PNAS RESEARCH ARTICLE | IMMUNOLOGY AND INFLAMMATION

Polyvalent immunization elicits a synergistic broadly neutralizing immune response to hypervariable region 1 variants of hepatitis C virus

Alexander I. Mosa[a,1,2], David S. Campo[b,1], Yury Khudyakov[b], Mounir G. AbouHaidar[c], Adam J. Gehring[d], Atif Zahoor[a], Jonathan K. Ball[e], Richard A. Urbanowicz[f], and Jordan J. Feld[a]

Edited by Andrea Cox, Johns Hopkins University School of Medicine, Baltimore, MD; received November 29, 2022; accepted April 29, 2023 by Editorial Board Member Adolfo Garcia-Sastre

A hepatitis C virus (HCV) vaccine is urgently needed. Vaccine development has been hindered by HCV's genetic diversity, particularly within the immunodominant hypervariable region 1 (HVR1). Here, we developed a strategy to elicit broadly neutralizing antibodies to HVR1, which had previously been considered infeasible. We first applied a unique information theory–based measure of genetic distance to evaluate phenotypic relatedness between HVR1 variants. These distances were used to model the structure of HVR1's sequence space, which was found to have five major clusters. Variants from each cluster were used to immunize mice individually, and as a pentavalent mixture. Sera obtained following immunization neutralized every variant in a diverse HCVpp panel (n = 10), including those resistant to monovalent immunization, and at higher mean titers ($1/ID_{50}$ = 435) than a glycoprotein E2 ($1/ID_{50}$ = 205) vaccine. This synergistic immune response offers a unique approach to overcoming antigenic variability and may be applicable to other highly mutable viruses.

hepatitis c virus | vaccine | HVR1

Significance

Hepatitis C virus (HCV) infects 58 million people worldwide, with an estimated 1.5 million new infections annually. Despite remarkable advances in treatment, new infections outpace cures, and a prophylactic vaccine is needed to achieve HCV elimination. Vaccine development has been impeded, however, by the extreme genetic variability of HCV. Our previous work indicates that even in highly variable epitopes, HCV is limited by phenotypic constraints that can be exploited by rational vaccine design. Here, we applied a unique measure of genetic distance to model these constraints into a network describing the global HCV sequence space. By combining variants from across this space to immunize mice, we elicited broadly neutralizing antibodies with greater neutralization breadth and potency than a classical vaccine candidate.

Hepatitis C is a leading cause of morbidity and mortality from liver disease worldwide (1). The introduction of curative direct-acting antivirals spurred hopes for global HCV elimination (2). However, with an estimated 1.5 million new infections and 300,000 deaths annually, it may be challenging to achieve the World Health Organization's 2030 elimination targets with treatment alone (3). Availability of an effective HCV vaccine would significantly aid in these efforts (4).

Vaccine development has been impeded, however, by the extreme genetic variability of HCV, which renders immune responses produced against one variant ineffective against others (5, 6). Though classified at the full genomic level into eight genotypes differing at 30 to 35% of nucleotide positions, HCV's heterogeneity is not distributed uniformly along the genome (7). The most heterogeneous region, hypervariable region 1 (HVR1), encodes the N-terminal 27 amino acid (aa) portion of the envelope protein E2 (8). Though HVR1 contains an immunodominant neutralizing epitope, mediates interactions with the HCV coreceptor scavenger receptor class B type 1 (SRB1), and is strongly positively selected in natural infection, its application to vaccine development has been limited due to its extraordinary genetic variability (9–12). Thus, despite the capacity of anti-HVR1 antibodies to prevent homologous infection, and the favorable accessibility of this epitope to neutralizing antibodies, vaccine efforts have been focused on eliciting antibodies to conserved regions outside of HVR1 (13, 14). However, even conserved regions seem to be affected by HVR1, which physically shields conserved neutralizing epitopes, modulates envelope conformation, and elicits strain-specific, dominant "decoy" immune responses, thus suppressing recognition of the conserved subdominant epitopes (15–17). Simply removing HVR1 from E2 did not improve responses following vaccination, but instead was inferior to native E2 in terms of neutralization, possibly related to conformational changes in E2 caused by the HVR1 excision or by disruption of discontinuous antigenic epitopes involving HVR1 (17–19).

The role of HVR1 in HCV neutralization, both as a dominant epitope and as a modifier of the response to conserved epitopes, must therefore be considered in the design of any HCV vaccine. Here, we describe a unique strategy to overcome the challenge of HVR1 heterogeneity. Using a unique information theory–based distance, we modeled HVR1 genetic variability and observed discrete, genotype-independent clusters. We selected five central sequences from these clusters to synthesize peptides for vaccination. The mixture of HVR1 variants resulted in an antibody response that was more broadly neutralizing

Competing interest statement: The University Health Network has filed a patent related to the approach to immunogen design described herein, of which A.I.M., D.S.C., R.A.U., M.G.A., and J.J.F. are listed as inventors. The other authors declare no competing interests. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the Centers for Disease Control and Prevention (CDC).

This article is a PNAS Direct Submission. A.C. is a guest editor invited by the Editorial Board.

[1]A.I.M. and D.S.C. contributed equally to this work.

[2]To whom correspondence may be addressed. Email: alexander.mosa@uhnresearch.ca.

Published June 5, 2023.

than each individual variant or pooled sera, indicating a synergistic interaction among immune responses to related, but distinct, HVR1variants. These findings open a path for the development of an HCV vaccine using sequence-complementary variants of genetically divergent HVR1 antigenic epitopes.

Results

Selection of Genetic Distance Relevant to Cross-Immunoreactivity. To identify HVR1 variants for immunization experiments, we modeled HVR1's genetic space, with the hypothesis that the space structure could inform variant selection and thus improve coverage. First, we explored how different measures of genetic distance were associated with a previously published cross-immunoreactivity dataset of 26,883 pairwise reactions among 262 HVR1 variants (20) (Fig. 1*A*). We compared the mean distance observed in pairs that did not cross-react, with the mean distance observed in pairs that did cross-react. If the ratio is 1, then the distance is not helping us to differentiate the two types of pairs, but the greater the ratio, the greater the relevance of the distance to cross-immunoreactivity. The ratio calculated using distances based on individual or joint physiochemical properties (21), Hamming distances (number of mismatches; ratio = 1.19; *t* test, *P* = 1.3668E-279), or the BLOSUM62 scores (ratio = 1.17; *t* test, *P* =5.5753E-270) showed very similar results, all indicating low association with cross-immunoreactivity (Fig. 1*B*).

Considering the importance of coordinated substitutions in HCV evolution (22), we devised a unique information-theory-based distance called MIH (mutual information and entropy, H) (23). The MIH distance considers the variability of each position (measured by entropy) and the existence of coordinated substitutions between position (measured by mutual information among position pairs) (Fig. 1*C*). The mean MIH of non-cross-reactive pairs was 1.89 times higher than the mean of cross-reactive pairs (*t* test, *P* = 8.88E-56), a ratio 58.7% greater than the second best, obtained with the Hamming distance. These results indicate that the MIH distance has a higher association with cross-immunoreactivity (Fig. 1*B*) and thus HVR1 variants with lower average MIH distance to other variants are also more likely to be broadly cross-immunoreactive.

HVR1 Sequence Space. There are 969 unique C-terminal 8aa sequences in the extended global dataset of 12,245 HVR1 sequences. Out of all HVR1 sequences published with known HCV genotype (n = 1,305), 8.6% were found in two or more genotypes, with one being found in all six of them. This result indicates that this small region is genetically convergent at the genotype level.

We then proceeded to measure the MIH distance among every pair of 8aa sequences. This matrix of distances was used to build a k-step network (Fig. 2), which is equivalent to the union of all minimum spanning trees and allows one to visualize the distances among all variants present. Thus, the network constitutes our model of the HVR1 sequence space, which we used to find modules and measure the centrality of each variant.

Given that early acute-phase variants (also referred to as transmitted-founder variants) are plausible targets for vaccine development, as they are the first variants encountered by the immune system (24), we studied their location in the HVR1 network. First, the eigenvector centrality of each HVR1 variant in the k-step network was established. Second, the average centrality of variants collected during acute (n = 119) or chronic (n = 251) infection was calculated. The acute HVR1 variants had an average centrality

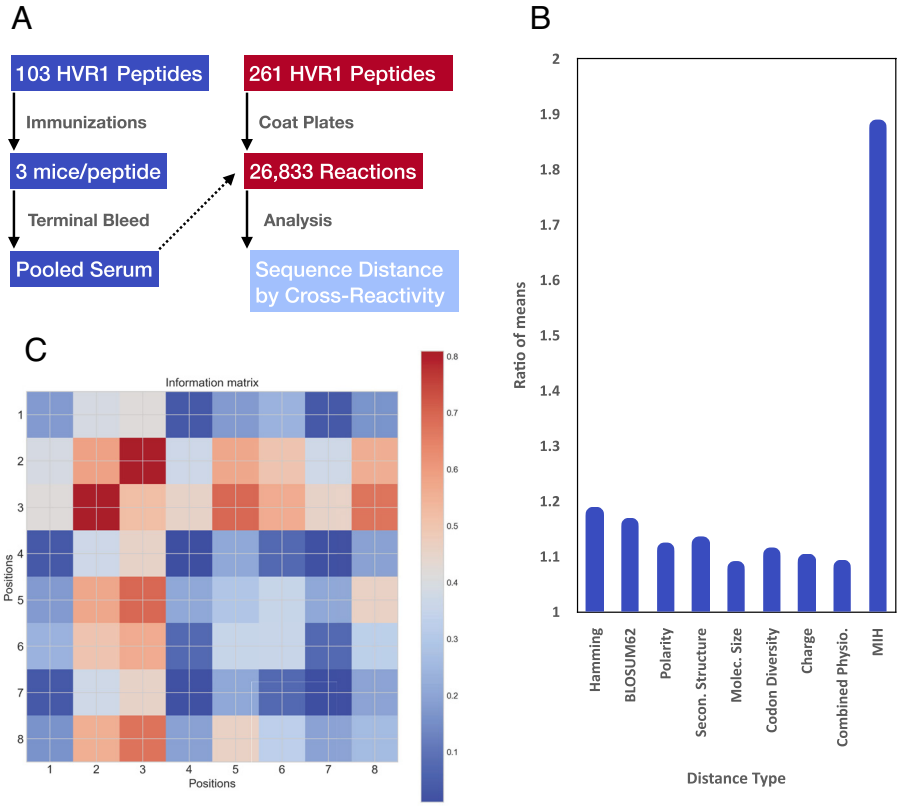

Fig. 1. Association of genetic distance and cross-reactivity. (*A*) Overview of the cross-reactivity experiment [for more details, see Campo et al. (20)], which generated a total of 26,833 HVR1 pairwise cross-immunoreactive assays. (*B*) Ratio between mean distance of noncross reactive pairs and cross-reactive pairs using different types of distances: Hamming, BLOSUM62 scores, MIH, and Euclidean distance of 5 physicochemical factors (F1, polarity; F2, secondary structure; F3, molecular size; F4, codon diversity; F5, charge) (21). (*C*) HVR1 information matrix using the entire sequence dataset. The diagonal shows the Shannon entropy of each position and the other entries of the matrix show the mutual information among all pairs of positions.

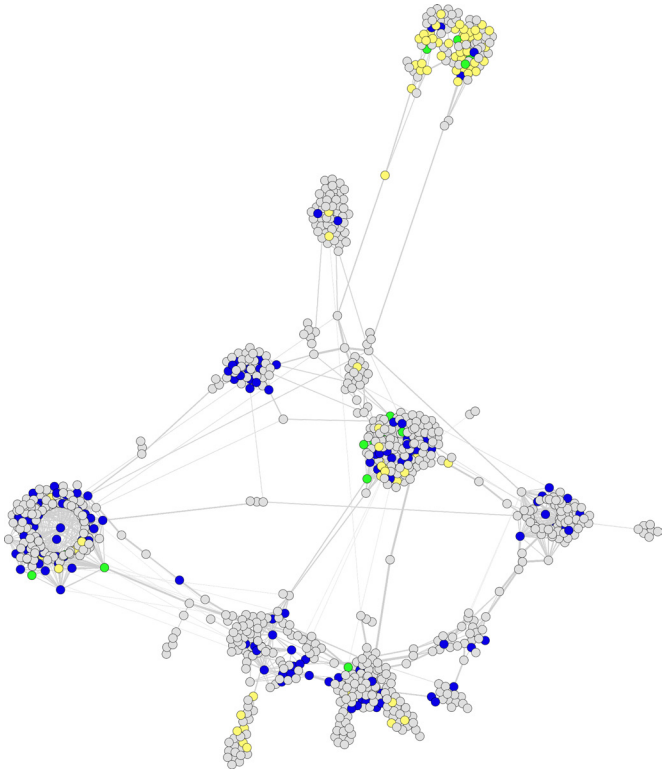

Fig. 2. K-step network of global HVR1 sequence space. All nonredundant HVR1 8aa sequences (n = 969) pooled across datasets were used to construct a k-step network with node radius corresponding to the square root of the haplotype frequency. Nodes in blue correspond to those sequences present only in 1a, yellow to those sequences only present in 1b, and green to those sequences present in both subtypes.

(9.50E-04) that was 9.73 times higher (*t* test, $P = 0.0077$) than the average of chronic variants (9.77E-05). These results indicate that the average MIH distance between acute and other variants in the network is significantly reduced relative to chronic variants and thus suggests that acute variants are more likely than chronic to be cross-immunoreactive. In addition, the acute variants were not locally confined but were found globally distributed across the network and independent of HCV genotype. This indicates that acute HVR1 variants, owing to their broad spread in the HVR1 genetic space, may possess complementary cross-immunoreactivities, which, if combined, may provide broad cross-immunoreactivity leading to broad neutralization.

Selection of HVR1 Variants for Immunization. To discover the combination of variants most likely to possess complementary cross-immunoreactivities, we evaluated whether the HVR1 network contained modules or clusters, with the hypothesis that each cluster would correspond to distinct HVR1 subphenotypes. The distribution of all pairwise MIH distances showed a bimodal distribution, suggesting the existence of modules (Fig. 3*A*). In contrast, distribution of the Hamming or physicochemical distances was unimodal. The bimodal distribution of MIH distances is an indication of clusters in the HVR1 space modeled, which leads to two types of distances: i) smaller within-cluster distances and ii) larger between-cluster distances. The modular organization of the MIH-based network suggests that a combination of HVR1 variants selected from each module may be capable of inducing immune responses covering the entire space. Thus, we created modularity-maximizing partitions between 2 and 40 modules. We identified the five-module solution as the best one, given that it showed the highest difference between average within-module distances and the distance obtained by random partitioning of the same size (Fig. 3*B*). All HCV genotypes were scattered across clusters: genotypes 1 (n = 1082), 2 (n = 40), 4 (n = 27), and 6 (n = 59) were present in all the five clusters, whereas genotypes 3 (n = 88) and 5 (n = 9) were present in four clusters. Within genotype 1, those belonging to subtype 1a (n = 774) were present in all the five clusters, with those belonging to 1b (n = 302) also present in all the five clusters (Fig. 2). Finally, we identified the most central acute-phase variant in each of the five modules and selected them as immunogens for synthesis (Fig. 3*C*).

Immunogens Elicit Cross-Reactive Antibodies. To evaluate whether our candidate peptides were immunogenic, six groups of Balb/c mice (n = 3 per group) were immunized with each of the peptides individually (monovalent) or combined (pentavalent) and terminally bled to characterize humoral responses (Fig. 4*A*). Both monovalent and pentavalent formulations elicited high-titer (1:25,000) peptide-specific antibodies following immunization, with higher reactivity observed with the pentavalent sera at the lowest dilution tested (*t* test, $P = 0.003$; Fig. 4*B*). Sera from mock-immunized mice (adjuvant + PBS) were not reactive at any dilution tested (Fig. 4*B*). A concern in multivalent formulations is diminished reactivity to each of the individual constituent immunogens. We therefore evaluated monovalent immunogenicity, based on self-reactivity, in comparison to the reactivity of the pentavalent immunized sera. Though we observed intrinsic differences in the antigenicity and immunogenicity of the monovalent immunogens, self-reactivity following pentavalent immunization was not inferior (Fig. 4*C*). Next, using competitive ELISA, we evaluated whether antibodies elicited by pentavalent immunization targeted the C-terminal neutralizing epitope of HVR1. We observed significant binding inhibition when sera were preincubated with a peptide fragment comprising the C-terminal eight amino acids, suggesting antibodies elicited by the pentavalent formulation predominantly, though not exclusively, target the C terminus of HVR1 (Fig. 4*D*).

Next, we sought to characterize heterologous cross-reactivity using a panel of HVR1 peptides (Fig. 5) representing global genetic diversity. This was based on a prior work to develop a standardized panel of HCV variants representing all major global genotypes, 1a intragenotypic diversity, and the spectrum of neutralization resistance (25, 26). The subpanel we selected was enriched for highly neutralization-resistant variants maximally differing in genetic distance from our vaccine immunogens (50 to 87.5% sequence divergence) (Fig. 5*A*). By ELISA, we observed universal cross-reactivity of pentavalent sera with the panel of HVR1 peptides (Fig. 5*B*)**.** No correlations between cross-reactivity and either HVR1 genotype or genetic distance to the pentavalent immunogens were observed. These findings indicate that pentavalent immunization elicited broadly cross-reactive antibodies targeting the neutralizing epitope containing HVR1 C terminus.

Pentavalent Immunogen Elicits Broadly Neutralizing Antibodies. Our previous experiments demonstrated cross-reactivity to genetically diverse HVR1 peptides. Cross-reactivity is necessary but not sufficient for viral neutralization. We therefore sought to characterize the protective breadth of the antibodies elicited by pentavalent immunization using HCV pseudoparticles (HCVpp). Briefly, for each HCV variant in our panel, HCVpp were generated, and residual infectivity in the presence of serial dilutions of mouse sera was used to calculate proportion neutralization and $1/ID_{50}$. We observed potent, universal neutralization across the HCVpp panel (Fig. 6*A*). Even highly neutralization-resistant variants, such as UKNP3.1.2, which are

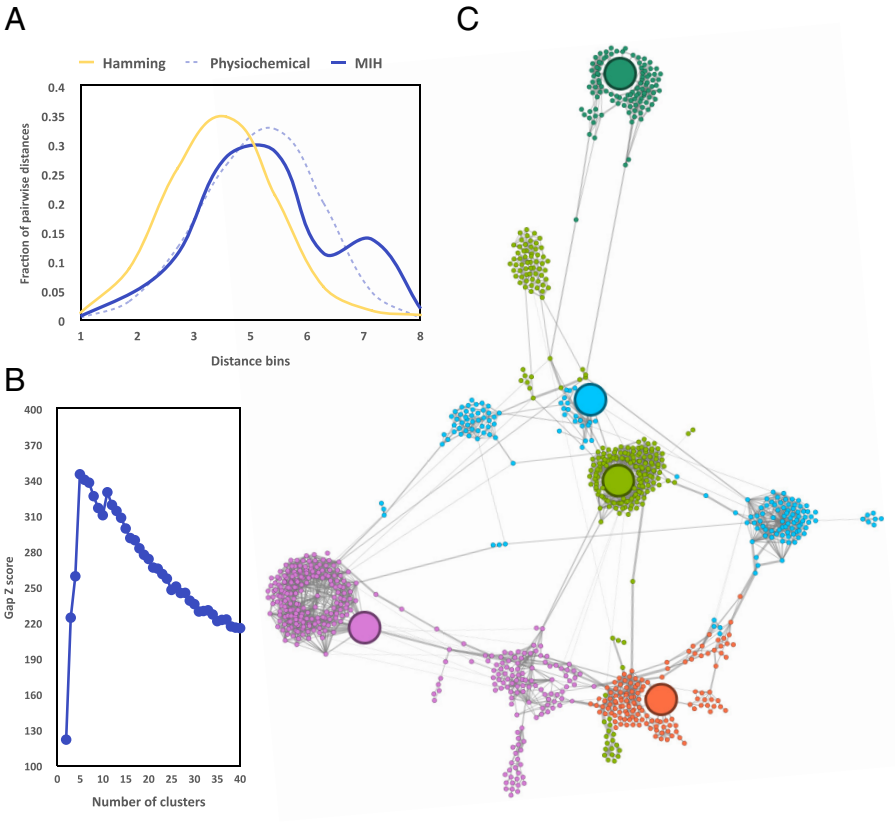

Fig. 3. Clusters in the HVR1 sequence space. (*A*) Histogram of distances among all pairs of sequences. Three types of distances are considered: Hamming, MIH, and Euclidean distances between physiochemical profiles. Each distance type is normalized by dividing by its maximum value. (*B*) Scatterplot of the goodness of each clustering (gap Z score) according to the number of clusters. (*C*) k-step network of all HVR1 sequences. Nodes are colored by membership to each cluster and the big nodes correspond to the most central one in each cluster.

almost completely resistant to neutralization by patient-derived sera (26), were potently neutralized by pentavalent sera ($1/ID_{50}$ = 1,280). Further, compared to a derivative of a gpE1/E2 vaccine entering clinical trials, neutralization potency against UKNP3.1.2 was more than 10-fold higher, with the average heterologous neutralization across the entire panel being 2.32-fold higher (*t* test, $P = 0.021$; Fig. 6*B*). We found no relationship between sequence divergence from the pentavalent immunogens and neutralization resistance, with HCVpp UKNP1.17.1, which has the greatest Hamming distance from any immunogen in the formulation, potently neutralized ($1/ID_{50}$ = 817; Fig. 6*C*). Collectively, these findings suggest that the antibodies elicited by the pentavalent formulation can potently neutralize even extremely genetically distant variants, with no escape detected for any HCVpp in this antigenically diverse panel.

Pentavalent Neutralization Breadth Exceeds Monovalent Constituents. Next, we evaluated whether pentavalent immunization elicited antibodies that could neutralize variants resistant to monovalent immunization. Interestingly, not only was pentavalent neutralization potency against the panel greater than average monovalent potency, but variants completely resistant to neutralization by every monovalent preparation were potently neutralized by pentavalent sera (UKNP1.7.1 and UKNP2.4.1). Across the panel, the average pentavalent potency was 3.93-fold greater (*t* test, $P = 0.009$) than the average monovalent potency ($1/ID_{50}$ = 111) and, for eight of the ten variants, was significantly greater than the most potent monovalent against each variant (Fig. 7*A*). We also compared the neutralization capacity of sera obtained following pentavalent immunization to sera obtained by sequentially immunizing mice with the same monovalent immunogens. Neutralization was not improved by sequentially administering the monovalent immunogens (mean $1/ID_{50}$ = 99), and was inferior to simultaneous (pentavalent) immunization (*t* test, $P = 0.004$; Fig. 7*B*), indicating that not only the valency, but also the method of immunization influences the humoral response and the potential for synergy. These findings suggest that a qualitatively distinct humoral response, rather than a summation of monovalent polyclonal responses, is operative in the broad neutralization observed following pentavalent immunization.

Discussion

Vaccines are one of the most efficient public health tools to control infectious disease in human populations (27). However, development of vaccines to highly mutable viruses such as HIV, influenza virus, and HCV is greatly impeded by the genetic variability of dominant epitopes, immune responses against which are largely strain specific, lacking the breadth of cross-immunoreactivity required for protection against a vast swarm of viral variants (28). HCV's HVR1 is a well-characterized example of a variable region eliciting only narrowly neutralizing antibodies following natural infection or vaccination (29). Here, we present data suggesting a strategy, based on a unique model of the HVR1 genetic space, for designing complementary formulations of HVR1 antigens capable of directing the immune response to conserved epitopes within a variable sequence region. We show that immunization of mice with a mixture of HVR1 variants selected from each of the five genetic modules of the space produces antibodies demonstrating broad, potent, and superior neutralization activity. This strategy is distinct from past vaccine approaches to variable viruses, which have attempted to direct immune responses to conserved epitopes (13, 14, 18). Though targeting conserved epitopes is a rational approach to addressing antigenic variability, the limitations of this approach are evident in the natural history of HCV infection. Not only can conserved epitopes directly evolve to evade immune pressure, but diversifying selection on HVR1 persists even in the presence of conserved epitope-targeting antibodies

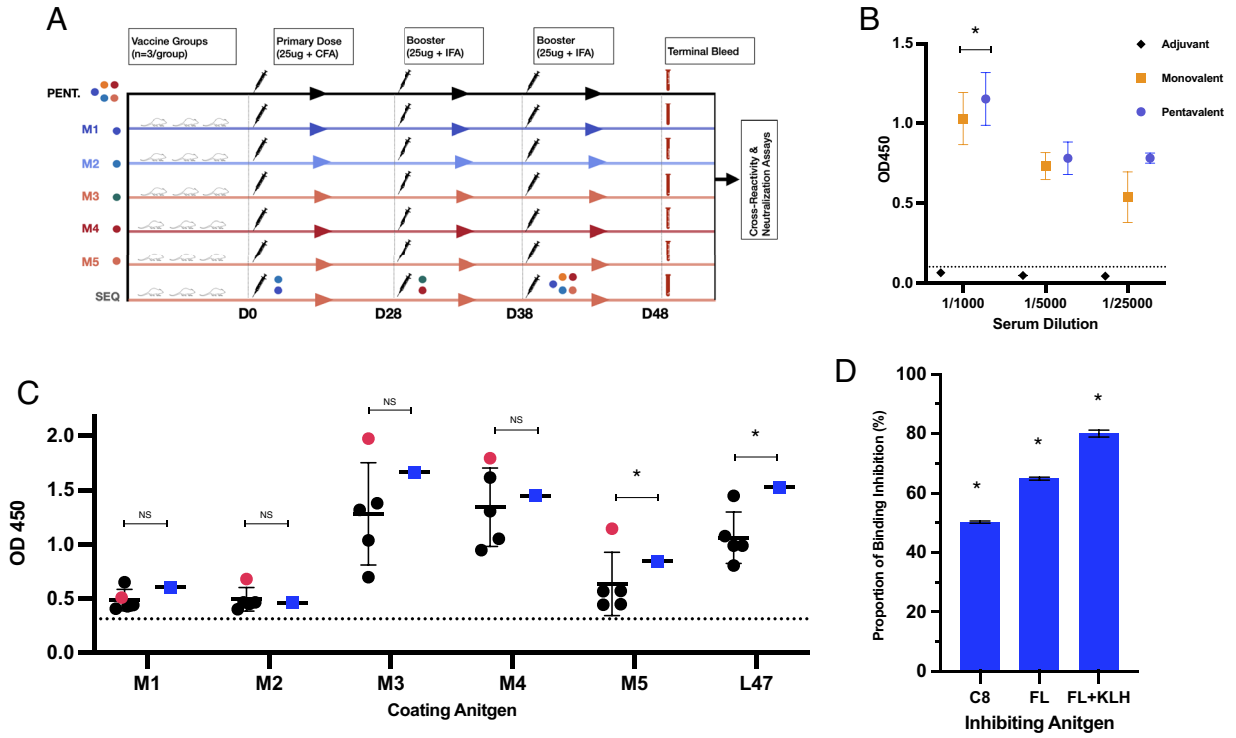

Fig. 4. Self and cross-reactivity of HVR1 antigens. Mice were immunized with monovalent or pentavalent immunogens conjugated to KLH and formulated with either complete (CFA) or incomplete (IFA) Freund's adjuvant and terminally bled at day 48 (*A*) to evaluate antiimmunogen (HVR1-KLH) titers (*B*). Sera from each group were evaluated for self- and cross-reactivity to each of the five antigens used for immunizations (M1-5) and a genotype 1 patient–derived isolate (L47) heterologous to all monovalent sera. Homologous monovalent sera are shown in red, pentavalent in blue, and the heterologous monovalents in black (*C*). Pentavalent sera were incubated with peptides containing either the immunogen (FL+KLH), full-length HVR1 alone (FL), or the C-terminal eight aa of HVR1 (C8) to measure binding inhibition to immunogen-coated ELISA plates (*D*). Error bars indicate mean with SD. **P* < 0.05.

(6, 30, 31). This suggests that HVR1 can evolve to attenuate the neutralizing potency of not only HVR1-specific antibodies, but antibodies targeting other epitopes on the virion, which is mechanistically consistent with findings that HVR1 modulates the accessibility of conserved regions (32). That the pentavalent candidate reported here neutralized a panel of highly neutralization-resistant, highly diverse HCV variants suggests that a reappraisal of the role of variable epitopes in vaccine design is warranted, especially when their genetic space indicates the presence of functional constraints bounding variability.

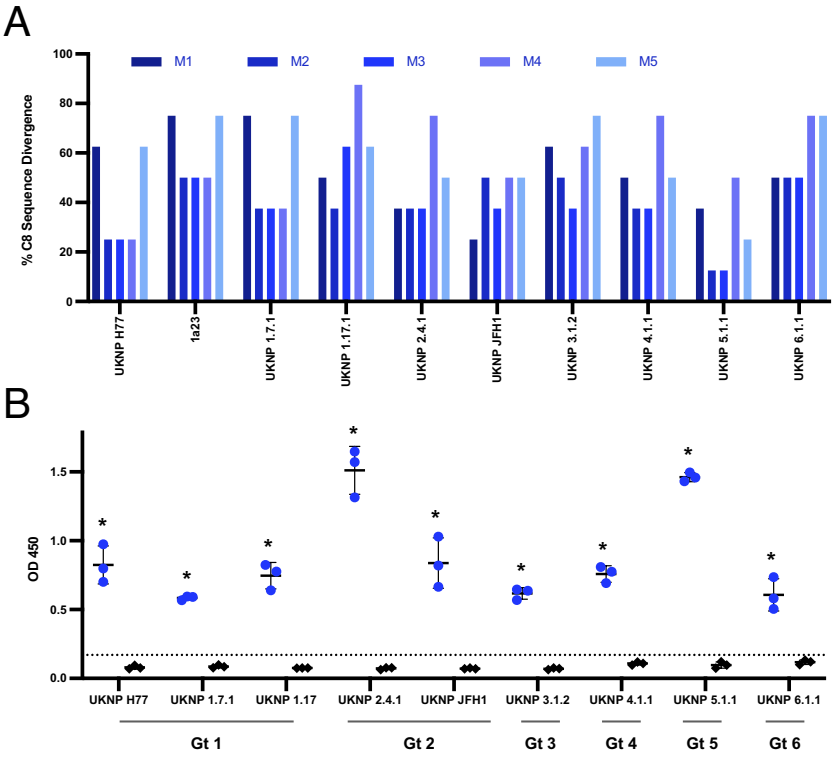

Fig. 5. Pentavalent sera broadly cross-react with antigenically diverse panel of HVR1 peptides. HCV variants with the greatest pairwise divergence in their eight C-terminal aa from each peptide used in the pentavalent formulation (*A*) were synthesized and used to evaluate pentavalent cross-immunoreactivity (blue circles) compared to adjuvant control (black diamonds) (*B*). Error bars indicate the mean with SD. Dotted line indicates two times the SD of adjuvant control. **P* < 0.05.

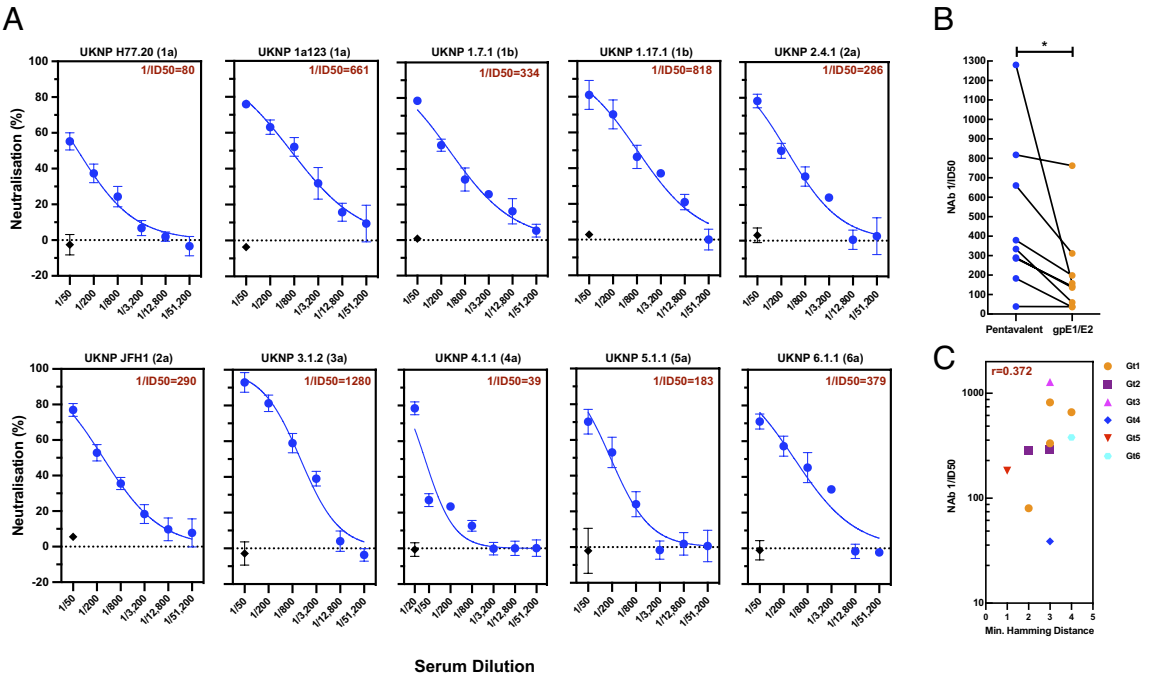

Fig. 6. Pentavalent sera neutralize panel of antigenically diverse HCVpp in excess of gpE1/E2 vaccine. Neutralizing activity of pentavalent sera against a multigenotype panel of HCVpp was evaluated in serial dilutions starting at 1:50, with the exception of 4.1.1 which was additionally tested at 1:20 (*A*). Neutralizing potencies (1/ID50s) were compared between pentavalent sera and sera obtained from mice immunized with a gpE1/E2 vaccine candidate (*B*). The 1/ID50 of pentavalent sera was evaluated as a function of the minimal Hamming distance between each HCVpp HVR1 (C-terminal eight aa) and the pentavalent peptides (*C*). Error bars indicate SD. *$P < 0.05$.

Considering the proximity of HVR1 to the E2 receptor–binding sites, the major function constraining the HVR1 genetic space is likely related to transmission and receptor binding. Indeed, HVR1 was shown to affect HCV infectivity by contributing to the optimal composition of virions and membrane fusion (15). It is a critical region for interaction between E2 and scavenger receptor class B type I (SR-BI) (33–35). HVR1 sequence diversity also has a role in protecting conserved epitopes against antibody binding (36), and thus affecting global HCV neutralization sensitivity. These results add credence to the approach presented here based on generating antibody with a broad HVR1 specificity to protect against HCV infection rather than targeting conserved epitopes exposed only in the neutralization-sensitive conformational state of the HCV envelope. If the HVR1 genetic space is largely shaped by balancing a single important function like transmissibility, with the diversifying selection of host immune pressure, there should be common structural features maintained by patterns of coordinated substitutions that permit immune evasion without compromising infectivity. Conservation of HVR1 size, physiochemical invariance, and extensive epistasis (i.e., coordinated substitutions) within HVR1 and between HVR1 and other positions in E2 support the existence of fitness-constrained structural features (22, 37). It is reasonable to expect that such conserved structural features, if properly presented to B cells as antigenic epitopes, would elicit broadly neutralizing antibodies despite marked sequence divergence.

It is not clear what determines the differential presentation of these conserved epitopes among HVR1 variants. It is also unknown what determines cross-reactivity between any two HVR1 variants. The HCV HVR1 genetic space is vast. It is conceivable, though, that sufficiently broad immune responses covering this space may be produced by a combination of HVR1 variants, each eliciting antibody with complementary immune reactivity. Criteria for rational selection of such complementary HVR1 variants are not clear because there are no data associating the breadth of immunoreactivity with HVR1 sequences in humans. Among many strategies, we considered a random selection and identification of the most genetically distant variants. However, these criteria do not inform how many

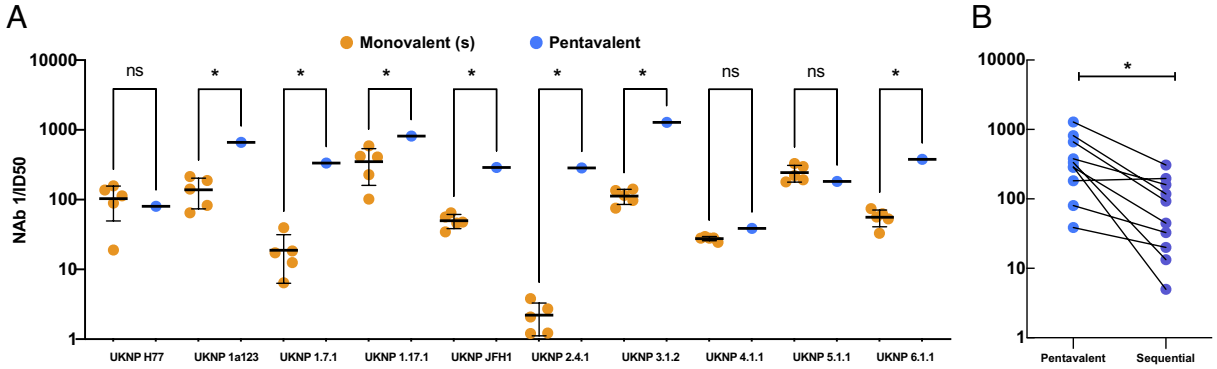

Fig. 7. Pentavalent sera neutralize variants resistant to neutralization by its monovalent constituents. Neutralizing potencies (1/ID50s) were compared across monovalent (orange) and pentavalent (blue) groups (*A*). Neutralizing potencies (1/ID50s) were compared between pentavalent sera and sera obtained from mice immunized with the same immunogens sequentially (*B*). Error bars indicate mean with SD. *$P < 0.05$.

such variants need to be selected or how to achieve adequate, or ideally, complete coverage. Another potential criterion is representation of all HCV genotypes. Although this seems to be clearer for identifying the number of potential variants and the space to be covered, antigenic convergence among HVR1 variants from different genotypes and subtypes (20) complicates the selection of the initial HVR1 variants for the study because there are no distinct genotype-specific clusters of HVR1 sequences. Here, we developed a different selection strategy for heuristic identification of complementary HVR1 variants. It is based on using the MIH distance, which we recently showed to better approximate phenotypic distances in both in silico and in vitro datasets (23). We found that while simple sequence similarity (Hamming distance) could moderately discriminate between cross-reactive pairs, the unique MIH distance was markedly superior. This result is particularly important as it indicates that the distance captures the well-known fact that not all substitutions are equivalent (21), and that the more radical the substitution, measured by capacity to increase MIH distance, the more likely it will abrogate cross-immunoreactivity. When we explored the structure of the HVR1 sequence space using MIH, the network was found to be pentamodular, indicating that the structural features defining breadth of immunoreactivity, and mutual reactivity between any two variants, are distributed across five major HVR1 clusters. Acute-phase variants were identified in all the five clusters and were found to occupy positions of centrality within each module, suggesting that founder viruses have a greater breadth of cross-immunoreactivity within each cluster than chronic-phase variants. This finding is in concert with the observation that early acute-phase variants, referred to as transmitted-founder variants, possess distinct, transmissibility enhancing phenotypes and occupy central positions within the sequence space, affording greater mutational robustness from which to diversify once infection is established (38, 39). It is important that the acute HVR1 variants are not locally confined but are distributed across the k-step network, entirely independent of HCV genotype, as this indicates the existence of multiple transmitted-founder phenotypes, which must all be neutralized by a putative HCV vaccine.

The identification of five clusters in the HVR1 MIH genetic space was used to guide selection of 5 HVR1 sequences for peptide synthesis and immunization. We hypothesized that peptides from these clusters could elicit cluster-neutralizing immune responses, the summation of which should provide responses covering the majority of HCV strains. Immunization with a mixture of all the five peptides was used to show that the same breadth of neutralization could be maintained after immunization with all peptides simultaneously. We found, however, that the combination of antibody against individual peptides and a mixture of sera from mice immunized with these peptides did not neutralize 2 HCVpp variants, whereas the pentavalent immunization did neutralize all the HCVpp tested. This synergy of pentavalency was not expected but is an important observation.

This suggests that to achieve a universal broad neutralization, the divergent HVR1 immunogens may need to be simultaneously presented. Sequential exposure to each cluster may instead successively direct maturation to module-specific features, limiting breadth of reactivity. This may explain why neutralization breadth and potency observed following sequential immunization with the five HVR1 peptides was inferior, and why chronic infection, with its repeated targeting of immunodominant epitopes followed by escape, does not produce the breadth of neutralization observed following pentavalent immunization (30, 31). The importance of simultaneous presentation is also supported by the finding that antibodies elicited by pentavalent immunization neutralized variants resistant to monovalent immunization. This synergistic interaction indicates that although the HVR1 variants selected for immunization were genetically distant, and occupied distinct modules, they shared the neutralizing epitope.

Polyvalent vaccines are a common strategy to broaden immune responses and have been in application for decades (40). The rationale is the expectation that each antigenic variant will be immunologically complementary, and thereby incrementally broaden coverage. However, simply combining antigenic variants is not sufficient for eliciting synergy. For example, despite application of polyvalent vaccines for decades, concerns of reduced protection (41) and antibody-dependent enhancement of disease (42), rather than synergy, predominate. The 50-valent inactivated rhinovirus vaccine is immunogenic only against one-third of circulating human rhinoviral types (43), suggesting that a mere blending of serologically distinct antigenic variants does not result in apparent synergy with certainty. Another example of the complex nature of synergy was reported by Lange et al. (44), who showed that immunization with a mixture of 4 HVR1 variants increased the strength of immune response compared to immunization with the individual variants, but without a detectable increase in the breadth of neutralization. All the four HVR1 sequences in that study belonged to HCV genotype 1b. Interestingly, we found that three of the variants they evaluated come from a single MIH cluster. This observation indicates that either a highly disproportionate presentation of clusters resulted in a limited synergistic effect focused on the dominant cluster, or presentation of variants from only two clusters is insufficient for increasing the breadth of neutralization.

We did not evaluate multivalency other than pentavalency but believe that all the five antigens are important. Notably, Fig. 4 shows that epitopes of M1 and M2 presented in peptides adsorbed on the solid phase are poorly recognized by antibodies to all HVR1 variants, including M1- and M2-vaccinated mice, but epitopes of M3, M4, and M5 react with all sera. This observation indicates that antibody was elicited to all HVR1 variants and that epitopes of M1 and M2 are highly conformation dependent, which is in keeping with previous data showing that lack of self-immunoreactivity is a sign of conformational dependence of the epitopes (20). The M1 and M2 peptides seemingly assume a conformation on the surface of microtiter plates that prevents interaction with the HVR1 antibody. However, as shown in Fig. 7, antibody to all HVR1 variants, including M1 and M2, are neutralizing, which indicates that they all most likely contribute to synergy.

There are some important limitations to the data presented. We recognize that a limited number of HVR1 variants were evaluated in the neutralization experiments. Although we selected known neutralization-resistant and diverse HCVpp for the neutralization panel (25, 26), the tested set is only an approximation of the entire HCV genetic space. However, the successful neutralization of all HCVpp, including highly neutralization-resistant variants, supports the strength of the approach. We did not compare our use of MIH cluster–based immunogen selection to other possible selection strategies and therefore note that while the results are promising, this may not be the only or the optimal method for immunogen selection. Our data demonstrate the synergistic effect for a mixture of five HVR1 variants; however, the precise mechanism of the immunological synergy remains unclear. Whether the number of epitopes can be reduced while achieving a similar synergistic effect was not evaluated, but given the high valency of approved (pneumococcal 23-valent) (45) and proposed (inactivated rhinovirus 50-valent) (43) vaccines, the current pentavalent strategy is well within the practical limits of vaccine technology. Additionally, all experiments conducted here were based on using HCVpp. It is known that these particles do not incorporate human lipoproteins, which are important for

escape from antibody binding. Although there is evidence indicating no major difference in the neutralizing breadth of mAbs measured using HCVpp or HCVcc (46), testing of synergistic neutralization in various experimental conditions is warranted. Future studies will address these open questions and compare antibodies produced against individual HVR1 variants and the polyvalent mixture to understand the mechanism of synergistic immunization for vaccine design. This will hopefully allow translation of the in vitro neutralization data to real protection against HCV infection in vivo.

In conclusion, synergistic immune responses to HVR1 variants selected using a sequence space model accounting for the heterogeneity of each position and the interactions among amino acid positions, offer a unique approach to overcoming HCV genetic heterogeneity and the dominance of strain-specific immunity by directing the immune response to cross-immunoreactive neutralizing epitopes within HVR1. Application of this approach opens an avenue for the development of a universal HCV vaccine. This approach may be generalizable to other highly mutable viruses.

Materials and Methods

HVR1 Sequences. All the HVR1 nucleotide sequences covering the hypervariable region (81bp) were obtained from the Virus Pathogen Database and Analysis Resource (ViPR) (47). In addition, the following sequences were added from previous studies: 119 sequences obtained from patients with recent HCV infection, 256 sequences from chronic HCV infection, and 262 sequences from our previously published cross-reactivity experiment (20, 48).

This set of 12,245 sequences belongs to all known HCV genotypes. All sequences were clipped and translated to the C-terminal HVR1 eight amino acid sites and cleaned in the following manner: i) only one sequence per patient was allowed, ii) only sequences without insertions or deletions were allowed, and iii) sequences with Ns or noncoding regions were removed. Finally, there were 969 distinct variants, which were used in all analyses conducted here.

Distance between HVR1 Variants. Genetic distances based on physical–chemical properties (21) were calculated as described in ref. 22. The MIH distance between every pair of variants was recently developed (23). The MIH is a distance inspired by the Mahalanobis distance that can be applied to any type of categorical data like nucleotide or amino acid sequences. The Mahalanobis distance accounts for the fact that the variance of each variable is different and that there may be covariance between variables. This distance is reduced to the Euclidean distance for uncorrelated variables with unit variance.

The MIH distance considers the variability of each position as measured by entropy and the existence of coordinated substitutions as measured by mutual information. The MIH distance between two sequences x and y is given by the following formula:

$$MIH(x, y) = xy^T . infMat . xy$$

where xy is the mismatch vector (with 1 where the symbols are different and 0 where they are the same) and xy^T is its transposed form; InfMat is the information matrix, with 1/entropy in the diagonals and 1/mutual information between position pairs in all other entries. Effectively, if the difference between two sequences occurs at a variable position, this difference receives a low weight. In the same manner, if the difference occurs at positions that are highly associated, this difference also receives a low weight. Thus, the MIH distance is reduced to the Hamming distance when the positions have maximum entropy, and every pair of positions has mutual information equal to zero. A modified version of the MIH distance showed the best performance separating known grouping in a biological validation dataset (23).

K-Step Network and Clustering. For the set of HVR1 variants, we visualized the matrix of MIH distances by means of a k-step network as previously described (49–51). The k-step network is equivalent to the union of all possible minimum spanning trees and allows for efficient visualization of the distances among all variants present in a sample. This network was then split into clusters using the Girvan–Newman method as implemented in GEPHI, which was also used to draw the networks (52). The number of clusters was chosen by using the gap statistic: For each desired number of clusters (from 2 to 40), we measured the average distance within clusters in the k-step network and compared it with the distance in 10,000 random partitions of the same size (53).

Immunizations. Peptides for immunization experiments were synthesized using Fmoc chemistry, conjugated to keyhole limpet hemocyanin (KLH) via maleimide linkage, and combined in a 1:1 emulsion with Freund's complete (primary) or incomplete (booster) adjuvant as previously described (54). For immunizations, female Balb/c mice (4 to 6 wk old) were ordered through the UHN animal care facility, acclimatized for 1 wk, prebled at ~7 wk of age (5–8), and then subcutaneously injected (25 μg peptide + 25 μL adjuvant) at days 0, 28, and 38, with terminal bleed via cardiac puncture at day 48 [3 mice per group – protocol approved by University Health Network (UHN) Animal Care Committee (ACC)]. Pentavalent immunizations were performed by combining 5 μg of each monovalent antigen into a single formulation with adjuvant (25 μL). Sequential immunizations were performed by administering M1/M2 (12.5 μg each peptide + 25 μL adjuvant) at day 0, M3/4 (12.5 μg each peptide + 25 μL adjuvant) at day 28, and the pentavalent formulation (5 μg each peptide + 25 μL adjuvant) at day 38. Mock immunizations were performed with adjuvant and sterile PBS. Both prebleed and mock-immunized sera served as negative controls in subsequent assays. gpE1/E2 sera served as positive control and was obtained by immunizing 5 to 7-wk-old female CB6F1 mice with H77 E1/E2 (2 μg of purified antigen) in a 1:1 ratio with alum (75 μg) and monophosphoryl lipid A (MPLA). To obtain sera in all groups, blood samples were processed by centrifugation, heat-inactivated, and stored at −80 °C until analysis was performed.

ELISA Assessment of HVR1 Binding. As previously described, ELISA was performed to measure HVR1-specific antibody responses in mouse sera (55). Briefly, 96-well plates (MaxiSorp, Thermo Fisher Scientific) were coated overnight with 2 μg/mL of HVR1 peptides at 4 °C. The next morning, plates were washed 5× with PBS containing 0.05% Tween 20 (PBST) and incubated with group-pooled, serially diluted mouse (PBST) sera for 1 h at room temperature. Postincubation, the plates were washed 5× with PBST and incubated for 1 h with a 1:10,000 dilution of HRP-conjugated anti-mouse IgG secondary antibody. After a final 5 washes, 3,3′,5,5′-tetramethylbenzidine (TMB) substrate was added to each well, dark-incubated for 15 min, then the reaction was terminated with Stop-Solution (0.16 M sulfuric acid). Absorbance was read at 450 nm, in triplicate, with measurements corresponding to visual color change in each well. For competitive ELISA, the same protocol was followed, except for the additional incubation of inhibiting peptides [C-terminal 8aa of HVR1, full-length (FL) HVR1, or FL-HVR1 conjugated to KLH] with diluted sera for 1 h prior to plate application. ELISA cutoff was calculated by multiplying (2×) the mean of negative controls (adjuvant immunized sera). Statistical analysis was done by unpaired *t* test using Prism8 software (56).

Neutralization Assays. HCVpp neutralization assays were performed as previously described (55). Briefly, HCVpp were generated by cotransfecting HEK 293T cells with the pNL4-3.lucR$^-$E$^-$ packaging plasmid and expression plasmids encoding patient-derived E1E2. To test sera for neutralizing activity, Huh7 cells were plated in 96-well plates (15,000 per well) and incubated overnight. The following day, HCVpp were incubated with heat-inactivated, group-pooled, serially diluted mouse serum for 1 h at 37 °C, and then added in triplicate to Huh7-plated wells. The plates were then incubated in a CO_2 incubator at 37 °C for 4 h before media was replaced. Seventy-two hours later, the media was removed and cells were lysed using cell lysis buffer (Promega, Southampton, UK) and placed on a rocker for 15 min. Luciferase activity was then measured in relative light units (RLUs) using a FLUOstar Omega plate reader (BMG Labtech, Aylesbury, UK) with MARS software. Each sample was tested in triplicate. The $1/ID_{50}$ was calculated as the serum dilution that caused a 50% reduction in relative light units compared to pseudoparticles incubated with prebleed serum. Values were calculated using a variable slope dose–response curve fit with nonlinear regression, and ordinary one-way ANOVA was used to compare difference between vaccine groups using Prism 9.3.1 (GraphPad Software).

Data, Materials, and Software Availability. All data associated with this study are present in the paper or publicly available (47). Physical clones and HVR1 peptides for L47, H77, 1a23, 1.4.1, 1.17.1, 1.4.1, JFH1, 2.4.1, 3.1.2, 4.1.1, 5.1.1, and 6.1.1. can be shared upon reasonable request.

ACKNOWLEDGMENTS. We gratefully acknowledge John Law and Michael Houghton for providing sera from mice immunized with gpE1/E2. We also acknowledge the input and guidance of John Tavis in designing the study and providing recommendations to improve the manuscript. A.I.M. also acknowledges the Toronto Centre for Liver Disease for financially supporting the project.

Author affiliations: [a]Toronto Centre for Liver Disease, Toronto General Hospital, Toronto, M5G 2C4 ON, Canada; [b]Molecular Epidemiology and Bioinformatics, Centers for Disease Control and Prevention, Atlanta 30333, Georgia; [c]Department of Cell and Systems Biology, University of Toronto, Toronto, M5S 3G5 ON, Canada; [d]Department of Immunology, University of Toronto, Toronto, M5S 1A8 ON, Canada; [e]Wolfson Centre for Global Virus Infections, University of Nottingham, Nottingham NG8 1BB, United Kingdom; and [f]Institute of Infection, Veterinary and Ecological Sciences, University of Liverpool, Liverpool CH64 7TE, United Kingdom

Author contributions: A.I.M., D.S.C., Y.K., R.A.U., and J.J.F. designed research; A.I.M., D.S.C., A.Z., and R.A.U. performed research; D.S.C. and J.K.B. contributed new reagents/analytic tools; A.I.M., D.S.C., Y.K., M.G.A., A.J.G., R.A.U., and J.J.F. analyzed data; M.G.A. writing–review & editing; A.J.G. and J.K.B. writing–review & editing; and A.I.M., D.S.C., Y.K., R.A.U., and J.J.F. wrote the paper.

1. J. F. Perz, G. L. Armstrong, L. A. Farrington, Y. J. F. Hutin, B. P. Bell, The contributions of hepatitis B virus and hepatitis C virus infections to cirrhosis and primary liver cancer worldwide. *J. Hepatol.* **45**, 529–538 (2006), 10.1016/j.jhep.2006.05.013.
2. G. J. Dore, S. Bajis, Hepatitis C virus elimination: Laying the foundation for achieving 2030 targets. *Nat. Rev. Gastroenterol. Hepatol.* **18**, 91–92 (2021), 10.1038/s41575-020-00392-3.
3. K. Page *et al.*, Randomized trial of a vaccine regimen to prevent chronic HCV infection. *N. Engl. J. Med.* **384**, 541–549 (2021), 10.1056/NEJMoa2023345.
4. T. J. Liang, J. J. Feld, A. L. Cox, C. M. Rice, Controlled human infection model–Fast track to HCV vaccine? *N. Engl. J. Med.* **385**, 1235–1240 (2021), 10.1056/NEJMsb2109093.
5. B. G. Pierce, Z. Y. Keck, S. K. Foung, Viral evasion and challenges of hepatitis C virus vaccine development. *Curr. Opin. Virol.* **20**, 55–63 (2016), 10.1016/j.coviro.2016.09.004.
6. T. von Hahn *et al.*, Hepatitis C virus continuously escapes from neutralizing antibody and T-cell responses during chronic infection in vivo. *Gastroenterology* **132**, 667–678 (2007), 10.1053/j.gastro.2006.12.008.
7. M. A. Martinez, S. Franco, Therapy implications of hepatitis C virus genetic diversity. *Viruses* **13**, 41 (2020), 10.3390/v13010041.
8. J. Prentoe, J. Bukh, Hypervariable region 1 in envelope protein 2 of hepatitis C virus: A linchpin in neutralizing antibody evasion and viral entry. *Front. Immunol.* **9**, 2146 (2018), 10.3389/fimmu.2018.02146.
9. P. Farci *et al.*, Prevention of hepatitis C virus infection in chimpanzees by hyperimmune serum against the hypervariable region 1 of the envelope 2 protein. *Proc. Natl. Acad. Sci. U.S.A.* **93**, 15394–15399 (1996), 10.1073/pnas.93.26.15394.
10. Y. K. Shimizu *et al.*, A hyperimmune serum against a synthetic peptide corresponding to the hypervariable region 1 of hepatitis C virus can prevent viral infection in cell cultures. *Virology* **223**, 409–412 (1996), 10.1006/viro.1996.0497.
11. B. Bartosch *et al.*, *In vitro* assay for neutralizing antibody to hepatitis C virus: Evidence for broadly conserved neutralization epitopes. *Proc. Natl. Acad. Sci. U.S.A.* **100**, 14199–14204 (2003), 10.1073/pnas.2335981100.
12. H. E. Drummer, Challenges to the development of vaccines to hepatitis C virus that elicit neutralizing antibodies. *Front. Microbiol.* **5**, 329 (2014), 10.3389/fmicb.2014.00329.
13. B. G. Pierce *et al.*, Structure-based design of hepatitis C virus vaccines that elicit neutralizing antibody responses to a conserved epitope. *J. Virol.* **91**, e01032-17 (2017), 10.1128/JVI.01032-17.
14. N. Tzarum *et al.*, An alternate conformation of HCV E2 neutralizing face as an additional vaccine target. *Sci. Adv.* **6**, eabb5642 (2020), 10.1126/sciadv.abb5642.
15. D. Bankwitz *et al.*, Hepatitis C Virus hypervariable region 1 modulates receptor interactions, conceals the CD81 binding site, and protects conserved neutralizing epitopes. *J. Virol.* **84**, 5751–5763 (2010), 10.1128/JVI.02200-09.
16. J. Prentoe, R. Velázquez-Moctezum, S. K. H. Foung, M. Law, J. Bukh, Hypervariable region 1 shielding of hepatitis C virus is a main contributor to genotypic differences in neutralization sensitivity. *Hepatology* **64**, 1881–1892 (2016), 10.1002/hep.28705.
17. J. Prentoe *et al.*, Hypervariable region 1 and N-linked glycans of hepatitis C regulate virion neutralization by modulating envelope conformations. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 10039–10047 (2019), 10.1073/pnas.1822002116.
18. J. L. M. Law *et al.*, Role of the E2 hypervariable region (HVR1) in the Immunogenicity of a recombinant hepatitis C virus vaccine. *J. Virol.* **92**, e02141-17 (2018), 10.1128/JVI.02141-17.
19. M. Law *et al.*, Broadly neutralizing antibodies protect against hepatitis C virus quasispecies challenge. *Nat. Med.* **14**, 25–27 (2008), 10.1038/nm1698.
20. D. S. Campo *et al.*, Hepatitis C virus antigenic convergence. *Sci. Rep.* **2**, 267 (2012), 10.1038/srep00267.
21. W. R. Atchley, J. Zhao, A. D. Fernandes, T. Drüke, Solving the protein sequence metric problem. *Proc. Natl. Acad. Sci. U.S.A.* **102**, 6395–6400 (2005), 10.1073/pnas.0408677102.
22. D. S. Campo, Z. Dimitrova, R. J. Mitchell, J. Lara, Y. Khudyakov, Coordinated evolution of the hepatitis C virus. *Proc. Natl. Acad. Sci. U.S.A.* **105**, 9685–9690 (2008), 10.1073/pnas.0801774105.
23. D. S. Campo, A. Mosa, Y. Khudyakov, A novel information-theory-based genetic distance that approximates phenotypic differences. *J. Comput. Biol.* **30**, 420–431 (2023), 10.1089/cmb.2022.0395.
24. H. Li, M. N. Zahid, S. Wang, G. M. Shaw, "Molecular identification of transmitted/founder hepatitis C viruses and their progeny by single genome sequencing" in *Hepatitis C Virus Protocols*. Methods in Molecular Biology, M. Law, Ed. (Springer New York, 2019), **vol. 1911**, pp. 139–155, 10.1007/978-1-4939-8976-8_9.
25. R. A. Urbanowicz *et al.*, A diverse panel of hepatitis C virus glycoproteins for use in vaccine research reveals extremes of monoclonal antibody neutralization resistance. *J. Virol.* **90**, 3288–3301 (2016), 10.1128/JVI.02700-15.
26. J. H. Salas *et al.*, An antigenically diverse, representative panel of envelope glycoproteins for hepatitis C virus vaccine development. *Gastroenterology* **162**, 562–574 (2022), 10.1053/j.gastro.2021.10.005.
27. A. J. Pollard, E. M. Bijker, A guide to vaccinology: From basic principles to new developments. *Nat. Rev. Immunol.* **21**, 83–100 (2021), 10.1038/s41577-020-00479-7.
28. R. B. Kennedy, I. G. Ovsyannikova, P. Palese, G. A. Poland, Current challenges in vaccinology. *Front. Immunol.* **11**, 1181 (2020), 10.3389/fimmu.2020.01181.
29. G. Vieyres, J. Dubuisson, A. H. Patel, Characterization of antibody-mediated neutralization directed against the hypervariable region 1 of hepatitis C virus E2 glycoprotein. *J. Gen. Virol.* **92**, 494–506 (2011), 10.1099/vir.0.028092-0.
30. H. Duan *et al.*, Hepatitis C virus with a naturally occurring single amino-acid substitution in the E2 envelope protein escapes neutralization by naturally-induced and vaccine-induced antibodies. *Vaccine* **28**, 4138–4144 (2010), 10.1016/j.vaccine.2010.04.024.
31. J. R. Bailey *et al.*, Constraints on viral evolution during chronic hepatitis C virus infection arising from a common-source exposure. *J. Virol.* **86**, 12582–12590 (2012), 10.1128/JVI.01440-12.
32. L. Stejskal *et al.*, Flexibility and intrinsic disorder are conserved features of hepatitis C virus E2 glycoprotein. *PLoS Comput. Biol.* **16**, e1007710 (2020), 10.1371/journal.pcbi.1007710.
33. E. Scarselli *et al.*, The human scavenger receptor class B type I is a novel candidate receptor for the hepatitis C virus. *EMBO J.* **21**, 5017–5025 (2002), 10.1093/emboj/cdf529.
34. B. Bartosch *et al.*, An interplay between hypervariable region 1 of the hepatitis C virus E2 glycoprotein, the scavenger receptor BI, and high-density lipoprotein promotes both enhancement of infection and protection against neutralizing antibodies. *J. Virol.* **79**, 8217–8229 (2005), 10.1128/JVI.79.13.8217-8229.2005.
35. J. Johnson *et al.*, A Recombinant hepatitis C virus genotype 1a E1/E2 envelope glycoprotein vaccine elicits antibodies that differentially neutralize closely related 2a strains through interactions of the N-terminal hypervariable region 1 of E2 with scavenger receptor B1. *J. Virol.* **93**, e00810-19 (2019), 10.1128/JVI.00810-19.
36. E. H. Augestad *et al.*, Global and local envelope protein dynamics of hepatitis C virus determine broad antibody sensitivity. *Sci. Adv.* **6**, eabb5938 (2020), 10.1126/sciadv.abb5938.
37. F. Penin *et al.*, Conservation of the conformation and positive charges of hepatitis C virus E2 envelope glycoprotein hypervariable region 1 points to a role in cell attachment. *J. Virol.* **75**, 5703–5710 (2001), 10.1128/JVI.75.12.5703-5710.2001.
38. D. S. Campo, J. Zhang, S. Ramachandran, Y. Khudyakov, Transmissibility of intra-host hepatitis C virus variants. *BMC Genomics* **18**, 881 (2017), 10.1186/s12864-017-4267-4.
39. I. V. Astrakhantseva, "Variation in physicochemical properties of the hypervariable region 1 during acute and chronic stages of hepatitis C virus infection" in *2011 IEEE International Conference on Bioinformatics and Biomedicine Workshops (BIBMW)* (IEEE, 2011), pp. 72–78, 10.1109/BIBMW.2011.6112357.
40. B. Schlingmann, K. R. Castiglia, C. C. Stobart, M. L. Moore, Polyvalent vaccines: High-maintenance heroes. *PLoS Pathog.* **14**, e1006904 (2018), 10.1371/journal.ppat.1006904.
41. S. Chakradhar, Updated, augmented vaccines compete with original antigenic sin. *Nat. Med.* **21**, 540–541 (2015), 10.1038/nm0615-540.
42. D. Normile, Safety concerns derail dengue vaccination program. *Science* **358**, 1514–1515 (2017), 10.1126/science.358.6370.1514.
43. S. Lee *et al.*, A polyvalent inactivated rhinovirus vaccine is broadly immunogenic in rhesus macaques. *Nat. Commun.* **7**, 12838 (2016), 10.1038/ncomms12838.
44. M. Lange *et al.*, Hepatitis C virus hypervariable region 1 variants presented on hepatitis B virus capsid-like particles induce cross-neutralizing antibodies. *PLoS One* **9**, e102235 (2014), 10.1371/journal.pone.0102235.
45. K. Cannon *et al.*, A trial to evaluate the safety and immunogenicity of a 20-valent pneumococcal conjugate vaccine in populations of adults ≥65 years of age with different prior pneumococcal vaccination. *Vaccine* **39**, 7494–7502 (2021), 10.1016/j.vaccine.2021.10.032.
46. V. J. Kinchen, J. R. Bailey, Defining breadth of hepatitis C virus neutralization. *Front. Immunol.* **9**, 1703 (2018), 10.3389/fimmu.2018.01703.
47. B. Pickett *et al.*, Virus pathogen database and analysis resource (ViPR): A comprehensive bioinformatics database and analysis resource for the Coronavirus research community. *Viruses* **4**, 3209–3226 (2012), 10.3390/v4113209.
48. P. B. Icer Baykal, J. Lara, Y. Khudyakov, A. Zelikovsky, P. Skums, Quantitative differences between intra-host HCV populations from persons with recently established and persistent infections. *Virus. Evol.* **7**, veaa103 (2021), 10.1093/ve/veaa103.
49. A. Quirin, O. Cordón, V. P. Guerrero-Bote, B. Vargas-Quesada, F. Moya-Anegón, A quick MST-based algorithm to obtain Pathfinder networks ($\infty, n-1$). *J. Am. Soc. Inf. Sci. Technol.* **59**, 1912–1924 (2008), 10.1002/asi.20904.
50. D. S. Campo *et al.*, Next-generation sequencing reveals large connected networks of intra-host HCV variants. *BMC Genomics* **15**, S4 (2014), 10.1186/1471-2164-15-S5-S4.
51. D. S. Campo *et al.*, Accurate genetic detection of hepatitis C virus transmissions in outbreak settings. *J. Infect. Dis.* **213**, 957–965 (2016), 10.1093/infdis/jiv542.
52. M. Bastian, S. Heymann, M. Jacomy, Gephi: An open source software for exploring and manipulating networks. *Proc. Int. AAAI Conf. Web. Soc. Media.* **3**, 361–362 (2009), 10.1609/icwsm.v3i1.13937.
53. R. Tibshirani, G. Walther, T. Hastie, Estimating the number of clusters in a data set via the gap statistic. *J. R. Stat. Soc. Ser. B. Stat. Methodol.* **63**, 411–423 (2001), 10.1111/1467-9868.00293.
54. A. I. Mosa *et al.*, A bivalent HCV peptide vaccine elicits pan-genotypic neutralizing antibodies in mice. *Vaccine* **38**, 6864–6867 (2020), 10.1016/j.vaccine.2020.08.066.
55. A. I. Mosa *et al.*, Role of HVR1 sequence similarity in the cross-genotypic neutralization of HCV. *Virol. J.* **17**, 140 (2020), 10.1186/s12985-020-01408-9.
56. X. Yu, P. B. Gilbert, C. E. Hioe, S. Zolla-Pazner, S. G. Self, Statistical approaches to analyzing HIV-1 neutralizing antibody assay data. *Stat. Biopharm. Res.* **4**, 1–13 (2012), 10.1080/19466315.2011.633860.