studies have also shown plants are capable of producing mAbs carrying N-glycans with terminal galactose (15) and sialic acid (33), glycans important for mAbs when Fe-mediated complement or anti-inflammatory activities, respectively, are important mechanisms of action.

Materials and Methods

N. benthamiana Expression Vectors. The sequence for 13F6 (accession numbers 2QHR_H and 2QHR_L) was used by Biovation (Edinburgh, Scotland) to generate the variable regions of h-13F6 (accession number TBD – sequence submitted to GenBank 7-11-11) via proprietary peptide threading software on a fee-for-service basis. Deimmunized (3) h-13F6 murine heavy and light chain variable regions joined with human IgG1 and lambda chain constant regions were codon optimized for expression in N. benthamiana. An aglycosylated version was designed by mutating the heavy chain Kappa region N-glycosylation (N297A) site. Genes were synthesized (GeneArt) and subsequently cloned into plant (TMV and PVX) expression vectors (Icon Genetics), followed by transformation into A. tumefaciens strain ICMP320 (30).

Production of h-13F6gagly and h-13F6mab in ΔXTT N. benthamiana. For transient expression of h-13F6 in plants, we used the “magnification” procedure (Icon Genetics, Halle (Saale), Germany) as described (34), with minor modifications. Plants grown for 4 wk in an enclosed growth culture room with 20–23 °C were used for vacuum infiltration. Equal volumes of overnight-grown Agrobacterium cultures were mixed in the infiltration buffer (10 mM Mes, pH 5.5/10 mM MgSO4, resulting in a 1:1,000 dilution for each individual culture. The infiltration solution was transferred into a 2-L custom-built vacuum chamber (Kentucky Bioprocessing, Owensboro, KY). The aerial parts of entire plants were dipped upside down into the bacterial/infiltration buffer solution. A vacuum of 0.5 bar was applied for 2 min. After infiltration, plants were returned to the growth room under standard growing conditions. Eight days after infiltration, the leaf tissue was extracted in a juicer (Green Star, Model GS-1000), using 25 mL of chilled extraction buffer (100 mM Tris/40 mM ascorbic acid/1 mM EDTA) per 100 g of green leaf tissue. The plant-derived extract was clarified by lowering the pH of the extract to pH 4.8 with 1 M phosphoric acid then readjusting it to pH 7.5 with 2 M Tris base to insolubilize plant debris, followed by centrifugation at 15,000 × g for 30 min. The supernatant was transferred and recentrifuged at 16,000 × g for an additional 30 min. The clarified extract was filtered through 0.2 μm before concentration via Minim Tangential Flow Filtration System (Pall) then 0.2 μm filtered again before loading onto 5 mL of HiTrap MabSelect SuRe (GE Healthcare) Protein A column at 2 mL/min. The column then was washed with running buffer (50 mM Hepes/100 mM NaCl, pH 7.5) and eluted with 0.1 M acetic acid (pH 3.0). The resulting eluate was neutralized to pH 7 using 2 M Tris (pH 8.0) and supplemented with Tween 80 (0.01%). The mAb solution was then polished via Q filtration (Mast Micro Acrodisc Q membrane; Pall), aliquoted, and stored at −80 °C until used.

Production of h-13F6CHO. A stable CHO cell line expressing h-13F6 EBOV mAb was cultured in CD OptiCHO medium (Invitrogen) and supplemented with fed-batch Bioreactor Supplement (Sigma). The CHO culture was grown in suspension using 37 °C shaker with glucose level monitored daily and adjusted with sterile 4% Glucose Solution (Mediatech). The culture was terminated when cell viability reached below 20%. The conditioned medium was harvested and clarified via centrifugation. The clarified 13F6CHO conditioned medium was filtered (0.2 μm) before concentration via Minim Tangential Flow Filtration System (Pall). The conditioned medium was concentrated 10-fold, filtered (0.2 μm), and loaded onto 1 mL of HiTrap MabSelect SuRe (GE Healthcare) Protein A column at 0.5 mL/min. The column then was washed with 1x PBS running buffer and eluted with 0.1 M acetic acid (pH 3.0). The resulting eluate was neutralized to pH 7 using 2 M Tris (pH 8.0) and buffer-exchanged against 1x PBS with 0.01% Tween 80 using Amicon Ultra (Millipore). The mAb solution was then polished via Q filtration (Mast Micro Acrodisc Q membrane; Pall), aliquoted, and stored at −80 °C until used.

Production of h-13F6agly. A stable CHO cell line expressing h-13F6 EBOV mAb was cultured in CD OptiCHO medium (Invitrogen) and supplemented with fed-batch Bioreactor Supplement (Sigma). The CHO culture was grown in suspension using 37 °C shaker with glucose level monitored daily and adjusted with sterile 4% Glucose Solution (Mediatech). The culture was terminated when cell viability reached below 20%. The conditioned medium was harvested and clarified via centrifugation. The clarified 13F6agly conditioned medium was filtered (0.2 μm) before concentration via Minim Tangential Flow Filtration System (Pall). The conditioned medium was concentrated 10-fold, filtered (0.2 μm), and loaded onto 1 mL of HiTrap MabSelect SuRe (GE Healthcare) Protein A column at 0.5 mL/min. The column then was washed with 1x PBS running buffer and eluted with 0.1 M acetic acid (pH 3.0). The resulting eluate was neutralized to pH 7 using 2 M Tris (pH 8.0) and buffer-exchanged against 1x PBS with 0.01% Tween 80 using Amicon Ultra (Millipore). The mAb solution was then polished via Q filtration (Sartorius Q; Sartorius), aliquoted, and stored at −80 °C until used.

All purified 13F6 mAb variants (CHO, ΔXF, agly) were fully assembled as determined by SDS/PAGE and had less than 5% aggregate as determined by HPLC-SEC.

N-Glycan Analysis. N-glycan analysis was carried out by liquid-chromatography electrospray ionization-mass spectrometry (LC-ESI-MS) of tryptic glycopeptides (35). In short, bands that correspond to the heavy chain in a Coomassie-stained SDS/PAGEs were excised, proteins S alkylated, digested with trypsin, and subsequently analyzed by LC-ESI-MS (35). In short, bands that correspond to the heavy chain in a Coomassie-stained SDS/PAGEs were excised, proteins S alkylated, digested with trypsin, and subsequently analyzed by LC-ESI-MS (35).
We thank Dr. Yuri Gleba for providing access to the receptor binding and cell-test (two-sided). Logistic regression models were used to obtain the point estimate and confidence interval for ED50 where the dependent variable was the logit of the probability of survival, and the independent variable was the log of dose. ED50 was estimated by using negative of the ratio of the model's intercept to the slope (the regression estimate of the log dose). The SE of the estimated ED50 was calculated using the model's variance-covariance matrix of the estimated intercept and slope. Relative potency, a quantity defined as the ratio of two ED50 and its 95% confidence interval were estimated using logistic regression models with two intercepts, and a common slope (for the two compared assays), under the assumption of parallel lines. The estimate of the relative potency was the ratio of the difference of the two intercepts to the slope estimate. Fieller's theorem (37) was used to derive the 95% confidence interval for the relative potency estimate. All analyses were performed using Prism software (GraphPad) and SAS software (38).

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