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A polyvalent inactivated rhinovirus vaccine is broadly immunogenic in rhesus macaques

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As the predominant aetiologic agent of the common cold, human rhinovirus (HRV) is the leading cause of human infectious disease. Early studies showed that a monovalent formalin-inactivated HRV vaccine can be protective, and virus-neutralizing antibodies (nAb) correlated with protection. However, co-circulation of many HRV types discouraged further vaccine efforts. Here, we test the hypothesis that increasing virus input titres in polyvalent inactivated HRV vaccine may result in broad nAb responses. We show that serum nAb against many rhinovirus types can be induced by polyvalent, inactivated HRVs plus alhydrogel (alum) adjuvant. Using formulations up to 25-valent in mice and 50-valent in rhesus macaques, HRV vaccine immunogenicity was related to sufficient quantity of input antigens, and valency was not a major factor for potency or breadth of the response. Thus, we have generated a vaccine capable of inducing nAb responses to numerous and diverse HRV types.
HRV causes respiratory illness in billions of people annually, a socio-economic burden. HRV also causes pneumonia hospitalizations in children and adults, and exacerbations of asthma and chronic obstructive pulmonary disease (COPD). HRV was found to be the second leading cause of community-acquired pneumonia requiring hospitalization in US children, second only to respiratory syncytial virus, and the most common pathogen associated with pneumonia hospitalization in US adults. A vaccine for HRV could alleviate serious disease in asthma and COPD, reduce pneumonia hospitalizations and have widespread benefits for society on the whole. Decades ago, researchers identified inactivated HRV as a protective vaccine, defined virus-neutralizing antibodies (nAb) as a correlate of protection, and estimated duration of immunity. Trials with monovalent HRV vaccine demonstrated that protection from homologous challenge and disease can be achieved with formalin-inactivated virus given intramuscularly (i.m.) or intranasally. Humoral immunity to heterologous virus types was not observed, though cross-reactive CD8 T cells can promote clearance. Limited cross-neutralizing antibodies can be induced by hyper-immunization in animals. The possibility of a vaccine composed of 50, 100 or more distinct HRV antigens has been viewed as formidable or impossible. Two main challenges, generating a broad immune response and the feasibility of composing such a vaccine. The Ab repertoire is theoretically immense, and most vaccines in clinical use are thought to work via a polyclonal Ab response. Deep-sequencing of human Ab genes following vaccination against influenza virus found thousands of Ab lineages. Whole pathogen and polyvalent vaccines carrying natural immunogens take advantage of this capacity. Valency has increased for pneumococcal and polyvalent vaccines carrying natural immunogens take advantage of this capacity. Valency has increased for pneumococcal and polyvalent vaccines. Immunogenicity of polyvalent inactivated HRV vaccines in recent years. Given the significance of HRV, we tested polyvalent HRV vaccines.

There are three species of HRV, A, B and C. Sequencing methods define 83 A types, 32 B types and 55 C types. It is thought there are 150–170 serologically distinct HRV types. HRV A and C are associated with asthma exacerbations and with more acute disease than HRV B. HRV C was discovered in 2006 and 2007 and recently cultured in cells. Here, we focused on HRV A, the most prevalent species. There are no permissive animal challenge models of HRV virus replication, but mice and cotton rats can recapitulate aspects of HRV pathogenesis. The best efficacy model is human replication, but mice and cotton rats can recapitulate aspects of HRV pathogenesis. Immunogenicity of polyvalent inactivated HRV vaccines.

**Results**

**Immunogenicity of 10-valent HRV vaccine in mice.** We first used BALB/c mice to test immunogenicity. We propagated HRVs in H1-HeLa cells and inactivated infectivity using formalin. Sera from naive mice had no detectable nAb against HRV-16 (Fig. 1). Alum adjuvant enhanced the nAb response induced by i.m. inactivated HRV-16 (Fig. 1). There was no effect of valency (comparing 1-, 3-, 5-, 7- and 10-valent) on the nAb response induced by inactivated HRV-16 or to the 3 types in the 3-valent vaccine (HRV-16, HRV-36 and HRV-78; Fig. 1). The 50% tissue culture infectious dose (TCID₅₀) titres of the input viruses before inactivation (inactivated-TCID₅₀) are provided in Supplementary Table 1. Original antigenic sin can occur when sequential exposure to related virus variants results in biased immunity to the type encountered first. In bivalent HRV-immune mice, we observed modest original antigenic sin following prime vaccination with 10-valent inactivated HRV, and boost vaccination partially alleviated the effect (Supplementary Fig. 1), similar to influenza virus. Collectively, these results prompted us to explore more fully the nAb response to polyvalent HRV vaccine.

**Sufficient input HRV titre determines immunogenicity.** In 1975, it was reported that two different 10-valent inactivated HRV preparations induced nAb titres to only 30–40% of the input virus types in recipient subjects. However, the input titres of viruses before inactivation ranged from 10¹.₅ to 10⁵.₅ TCID₅₀ per ml, and these were then diluted 10-fold to generate 10-valent 1.0 ml doses given i.m. as prime and boost with no adjuvant. We hypothesized that low input antigen doses are responsible.

**Figure 1 | Immunogenicity of inactivated HRV is not affected by increasing valency from one to ten.** Mice were vaccinated i.m. with 1-valent inactivated HRV-16 with or without alum adjuvant (5 mice per group) or with 3-valent, 5-valent, 7-valent or 10-valent inactivated HRV with alum (20 mice per group). HRV types and inactivated-TCID₅₀ doses are specified in Supplementary Table 1. Sera were collected 18 days after vaccination and pooled for each group. Serum nAb titres were measured against HRV-16, HRV-36 and HRV-78. The dashed line represents limit of detection (LOD). Error bars show 95% confidence interval. Data depict three independent experiments combined.
for poor nAb responses to 10-valent inactivated HRV. We
reconstituted the 1975 10-valent vaccine, as closely as possible
with available HRV types, over a 10^1 to 10^6 inactivated-TCID_{50}
per vaccine dose, and we compared it with a 10-valent vaccine of
the same types with input titres ranging from > 10^3 to > 10^7
inactivated-TCID_{50} per dose. The reconstituted 1975 vaccine
resulted in no detectable nAb after prime vaccination and,
following boost vaccination, nAb to the five types that had the
highest input titres (Fig. 2). The high titre vaccine resulted in nAb
to 5 of 10 types after prime vaccination and all 10 types after
the boost (Fig. 2). Following the boost vaccinations, there
appeared to be a 10^4 inactivated-TCID_{50} per vaccine dose
threshold for the induction of nAb in this model (Fig. 2b).
Above this titre, there was no correlation between input load and
nAb induction.

**Immunogenicity of 25-valent HRV vaccine in mice.** Injectable
vaccines used in people are commonly given in a 0.5 ml dose.
In our facility, the highest allowable i.m. vaccine volume in
mice was 0.1 ml. We tested a 25-valent per 0.1 ml HRV vaccine in
mice as a scalable prototype. The 25-valent inactivated HRV
vaccine had a 7.4-fold lower average inactivated-TCID_{50} per type
per dose than the 10-valent composition (Supplementary Table 2)
to accommodate the volume adjustment. The 10-valent
inactivated HRV vaccine induced nAb to 100% of input types
following the prime and the boost (Fig. 3a). The nAb induced by
10-valent inactivated HRV were persisting at 203 days post-boost
(Supplementary Fig. 2). We used two different sets of virus stocks
for the prime and boost 25-valent vaccinations in these
experiments (Supplementary Table 2). The reason is that in the
interim between the prime and boost vaccinations, we obtained
higher titre virus stocks of eleven of the input types (HRV-32, -49,
-58, -55, -41, -33, -39, -50, -1B, -21 and -60). The higher
titre stocks of these eleven were used in the boost vaccination.
The 25-valent inactivated HRV prime vaccination induced nAb
to 18 of 25 (72%) virus types, and the 25-valent boost resulted in
nAb against 24 of the 25 types (96%; Fig. 3b). The average nAb
titre resulting from prime and boost was 2^7 for 10-valent and 2^6.8
for 25-valent. These data demonstrate broad neutralization of
diverse HRV types with a straightforward vaccine approach.
Immunogenicity of 25- and 50-valent HRV in RMs. To increase vaccine valency, we chose RMs and a 1.0 ml i.m. vaccine volume. Two RMs were vaccinated with 25-valent inactivated HRV, and two RMs were vaccinated with 50-valent inactivated HRV. Pre-immune sera in RM A and RM B had no detectable nAb against the 25 HRV types included in the 25-valent vaccine. The inactivated-TCID₅₀ titres per dose were higher in RMs than in mice (Supplementary Table 3). The 25-valent vaccine induced nAb to 96% (RM A) and 100% (RM B) of input viruses following the prime vaccination (Fig. 4c). The breadth of nAb following prime vaccination in RM was superior to what we observed in mice, which may have been due to animal species differences and/or higher inactivated-TCID₅₀ input titres in the RM vaccines. Following boost vaccination, there were serum nAb titres against 100% of the types in 25-valent HRV-vaccinated RMs (Fig. 4b) and 98% (49 out of 50) of the virus types in 50-valent HRV-vaccinated RMs (Fig. 4d). The average nAb titre resulting from prime and boost in RMs was 2.93 for 25-valent and 2.86 for 50-valent. The nAb responses were type-specific, not cross-neutralizing, because there were minimal nAbs induced by the 25-valent vaccine against 10 non-vaccine types (Supplementary Fig. 3). The nAb response to 50-valent inactivated HRV vaccine was broad and potent in RMs.

HRY vaccine in WI-38 cells and semi-purification by HPLC. The HRV stocks used in our vaccinations were produced in H1-HeLa cells, a good substrate for HRV replication but not suitable for vaccine manufacturing. We compared the infectious yield of 10 HRV types in H1-HeLa and WI-38, which can be qualified for vaccine production. Adequate yields were obtained from WI-38 cells (Supplementary Fig. 4). Injectable vaccines require defined purity. As proof of principle, we semi-purified three HRV types by high-performance liquid chromatography and found uncompromised immunogenicity of trivalent inactivated semi-purified HRV in mice (Supplementary Fig. 5).

Discussion
In this study, we demonstrate that polyclonal inactivated HRV vaccine expanded to a 50-valent composition, with alum adjuvant, is immunogenic against approximately one-third of circulating HRV types. Although fifty HRV types is a minority, these data provide proof of principle for a highly polyclonal vaccine approach. Forty years ago, the prospects for a polyclonal HRV vaccine were dour for good reasons. However, progress in technology and advancement of more complex vaccines renders impediments to a polyclonal HRV vaccine manageable. Scale-up of HRV vaccines may be facilitated by related vaccine production processes and new cost-saving manufacturing technologies. Inactivated HRV has a positive history of clinical efficacy.

On the basis of our results and doses of early immunogenic HRV vaccines, we estimate 10⁻⁵ inactivated-TCID₅₀ per type per dose will be useful. Therefore, HRV stock titres ≥ 10⁷ TCID₅₀ per ml are required for a potential 83-valent HRV A formulation in a 0.5 ml dose containing alum adjuvant. In future studies, we hope to produce a comprehensive 83-valent HRV A vaccine. A limitation of our study is that we have not included HRV C antigens, which will be important for HRV vaccine development, especially for pediatric populations. Ongoing efforts are aimed at propagation of HRV C strains to high titre in cell lines and development of serology assays. Ultimately, our approach may lead to vaccines for rhinovirus-mediated diseases including asthma and COPD exacerbations and the common cold. Advancing valency may be applicable to vaccines for other antigenically variable pathogens.

Methods

Cell lines and viruses. H1-HeLa (CRL-1958) and WI-38 (CCL-75) cells were obtained from the American Type Culture Collection (ATCC) and cultured in minimal essential media with Richter’s modification and no phenol red (MEM) (Thermo Fisher) supplemented with 10% fetal bovine serum. The cell lines were not authenticated but are not commonly misidentified (International Cell Line Authentication Committee). We tested HeLa-H1 cells using the LookOut® Mycoplasma Amplification Detection kit (Sigma) and Vigorous Viron dectection kit (Virofanix) (Fig. 7, Supplementary Table 5). The primary vaccine (HRV-7 (VR-1601), HRV-9 (VR-1745), HRV-11 (VR-1567), HRV-13 (VR-286), HRV-14 (VR-284), HRV-16 (VR-283), HRV-19 (VR-1129), HRV-24 (VR-1134), HRV-29 (VR-1809), HRV-30 (VR-1140), HRV-31 (VR-1795), HRV-32 (VR-349), HRV-36 (VR-509), HRV-38 (VR-531), HRV-40 (VR-341), HRV-41 (VR-1513), HRV-49 (VR-11176), HRV-53 (VR-1166), HRV-55 (VR-1169), HRV-60 (VR-1473), HRV-64 (VR-1174), HRV-66 (VR-1176), HRV-75 (VR-1185), HRV-76 (VR-1186), HRV-77 (VR-1187), HRV-78 (VR-1188), HRV-80 (VR-1190), HRV-81 (VR-1191), HRV-85 (VR-1195), HRV-88 (VR-1196), HRV-89 (VR-1199), HRV-96 (VR-1298), and HRV-97 (VR-590) HRV proteins were purchased from ATCC. HRV-1B, HRV-10, HRV-21, HRV-28, HRV-34, HRV-39, HRV-45, HRV-50, HRV-51, HRV-54, HRV-55 and HRV-94 strains were obtained from the Centers for Disease Control and Prevention. The HRVs in the study are species A, with the exception of HRV-14 (B), and represent A species broadly.

HRV propagation and titration. HRV stocks were generated in H1-HeLa cells. Approximately 0.5 ml of HRV was inoculated onto subconfluent H1-HeLa cells. After adsorption of HRV for 1 hour at 4°C, the supernatant was transferred to a closed room and the HRV propagated at 33°C with rocking. Sonication yield higher titres than freeze–thaw. The suspension was clarified by centrifugation at 931 g for 10 min. The supernatant was transferred to cryovials, snap-frozen in liquid nitrogen and stored at –80°C. For comparing HRV yield in H1-HeLa and WI-38 cells, 2×10⁵ cells were infected with HRV and the multiplicity of infection of 0.1 TCID₅₀ per cell, and 20 ml of culture medium were discarded before scraping the cells in the remaining 5 ml followed by sonication. For all stocks, TCID₅₀ ml⁻¹ titres were determined by infecting subconfluent H1-HeLa cells in 96-well plates with serially diluted samples, staining the cells 6 days post-infection with 0.1% crystal violet/20% methanol, scoring wells for CPE and calculating the end point titre using the Reed and Muench method.

HRV purification. HRV stock was collected from H1-HeLa cell monolayers as described above and clarified by brief centrifugation at low speed to remove large cellular debris (931g, 10min, 4°C). To remove excess albumin from the crude virus stock by affinity chromatography, the supernatant was loaded onto a Hitrap Blue HP column (GE Healthcare) using an AKTA Purifier system (GE Healthcare) according to the manufacturer specifications. Flowthrough was subsequently loaded through a Hitrap Capto Core 700 column (GE Healthcare) to refine the virus prep by size exclusion chromatography. The flowthrough from the Hitrap Blue HP and the Hitrap Capto Core 700 was captured using the AKTA Purifier system (GE Healthcare) with a 20 mM sodium phosphate buffer (pH 7.0). Flowthrough from size exclusion chromatography was dialyzed overnight with 0.1 M Tris-HCl buffer (pH 8.0), then loaded onto a Hitrap Q XL column (GE Healthcare) and separated into fractions by ion exchange chromatography. Virus-containing fractions were eluted using the AKTA Purifier system (GE Healthcare) with a 0.1 M Tris-HCl buffer (pH 8.0) and a sodium chloride gradient. Fractions showing high viral titres were pooled at 280 mM NaCl and analyzed by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) and point dilution assay, and fraction purity visualized on a 10% SDS-PAGE gel by silver staining (Thermo Fisher Scientific; Supplementary Fig. 6 and Supplementary Table 4). Fractions of HRV-16, HRV-36 and HRV-78 of high virus titre and purity were combined for formalin inactivation as described below.

Mice and RMs. All experiments involving animals were performed at Emory University and the Yerkes National Primate Research Center in accordance with guidelines established by the Animal Welfare Act and the NIH Guide for the Care and Use of Laboratory Animals. Animal facilities at Emory University and the Yerkes Center are fully accredited by the Association for Assessment and Accreditation of Laboratory Animal Care (AAALAC). The Institutional Animal Care and Use Committee (IACUC) of Emory University approved these studies. Mice were pathogen-free, 6–7-week-old female BALB/c mice were purchased from the Jackson Laboratory (Bar Harbor, ME, USA). Mice were randomly assigned to groups based on the sequential selection from an inventory, and investigators were not
Figure 4 | Broad nAb responses against 25-valent and 50-valent inactivated HRV in RMs. The inactivated-TCID₅₀ input titres per dose are specified in Supplementary Table 3. Two RMs (RM A and RM B) were vaccinated i.m. with 25-valent HRV and alum (a,b), and two RMs (RM C and RM D) were vaccinated i.m. with 50-valent HRV and alum (c,d). nAb titres against input virus types were measured in individual serum samples collected at day 18 (a,c). The RM received an identical boost vaccination at day 28, and sera were collected at day 46 for determining nAb titres post-boost vaccination (b,d). Error bars depict 95% confidence interval. The dashed line represents LOD. Undetectable nAb were assigned LOD/2.
blinded to outcome assessment. No statistical methods were used in predetermined sample sizes.

**Vaccination.** Before immunization, all HRV types were inactivated by addition of 0.025% formalin followed by incubation with stirring for 72 h at 37 °C, as previously described for HRV vaccine33. Complete inactivation of infectivity was confirmed by end point TCID₅₀ titration in H1-HeLa cells. Formalin inactivation by this method resulted in greater immunogenicity in mice than alternative inactivation by β-propiolactone, suggesting formalin inactivation preserved antigenic determinants. Mice were vaccinated i.m. with inactivated HRV strains mixed with 100 μg of Alhydrogel adjuvant 2% (aluminium hydroxide wet gel suspension, alum; Sigma catalog A8222 or Invivogen catalog vac-alu) according to instructions of the manufacturers. The total volume per mouse was 100 μl, administered in 50 μl per leg. Mice were scored for signs of anaphylaxis (boost) at the time indicated in figure legends. RM s were vaccinated i.m. with inactivated HRV strains mixed with 500 μg of Alhydrogel adjuvant 2%. The total volume per RM was 1 ml, administered in one leg. RM s were boosted with an identical vaccination at four weeks.

**Serum collection.** In mice, peripheral blood was collected into microcentrifuge tubes from the submandibular vein. Samples were incubated at room temperature for 20 min to clot. The tubes were centrifuged 7,500 g for 30 min at 4 °C. For each type, a mixture was transferred onto H1-HeLa cell monolayers in 96-well plates in triplicate, and plates were incubated at 35.5 °C for 30 min at 4 °C. For each type, a no-serum control was added to test the input 500 TCID₅₀. We tested pooled HRV-16 anti-sera against HRV-16 in each assay as a standard. After spinoculation, 150 μl of HRV infection medium were added to each well. The 95% confidence interval indicates variability of three technical replicates with a single nAb experiment. An example of the nAb assay and titration calculation is provided in Supplementary Fig. 7.

**Data availability.** Primary data that support the findings of this study are available from the corresponding author on request.

**References**

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**Author contributions**

S.L., M.T.N., M.G.C., J.B.J., E.A.S., A.E.K. and R.M.-L. performed experiments. K.R., Y.A.B., J.E.G. and P.S. provided reagents and advice. X.L. and D.D.E. provided rhinovirus types. S.L., M.T.N. and M.L.M designed the experiments, analysed data and wrote the paper. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the Centers for Disease Control and Prevention.

**Additional information**

**Supplementary Information** accompanies this paper at http://www.nature.com/naturecommunications

**Competing financial interests:** M.L.M. co-founded and serves as Chief Scientific Officer for Meissa Vaccines, Inc. S.L., M.T.N. and M.L.M are co-inventors in a patent application (PCT/US2016/037658) describing the rhinovirus vaccine reported in this paper. The vaccine technology has been optioned to Meissa Vaccines, Inc. by Emory University. The remaining authors declare no competing financial interests.

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