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TITLE:
Optimization of antigen dose for a receptor-binding domain-based subunit vaccine against MERS coronavirus

ABSTRACT:
Middle East respiratory syndrome (MERS) is an emerging infectious disease caused by MERS coronavirus (MERS-CoV). The continuous increase of MERS cases has posed a serious threat to public health worldwide, calling for development of safe and effective MERS vaccines. We have previously shown that a recombinant protein containing residues 377–588 of MERS-CoV receptor-binding domain (RBD) fused with human Fc (S377-588-Fc) induced highly potent anti-MERS-CoV neutralizing antibodies in the presence of MF59 adjuvant. Here we optimized the doses of S377-588-Fc using MF59 as an adjuvant in order to elicit strong immune responses with minimal amount of antigen. Our results showed that S377-588-Fc at 1 μg was able to induce in the immunized mice potent humoral and cellular immune responses. Particularly, S377-588-Fc at 1 μg elicited strong neutralizing antibody responses against both pseudotyped and live MERS-CoV similar to those induced at 5 and 20 μg, respectively. These results suggest that this RBD-based subunit MERS vaccine candidate at the dose as low as one μg is sufficiently potent to induce strong humoral and cellular immune responses, including neutralizing antibodies, against MERS-CoV infection, thus providing guidance for determining the optimal dosage of RBD-based MERS vaccines in the future clinical trials and for applying the dose-sparing strategy in other subunit vaccine trials.

Introduction:
Middle East respiratory syndrome (MERS) is a newly emerged infectious disease caused by MERS coronavirus (MERS-CoV).1,2 First reported in Saudi Arabia in 2012,3 the virus has now been identified in 20 other countries of the world and has led to the infection of 965 individuals with 357 deaths worldwide (a mortality rate ~37%) (http://www.who.int/csr/don/03-february-2015-mers/en/). Studies have indicated bats and camels as the natural reservoirs and intermediate transmission hosts of MERS-CoV, respectively, and they have, moreover, elucidated the bat-to-human transmission mechanism of MERS-CoV.4-9 MERS-CoV has caused diseases in several family clusters and healthcare workers.10-13 With continuous increase of human cases, MERS-CoV has posed a serious threat to public health worldwide, demonstrating the need to develop safe and effective vaccines against virus infection.
MERS-CoV spike (S) protein plays significant roles in mediating virus entry into target cells expressing viral receptor dipeptidyl peptidase 4 (DPP4) and subsequent fusion of virus and cell membranes.14-16 To accomplish this, MERS-CoV depends on the receptor-binding domain (RBD) in the S1 subunit to bind host cellular receptors.17-19 As such, RBD is an important target for the development of MERS vaccines.20-24 Previous studies have mapped the RBD to the regions containing residues 358–588, 367–588, 377–588, and 367–606 of MERS-CoV S protein.17–19,22,23,25
It is known that a fragment containing residues 377–588 of MERS-CoV RBD is a critical neutralizing domain.22-23,26 After comparing 5 different RBD fragments respectively containing residues 350–588, 358–588, 367–588, 367–606, and 377–588 of MERS-CoV S protein fused with Fc of human IgG, namely S350-588-Fc, S358-588-Fc, S367-588-Fc, S367-606-Fc, S377-588-Fc, we found that S377-588-Fc induced the highest antibody responses and neutralizing antibodies in immunized animals.22–23 We have further compared the effects of several commercially available adjuvants, such as Freund's, aluminum, Monophosphoryl lipid A, Montanide ISA51, and MF59, in the promotion of immunogenicity of the aforementioned S377-588-Fc, and demonstrated that MF59 is an ideal adjuvant for use with this protein.27 However, the minimal dose of the RBD protein required to induce sufficient immune responses against MERS-CoV infection remains to be elucidated. This calls for further optimization of the antigen dose for MERS subunit vaccines.
In this study, we examined the immunization potential of different doses of S377-588-Fc and compared their ability to induce specific humoral and cellular immune responses, particularly neutralizing antibodies against infection of MERS-CoV, using S377-588-Fc as a model antigen and MF59 as a selected adjuvant.

S377-588-Fc at 1 μg was able to induce strong humoral immune responses ::: Results:

To optimize the dose of S377-588-Fc required to induce sufficient antibody responses, we immunized mice with S377-588-Fc at 1, 5, and 20 μg, respectively, and detected specific IgG antibody, as well as IgG1 and IgG2a subtypes, in immunized mouse sera.
As shown in Figure 1A, S377-588-Fc at all 3 test doses was able to induce MERS-CoV S1-specific IgG antibody response, with the antibody rapidly reaching a high level after the 2nd immunization and maintaining similar levels thereafter, suggesting that 2 doses of S377-588-Fc formulated with MF59 adjuvant are sufficient to induce strong antibody responses. As expected, only a background level of IgG antibody response was induced in the adjuvant only group (S377-588-Fc at 0 μg).

We then calculated and compared the endpoint IgG titers from the 3rd sera of mice immunized with the 3 RBD doses. Results, as shown in Figure 1B, revealed that S377-588-Fc at 1 μg induced high levels of IgG antibody response, but such response was significantly increased when the mice received 5 and 20 μg of the S377-588-Fc. Nevertheless, no significant difference was observed for IgG titers in the 5 and 20 μg immunization groups. As expected, mice receiving adjuvant only (S377-588-Fc at 0 μg) failed to induce MERS-CoV S1-specific IgG antibody response (Fig. 1B).
To elucidate the IgG subtypes induced by different doses of S377-588-Fc, we detected IgG1 and IgG2a production using mouse sera from the 3rd immunization. As shown in Figure 2, high titers of IgG1 (Th2) and IgG2a (Th1) antibodies were induced by 1, 5, and 20 μg of S377-588-Fc. However, S377-588-Fc at 5 and 20 μg induced a significantly higher level of IgG1 antibody than that at 1 μg (Fig. 2A). Notably, while no significant difference was revealed between titers of IgG1 and IgG2a antibodies induced by 5 and 20 μg of S377-588-Fc, 5 μg of S377-588-Fc appears to elicit stronger IgG2a antibodies than either 1 or 20 μg (Fig. 2B). As expected, no IgG subtypes were induced in the adjuvant control group (Fig. 2).

The above results suggest that 1 μg of S377-588-Fc is sufficient to induce high titers of RBD-specific antibody responses. Although S377-588-Fc at 5 and 20 μg could induce higher titers of total IgG and IgG1 subtype than those at 1 μg, the increased level of IgG and IgG1 may not necessarily provide stronger neutralizing antibody response that is required for protecting animals from MERS-CoV infection.

S377-588-Fc at 1 μg induced high levels of neutralizing antibody responses, similar to those induced by 5 and 20 μg in immunized mice ::: Results:
To elucidate the neutralizing potential induced by different doses of S377-588-Fc and determine the minimal dose of such an antigen required to elicit strong neutralization against MERS-CoV infection, we investigated neutralizing antibodies in mouse sera from the 3rd immunization based on MERS pseudovirus and live MERS-CoV neutralization assays. Results, as shown in Figure 3, demonstrated that S377-588-Fc at all 3 doses tested was able to induce potent neutralizing antibody titers against infections of MERS pseudovirus in Huh-7 cells (Fig. 3A) and live MERS-CoV in Vero E6 cells (Fig. 3B). There were no significant differences in the neutralizing activity among the sera of mice immunized with S377-588-Fc at 1, 5, and 20 μg, respectively, in the presence of MF59 adjuvant, while the sera from the adjuvant control mice (S377-588-Fc at 0 μg) showed no neutralizing activity (Fig. 3). These data suggest that S377-588-Fc at 1 μg concentration is able to induce sufficient MERS-CoV neutralizing antibodies in the immunized mice.

S377-588-Fc at 1 μg induced high levels of IFN-γ-expressing T cell responses in immunized mice ::: Results:
To compare the cellular immune responses induced by different doses of S377-588-Fc, we immunized mice with the protein at 1, 5, and 20 μg, respectively, and detected MERS-CoV S1-specific IL-2-and IFN-γ-expressing T cells in mouse splenocytes collected from the 3rd immunization. As shown in Figure 4, S377-588-Fc at 1 μg was capable of inducing strong IFN-γ-expressing T cells in both CD4+ (Fig. 4A) and CD8+ (Fig. 4B) populations, while S377-588-Fc at the increased doses (5 or 20 μg) did not induce higher T cell responses. In addition, S377-588-Fc at 1, 5, or 20 μg failed to elicit strong IL-2-expressing CD4+ and CD8+ T cells. As expected, the

adjuvant control group (S377-588-Fc at 0 μg) induced a background level of specific T cell responses. These results suggest that 1 μg of S377-588-Fc is sufficient to induce potent IFN-γ-expressing T cell responses in immunized mice.

Discussion:

Development of effective vaccines is urgently needed to prevent continuous epidemic of MERS. Currently, several MERS vaccine candidates have been tested in preclinical settings, some of which show immunogenicity.21,23,24,28–30 It was reported that a modified vaccinia virus Ankara (MVA) expressing full-length S protein and adenoviruses encoding full-length S protein or S1 subunit induced S-specific antibody responses that neutralized MERS-CoV infection in vitro,28,29 indicating the potential of developing viral vector-based MERS vaccines. The nanoparticle-conjugated full-length S protein elicited neutralizing antibodies in mice, bringing some hopes for developing nanoparticle-based MERS vaccine.31 An engineered replication-competent, propagation-defective MERS-CoV provides a platform to develop attenuated viruses as MERS vaccine candidates.30 We and others have identified several protein fragments, including residues 350-588, 358-588, 367-588, 367-606, 377-588 and 377-622, of the RBD of MERS-CoV S protein that induced neutralizing antibodies in mice or rabbits,21-23,25 suggesting the potential to develop subunit vaccines against MERS-CoV.

Among various vaccine types, such as those based on inactivated and live-attenuated viruses and viral vectors, recombinant protein-based subunit vaccines are considered to be the safest type of vaccines against virus infection.20,26,32 However, the efficacy of subunit vaccines largely depends on the identification of suitable antigens and selection of appropriate adjuvants.20,32 We have shown that a recombinant protein containing residues 377-588 of MERS-CoV RBD elicited the highest neutralizing antibodies among the 5 RBD fragments tested against MERS-CoV infection.22,23,27In addition, we have demonstrated that MF59 is most potent among the 5 adjuvants, including Freund's, aluminum, Monophosphoryl lipid A, MF59, and Montanide ISA51, to augment the immunogenicity of S377-588-Fc to induce strong antibody responses, neutralizing antibodies, and protection against MERS-CoV infection, suggesting it an ideal adjuvant for MERS-CoV RBD-based subunit vaccines.27 Apart from antigens and adjuvants, an equally crucial, but often neglected, aspect of immunization is the optimization of antigen dosage to find the minimal antigen dose able to induce strong immune responses.33,34

In this study, we compared the levels of immune responses in mice immunized with S377-588-Fc at 1, 5, and 20 μg, respectively, formulated with MF59 adjuvant. This range of doses was selected based on our previous studies showing that 10 μg of this protein induced strong immune responses with neutralizing activity that protected all of the vaccinated mice from challenge of MERS-CoV.22,23 Here, we found that S377-588-Fc at 1 μg was able to elicit strong humoral and cellular immune responses in the immunized mice. Particularly, this protein at 1 μg induced high levels of neutralizing antibodies against infections of both MERS pseudovirus and live MERS-CoV, similar to those induced at 5 and 20 μg, respectively, suggesting that 1 μg of S377-588-Fc formulated with MF59 is sufficient to induce strong neutralizing antibody response capable of protecting mice from MERS-CoV challenge, as that was induced by 10 μg of S377-588-Fc formulated with MF59 in our previous study.27 Therefore, only about 10% of S377-588-Fc that we tested before is actually needed to achieve the efficacy for prevention of MERS-CoV infection in vaccinated mice, based on the results from the present study.

Application of the lowest possible amount of the antigen and fewer injections is an important dose sparing strategy for a vaccine with low productivity (e.g., a subunit vaccine), especially during a pandemic or epidemic of an emerging infectious disease, like MERS. This study provides important information for rational design of optimal dosages of vaccines against MERS and other emerging infectious diseases for their future clinical trials.

Ethics statement ::: Materials and Methods:

Four-to six-week-old female BALB/c mice were used in the study. The animal studies were carried out in strict accordance with the recommendations in the Guide for the Care and Use of Laboratory Animals of the National Institutes of Health. The animal protocol was approved by the Committee on the Ethics of Animal Experiments of the New York Blood Center (Permit Number: 194.15).

Recombinant MERS-CoV RBD and S1 proteins ::: Materials and Methods:

The recombinant S377-588-Fc containing residues 377-588 of MERS-CoV spike plus a C-terminal Fc tag (S377-588-Fc, hereinafter named RBD) was used as the antigen to optimize antigen doses for RBD-based subunit vaccines. The construction, expression and purification of the S377-588-Fc were described previously by fusing the RBD gene with human IgG Fc (InvivoGen, San Diego, CA), expressing the S377-588-Fc protein in 293T cell culture supernatant, and purifying it by Protein A affinity chromatography (GE Healthcare, Piscataway, NJ).22,23 MERS-CoV S1 protein (residues 18–725) plus a C-terminal His6 (S1-His) was constructed using the pJW4303 expression vector (Jiangsu Taizhou Haiyuan Protein Biotech, Co., Ltd., China), expressed in 293T cell culture supernatant, and purified using Ni-NTA Superflow (Qiagen, Valencia, CA).23,24

Animal immunization and sample collection ::: Materials and Methods:
Mice were immunized with S377-588-Fc as previously described with some modifications.21,23,35 Briefly, mice were subcutaneously prime-immunized with S377-588-Fc at 1, 5, and 20 μg, respectively, in the presence of MF59 adjuvant,36 and boosted twice with the same immunogen and adjuvant at 3-week intervals. Adjuvant only without antigen (0 μg) was included as the negative control. Sera were collected before immunization and 10 d post-each vaccination to assess MERS-CoV S1-specific antibody responses and neutralizing antibodies. Immunized mice were sacrificed at 10 d after the last immunization, and splenocytes were collected to detect MERS-CoV S1-specific T cell responses.

ELISA ::: Materials and Methods:
ELISA was used to test MERS-CoV S1-specific antibody responses in mouse sera based on our previously described protocols.23,37 Briefly, ELISA plates were precoated with MERS-CoV S1-His protein overnight at 4°C, followed by addition of serially diluted sera and incubation at 37°C for 1 h. After four washes with PBST, the plates were incubated with horseradish peroxidase (HRP)-conjugated anti-mouse IgG (1:3000, GE Healthcare), IgG1 (1:2000), or IgG2a (1:5000) (Invitrogen, Carlsbad, CA), respectively, at 37°C for 1 h, and washed 4 times. The reaction was visualized by substrate 3,3′,5,5′-tetramethylbenzidine (TMB) (Invitrogen, Carlsbad, CA) and stopped with 1 N H2SO4. The absorbance at 450 nm (A450) was measured by ELISA plate reader (Tecan, San Jose, CA).

MERS pseudovirus neutralization assay ::: Materials and Methods:
This was done as previously described with some modifications.38,39 Briefly, 293T cells were co-transfected with a plasmid encoding Env-defective, luciferase-expressing HIV-1 genome (pNL4-3.luc.RE) and a plasmid encoding MERS-CoV (EMC-2012 strain) S protein using the calcium phosphate method. Cells were changed into fresh DMEM 8 h later, and pseudovirus-containing supernatants were harvested 72 h post-transfection for single-cycle infection of Huh-7 cells. The pseudovirus was incubated with serially diluted mouse sera at 37°C for 1 h before adding to the cells preplated in 96-well culture plates. Twenty-four hours later, cells were refed with fresh medium, which was followed by lysing cells 72 h later using cell lysis buffer (Promega, Madison, WI) and transferring the lysates into 96-well luminometer plates. Luciferase substrate (Promega) was added to the plates, and relative luciferase activity was determined in an Infinite 200 PRO Luminator (Tecan). MERS pseudovirus neutralization was calculated and expressed as 50% neutralizing antibody titer, NT50.40

Live MERS-CoV neutralization assay ::: Materials and Methods:
A standard micro-neutralization assay was used to confirm the anti-MERS-CoV neutralizing antibodies as previously described.23,41 Briefly, mouse sera were diluted at serial 2-fold in 96-well tissue culture plates and incubated for 1 h at room temperature with ~100 infectious MERS-CoV (EMC-2012) before transfer to Vero E6 cells. Seventy-two hours later, the neutralizing capacity of serum samples was assessed by determining the presence or absence of virus-induced cytopathic effect (CPE). Neutralizing antibody titers were expressed as the reciprocal of the highest dilution of sera that completely inhibited virus-induced CPE in at least 50% of the wells (NT50).

Intracellular cytokine staining and flow cytometry analysis ::: Materials and Methods:
MERS-CoV S1-specific cellular immune responses were evaluated in immunized mice by intracellular cytokine staining followed by flow cytometric analysis as previously described.21,42,43 Briefly, mouse splenocytes (2 × 106) were stimulated with MERS-CoV S1-His protein for 5 h at 37°C with 5% CO2 in the presence of GolgiPlug™ containing brefeldin A (1 μl/

ml; BD Biosciences, San Jose, CA). The cells were stained with conjugated anti-mouse-CD4 (APC) and -CD8 (P-Cy5-5) antibodies for 30 min at 4°C. After washes, the cells were fixed using the Cytofix/Cytoperm™ Kit (BD Biosciences) and stained with anti-mouse-IL-2 (FITC) and -IFN-γ (PE) (BD Biosciences) antibodies for 30 min at 4°C. The stained cells were analyzed using a FACSCalibur (BD Biosciences) and FACSDiva software v.6.1.2 (BD Biosciences).

Statistical analysis ::: Materials and Methods:
Values are presented as mean and standard deviation (SD). Statistical significance among different vaccination groups was calculated by Student's t-test using GraphPad Prism statistical software. P values less than 0.05 were considered statistically significant.