Introduction

CD8+ T cells recognize short peptide fragments presented by MHC class I (MHC-I) molecules on the surface of nucleated cells (1–3). These peptide–MHC-I (pMHC-I) molecular arrays are scanned by clonotypically distributed αβ T cell receptors (TCRs) (4), which trigger T cell activation beyond a preset monomeric TCR/pMHC affinity threshold (5–8). This process enables the immune system to identify and eliminate infected and abnormal cells via targeted cytotoxicity, while remaining inert in the presence of healthy cells expressing a repertoire of unaltered self-derived peptides. Attenuated whole organisms, protein subunits, and/or peptides are typically used in vaccine formulations to prime immune responses against various cancers and dangerous pathogens. In the setting of infectious disease alone, prophylactic vaccines are thought to prevent approximately 9 million deaths annually (9). However, effective prophylaxis is lacking for most human diseases, and the global economic burden of current operational vaccines is high, costing around $4 billion annually (10). In particular, the temperature-controlled supply chain for these sensitive biological compounds can account for up to 80% of the total deployment cost (11). Environmental stability is therefore a strategic priority for current vaccine research and development.

Synthetic biology can be described as the design and refabrication of existing biological systems using nonnatural components. The vast majority of proteins in nature are constructed from L-amino acids, which are highly susceptible to degradation by endogenous and environmental proteases. In contrast, D–amino acids are rarely found in nature and typically exist as point mutations in enzymous and environmental proteases. In contrast, D–amino acids are rarely found in nature and typically exist as point mutations in natural antibiotics, certain animal proteins and venoms, and neuroregulators in the human brain (12–16). Although D–amino acids are mirror image stereoisomers of L–amino acids with identical chemical and physical properties, the corresponding proteins are intrinsically resistant to protease-mediated hydrolysis (13). Immunogens designed from these building blocks may therefore allow the production of stable vaccines with enhanced bioavailability and in vivo efficacy. Additional benefits include the potential for therapeutic activity via oral ingestion.
Large-scale T cell scanning studies using combinatorial peptide libraries (CPLs) (17–19) and yeast-displayed pMHC libraries (20) have shown that cross-reactivity is an inherent property of TCRs (reviewed in ref. 21). Accordingly, it may be feasible to generate nonnatural D–amino acid agonists that mimic their native counterparts (22, 23). In this study, we synthesized a nonamer CPL using only D–amino acid subunits to reverse engineer a fully synthetic agonist in the setting of a relevant human disease. The data validate what we believe to be a novel and systematic approach to the design of nonnatural immunogens that offers substantial advantages over current vaccine formulations.

Results

Identification of D–amino acid agonists via CPL screening. Our first task was to design a system that allowed robust and reproducible testing of synthetic T cell agonists in vitro and in vivo using a disease-relevant target. Influenza A virus was selected as an expedient model for this purpose, because antigen-specific memory T cell populations are commonly present in adult humans, and pathogen challenge experiments are feasible in humanized mice. The blueprint for synthetic agonist design was the immunodominant HLA-\(\text{A}^{*}\)0201–restricted GILGFVFTL–specific CD\(\text{8}^{\text{+}}\) T cell clone (ALF3). In this particular setting, however, the retroinverted D peptide was not immunogenic (Supplemental Figure 1A; supplemental material available online with this article; https://doi.org/10.1172/JCI91512DS1).
number of residues (19). Surprisingly, the L- and D-amino acid scans revealed very different recognition patterns across the peptide mixtures, indicating that D-amino acid agonists cannot be predicted from their known biological counterparts. These parallel scans also suggested that the ALF clone recognized at least as many D-amino acid agonists as L-amino acid agonists, further highlighting the vast cross-reactive potential of αTCR surveillance. Moreover, the L-amino acid scan data were similar to those generated with other TRBV19+ cells, indicating that T cells with different TCRs with similar antigen specificities generated related cross-reactivity profiles (data not shown).

Informed by these quantitative data, we designed and synthesized D-amino acid agonists for competitive testing in functional experiments. Dose-response titrations using MIP-1β production as a readout showed that gppqwnnpp (gpp) was the most potent agonist predicted from the D-amino acid CPL scan (Figure 1). MIP-1β release in the supernatants was quantified by ELISA. Errors from 2 replicates depict SEM. Figure 2. A fully synthetic agonist designed from CPL scan data is recognized by multiple influenza-specific clones and is highly resistant to human proteases and gastric acid. (A) Clone ALF3 was incubated with CIR-A2 target cells pulsed with the indicated concentrations of D-amino acid candidate agonists predicted from the D-amino acid CPL scan (Figure 1). MIP-1β release in the supernatants was quantified by ELISA. Errors from 2 replicates depict SEM. (B) ALF3 was also incubated overnight with the indicated concentrations of GILGFVFTL and gppqwnnpp. Errors from 2 replicates depict SEM. (C) Chromium release cytotoxicity assay using ALF3 and CIR-A2 targets incubated with gppqwnnpp and GILGFVFTL peptides at the concentrations shown. Errors from 2 replicates depict SEM. (D) As in A but including GILGFVFL with clones GD, SG11, and SG25. ALF3 was also included for comparison. Errors from 2 replicates depict SEM. (E) The GILGFVFTL or gppqwnnpp peptides were added to human serum or MilliQ water and sampled in triplicate at the indicated time points. Ion peak signals that identified each peptide were quantified using LC-MS. Stability was calculated as the area percentage of each serum-treated or water-treated ion peak relative to the same ion peak at 0 minutes. (F) GILGFVFTL and gppqwnnpp were added to simulated gastric acid (NaCl, pepsin, and HCl; pH 1.2) and sampled in triplicate at the indicated time points. Ion peak signals that identified each agonist were quantified using LC-MS. Stability was calculated as the area percentage of each gastric acid–treated ion peak relative to the same ion peak at 0 minutes. Recovery rates of gppqwnnpp in human serum and gastric acid were significantly higher compared with GILGFVFTL at all time points beyond 0 minutes (P < 0.00001). Errors from 3 replicates depict SEM. In some panels, error bars are smaller than the plot symbols.

These observations were not entirely surprising, given the paucity of examples of immunogenic D-amino acid retroinversion T cell agonists described to date (22). In subsequent experiments, we used CPL scanning to conduct a systematic search for nonnatural D-amino acid agonists capable of triggering HLA-A2–GILGFVFTL–specific CD8+ T cells. This approach has been employed successfully in the past to identify and augment L-amino acid ligands (18, 19, 25, 26). A novel D-amino acid nonamer CPL was synthesized and used in positional scanning format to screen the ALF3 clone (Figure 1), selected to represent a common bias toward TRBV19 gene usage within GILGFVFTL-specific memory CD8+ T cell populations (24, 27, 28). Of note, the D-amino acid CPL was length-matched to the GILGFVFTL peptide, given previous data showing that MHC-I-restricted TCRs are preprogrammed to engage bound ligands spanning a defined
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RESEARCH ARTICLE

The power of combinatorial screening to identify novel agonists

Protease and acid resistance of native versus synthetic agonists

To elicit immune responses in vivo, antigenic structures must navigate host barriers associated with the route of entry, such as serum complement/proteases, gastric acid, and digestive enzymes. It is pertinent to note in this regard that strings of D–amino acids are thought to be sterically incompatible with protease-induced hydrolysis (13). We therefore compared the stability of gppqwnnpp and GILGFVFTL in human serum and simulated gastric acid as potential indicators of long-term biostability and immunogenicity. GILGFVFTL was rapidly degraded in human serum, reaching almost undetectable levels within 10 minutes (Figure 2E). In contrast, gppqwnnpp activating the ALF3 (Figure 2A). The gppqwnnpp sequence incorporated the dominant residue in terms of signal strength at each sub-library position. It is also notable that gppqwnnpp bears no resemblance to GILGFVFTL in terms of primary sequence, barring the N-terminal glycine residue for which there is no chiral counterpart. Higher concentrations of gppqwnnpp peptide were required to induce activation of the ALF3 clone (Figure 2B) and target cell killing (Figure 2C) compared with the GILGFVFTL peptide. This reduced potency likely reflects decreased binding of D–amino acid peptides to MHC (see below). In further experiments, we demonstrated that the gppqwnnpp agonist could activate 4 clonotypically distinct GILGFVFTL-specific CD8+ T cell clones derived from genetically unrelated individuals (Figure 2D). Each of these T cell clones expressed TRBV19 with a unique TCRα chain and varying degrees of residue similarity in the third complementarity-determining region of the TCRβ chain (CDR3β) (Supplemental Figure 1B). These data demonstrate the power of combinatorial screening as a means to identify novel agonists.

Protease and acid resistance of native versus synthetic agonists. To elicit immune responses in vivo, antigenic structures must navigate host barriers associated with the route of entry, such as serum complement/proteases, gastric acid, and digestive enzymes. It is pertinent to note in this regard that strings of D–amino acids are thought to be sterically incompatible with protease-induced hydrolysis (13). We therefore compared the stability of gppqwnnpp and GILGFVFTL in human serum and simulated gastric acid as potential indicators of long-term biostability and immunogenicity. GILGFVFTL was rapidly degraded in human serum, reaching almost undetectable levels within 10 minutes (Figure 2E). In contrast, gppqwnnpp...
remained largely intact after 1 hour in human serum. Similar disparities were observed in simulated gastric acid (Figure 2F). These observations indicate that gppqwnnpp is likely to be highly stable in vivo, in contrast to GILGFVFTL.

**Functional and priming characteristics of native versus synthetic agonists.** Next, we explored the lower functional sensitivity of gppqwnnpp relative to GILGFVFTL, hypothesizing that such differences may reflect a lack of traditional HLA-A2 anchor residues in the D-amino acid sequence, thereby destabilizing the binary pMHC-I complex. Using a T2 peptide binding assay (29), we observed no upregulation of HLA-A2 in the presence of gppqwnnpp (Supplemental Figure 1C), with no improvement following the addition of exogenous β2-microglobulin (data not shown) (30). Given the limited dynamic range of this assay (29), we sought to confirm epitope recognition using an endogenous epitope presentation system (Figure 3 and refs. 31–33). The GIL-GFVFTL-specific CD8 T cell clone GD killed gppqwnnpp-pulsed CIR cells transduced with HLA-A2 (CIR-A2), but did not kill WT CIR cells under the same conditions (Figure 3A). To minimize peptide cross-presentation among T cells, we next used enzyme-
linked immunospot (ELISpot) assays with a limited number of T cells on a “carpet” of antigen-presenting cells, as used previously for examining the requirements for the presentation of pyrophosphate antigens to human Vγ9Vδ2 T cells (34). ELISpot with 250 ALF3 and 100,000 CIR-A2 cells per well revealed good responses to gppqwnnpp peptide (Figure 3B). Conversely, a carpet of WT CIR cells lacking HLA-A2 did not activate clonal ALF3 in parallel assays (Figure 3B). In addition, CIR-A2 targets with enhanced CD8 binding due to a Q115E mutation in the α2 domain of HLA-A2 (33) were effective presenting cells for gppqwnnpp, whereas CIR-A2 targets with abrogated CD8 binding due to a compound D227K/T228A mutation in the α3 domain of HLA-A2 (31) did not enable gppqwnnpp to activate ALF3. These observations show that gppqwnnpp is restricted by HLA-A2 and elicits functional outputs that are dependent on the interaction between HLA-A2 and the CD8 glycoprotein.

Next, we used intracellular cytokine staining to examine the agonist-induced functional profile of the CD8+ T cell clone GD in
response to gppqwnnpp and GILGFVFTL. Five different effector outputs (CD107a, IFN-γ, IL-2, MIP-1β, and TNF-α) were measured simultaneously by flow cytometry in response to 2 different concentrations of gppqwnnpp, GILGFVFTL, and irrelevant Melan A peptide (sequence ELAGIGILTV) (Figure 3C). At 10⁻⁴ M, gppqwnnpp elicited multiple functions, with more than 80% of clonal GD cells expressing both MIP-1β and TNF-α. In line with the cytotoxic release and cytotoxicity data, however, a weaker profile was observed at 10⁻⁵ M. This loss of sensitivity likely relates to the weak affinity of gppqwnnpp for HLA-A2. To extend these observations, we investigated the ability of gppqwnnpp to amplify GILGFVFTL-specific human memory T cells in vitro. Peripheral blood mononuclear cells (PBMCs) from healthy HLA-A2+ individuals were stimulated with either gppqwnnpp or GILGFVFTL for 14 days, and specific T cell expansions were quantified by flow cytometry after staining with a fluorochrome-labeled tetrameric HLA-A2–GILGFVFTL complex (Figure 4). Remarkably, we found that gppqwnnpp expanded comparable (donor 305N, Figure 4A) or even larger populations of tetramer-binding CD8+ T cells compared with GILGFVFTL (donor 860Z, Figure 4B and donor 225M, Figure 4C). Moreover, these effects occurred in the absence of bystander expansion (Figure 4, A and B and flow cytometry plots in Supplemental Figures 2 and 3). In addition, the T cell lines from donor 225M exhibited equivalent functional reactivity against CIR-A2 target cells expressing the full-length influenza A virus M1 protein, but did not respond to CIR-A2 target cells expressing the irrelevant protein glutamic acid decarboxylase (GAD65) (Figure 4D). These data show that gppqwnnpp can expand GILGFVFTL-specific memory CD8+ T cells capable of recognizing the endogenously processed L-amino acid index peptide in the context of HLA-A2.

**T cell repertoire mobilization in response to native versus synthetic agonists.** A detailed understanding of the elicited TCR repertoire is an important consideration in the rational design of prototypic T cell vaccines (4). We therefore examined the clonotypic composition of antigen-specific memory CD8+ T cell populations expanded by gppqwnnpp and GILGFVFTL (Figure 5A). Three donors with a similar level of priming for the gppqwnnpp and GILGFVFTL peptides (Figure 5A for 2 of the donors) were used for clonotypic analysis of the T cell receptor repertoire. Using a fully quantitative template switch–anchored reverse transcription PCR (RT-PCR) in conjunction with Sanger sequencing (35), we found no significant difference in the number of clonotypes mobilized by these distinct peptides (Figure 5B). A strong bias toward the expansion of TRBV19+ clonotypes was observed in GILGFVFTL-stimulated cultures from donor 1 and donor 2 (Figure 5C), in line with previous studies of human naive and memory repertoires specific for this antigen (24, 27, 28). The corresponding gppqwnnpp-primed cultures displayed a similar gene bias, and overlapping TCRβ sequences across the 2 peptide conditions were detected within donors (Supplemental Table 1). Incongruously, the GILGFVFTL-stimulated culture from donor 3 was dominated by TRBV7-2+ and TRBV9+ clonotypes, which is unusual in the context of earlier work (24, 27, 28). In the same donor, however, gppqwnnpp remodeled these clonotypic expansions toward a more archetypal repertoire dominated by TRBV19+ sequences incorporating classical motifs in the CDR3β chain (Supplemental Table 1). Moreover, both gppqwnnpp and GILGFVFTL elicited public and near-public TRBV19+ clonotypes (Supplemental Table 1). We observed less-stringent TRBJ gene selection in these experiments (Figure 5D), again consistent with current knowledge (24, 27, 28). A bias toward TRBJ2-7+ clonotypes was nonetheless apparent in both agonist-primed cultures from donor 1 and donor 2, and a preference for TRBJ2-5 gene usage in the GILGFVFTL-primed culture from donor 3 was remodeled by gppqwnnpp toward a more conventional pattern, aligned with previous reports demonstrating frequent TRBV19/TRBJ2-7+ gene rearrangements (24, 27, 28). The synthetic gppqwnnpp agonist therefore mobilizes antigen-specific CD8+ T cell repertoires that closely mimic those elicited by the native peptide.

**Structural conformation of native versus synthetic agonists.** To determine the molecular basis of agonist cross-recognition in this setting, we attempted to solve the binary structure of the HLA-A2–gppqwnnpp complex. Although refolded protein yields were very low, presumably reflecting the weak affinity of gppqwnnpp for HLA-A2, we were able to generate small crystals. However, these crystals were not capable of diffracting to atomic resolution. We therefore modeled the HLA-A2–gppqwnnpp structure in silico (Figure 6, A and B), using the JM22–HLA-A2–GILGFVFTL ternary complex as a guide (36). The model indicated that gppqwnnpp could be presented by HLA-A2 in an overall conformation similar to that of GILGFVFTL. In particular, the D-amino acid residues Glu4, Trp5, Asp6, and Pro8 were solvent exposed, mimicking in 3 dimensions the main TCR contact residues identified in the JM22–HLA-A2–GILGFVFTL complex (Figure 6C and ref. 36). Thus, despite a lack of sequence homology between gppqwnnpp and GILGFVFTL, both antigens may look similar in terms of shape complementarity.

The synthetic agonist effectively primes T cell responses that can protect from lethal influenza challenge. To assess the biological relevance of these observations, we tested the ability of gppqwnnpp
to prime effective de novo responses from the naive T cell pool. We used transgenic HLA-A2 mice (HHD mice) for this purpose, based on earlier work in similar transgenic murine systems (37). Mice were injected on day 0 and day 14 with GILGFVFTL, gppqwnnpp, or an irrelevant HLA-A2-restricted L-amino acid peptide (ELA-GIGILTV) in incomplete Freund’s adjuvant (IFA). Preliminary dosing experiments showed that gppqwnnpp was safe and non-toxic (data not shown). One week after the second injection, cells were harvested from the spleen and peripheral lymph nodes (PLNs). Using direct ex vivo IFN-γ ELISpot analysis, we found that gppqwnnpp induced a GILGFVFTL-specific response in vivo, detectable most prominently in the PLNs (Figure 7A). No such response was observed with the ltfvfglig retroinversion of the GILGFVFTL L-peptide sequence (Figure 7B).

To elaborate on these data, we vaccinated mice using the same regimen and performed intranasal challenge experiments with influenza A virus H1N1 strain A/Puerto Rico/8/34 (PR8). In accordance with local regulations, mice were euthanized if 20% or more of their initial body weight was lost, at which point the viral challenge was considered fatal. Female and male animals required 50 and 100 PFU, respectively, for 100% fatality (Supplemental Figure 4). On day 6 after PR8 infection, mice vaccinated with the control ELA-GIGILTV peptide began to succumb rapidly (Figure 8A). In contrast, mice vaccinated with either GILGFVFTL or gppqwnnpp fared significantly better, with survival rates greater than 60% at day 8 (Figure 8B). It is also notable that we observed a trend toward better outcomes in the gppqwnnpp versus GILGFVFTL groups. This counterintuitive observation may reflect the greater in vivo stability and half-life of the D-amino acid peptide.

Further oral administration experiments using HHD mice showed that gppqwnnpp and GILGFVFTL were similarly immunogenic (Supplemental Figure 5B). Collectively, these experiments demonstrate that gppqwnnpp can prime protective immune responses in a humanized mouse model of influenza virus infection.

**Discussion**

We used synthetic CPL arrays to design a nonnatural D-amino acid mimic of an immunodominant peptide epitope from the influenza virus matrix protein. This prototype agonist, gppqwnnpp, stimulated and expanded polyfunctional CD8+ T cells in vitro that cross-recognized the naturally presented L-amino acid epitope GILGFVFTL. Despite minimal sequence homology and nonclassical anchoring to HLA-A2, gppqwnnpp mobilized clonotypic repertoire entries in culture similar to those elicited by GILGFVFTL, in line with a structural model indicating common antigenic features and shape complementarity. Moreover, gppqwnnpp effectively primed GILGFVFTL-specific responses in naïve, humanized mice, conferring protection from lethal influenza challenge. The stimulation of GILGFVFTL cross-reactive T cells by gppqwnnpp in 2 species that have very different TCR repertoires attests to how effectively HLA-A2–gppqwnnpp must mimic the key structural features of HLA-A2–GILGFVFTL. These findings validate an unbiased approach to the identification of synthetic ligands that could revolutionize the development of immunotherapies.

There is a clear strategic need to enhance the environmental and in vivo stability of T cell vaccines, both to minimize temperature-controlled supply chain burdens and to maximize biological efficacy. Previous attempts to optimize peptide-based interventions have been limited to the L-amino acid universe. For example, specific residues at MHC anchor or TCR contact sites can be replaced to enhance T cell activation and functionality (6, 26, 38, 39). Akintoth's parent epitopes, however, such altered peptide ligands are rapidly destroyed in vivo by extracellular proteases and other components of various biofluids. In contrast, the D-amino acid peptide gppqwnnpp was vastly more stable than its natural counterpart in human serum and simulated gastric acid. Consistent with the latter finding, orally administered gppqwnnpp primed effector T...
both in vitro and in vivo (42–45, 47). D–amino acid agonists have also been explored in phase I/II clinical trials (48, 49). However, retroinverted D–amino acid peptides rarely mimic their parent antigens, and random synthetic component insertions can modify the immunogenicity profile of an L–amino acid blueprint (22).

In the present study, we overcome these limitations by using nonnatural CPL mixtures to screen rapidly and systematically for novel synthetic epitopes with defined agonist properties. Importantly, this platform is flexible and potentially applicable to any target antigen. Moreover, advances in solid-phase peptide synthesis (SSPS) (50) and the development of bioreactors that exploit organisms with expanded genetic codes (51) may enable industrial-scale production of synthetic T cell immunogens. Further effort is therefore warranted to translate the current proof-of-concept findings into real-world vaccine pipelines.

**Methods**

*Human T cell clones and target cells.* The CD8+ T cell clones ALF3, GD, SG1, and SG25 were maintained in RPMI medium supplemented with 100 IU/ml penicillin, 100 μg/ml streptomycin, 2 mM L-glutamine, and 10% heat-inactivated FCS (R10), together with 25 ng/ml IL-15 (Pepro-
In vitro expansion of human T cells. PBMCs were isolated by standard density gradient centrifugation from locally sourced venous blood samples or buffy packs obtained from the Welsh Blood Service (Pon-tyclun, United Kingdom). PBMCs were stimulated with various concentrations of peptide in R2 for 25%–200 μg/ml after staining with PE- or APC-conjugated streptavidin (clone H1B19, BioLegend). The cells were then fixed and permeabilized using a Cytofix/Cytoperm Kit (BD Biosciences) and stained intracellularly with anti-CD8α-FITC, anti-CD4-PeCy7, anti-CD25-PacificBlue (clone UCHT1, BioLegend), and anti-CD107a-PETC (clone MQ1-17H12) (all from BioLegend) and anti-MIP-1β-PE (clone D21-I351, BD Biosciences). Data were acquired using a FACSCantoII flow cytometer and analyzed with FlowJo software.

Intracellular cytokine staining. T cells were restimulated at 1 × 10⁴ per ml in R2 (as for R10 with 2% FCS) and added to peptide-pulsed targets at an effector/target ratio of 1:2 in the presence of 5 μg/ml brefeldin A (Sigma-Aldrich), 0.35 μl/ml monensin (BD Biosciences), and 5 μl/ml nCD107a-FTTC (clone H4A3, BD Biosciences). After 5 hours at 37°C, the cells were washed and stained with LIVE/DEAD Fixable Aqua followed by nCD3-PacificBlue (clone UCHT1, BioLegend), nCD8-APC-H7 (clone SKI, BD Biosciences), nCD19-IVS21 (clone HIB19, BioLegend). The cells were then fixed and permeabilized using a Cytofix/Cytoperm Kit (BD Biosciences) and stained intracellularly with isotype controls as described previously

Clonotype analysis. Viable tetramer-positive CD8+CD4+ cells were sorted at greater than 98% purity using a custom-modified FACSAria II flow cytometer (BD Biosciences). Molecular analysis of expressed TRB gene rearrangements was conducted using a template switch-anchored RT-PCR with Sanger sequencing technology as described previously

Structural modeling. The structure of gp160/105npp complexed with HLA-A2 was modeled in WinCoot (57) using the JM22 TCR-HLA-A2–GILGFVFTL ternary structure as a reference (36). The model was regularized using REFMAC5 (CCP4 Program Suite) (58). Figures were made using the PyMol Molecular Graphics System (Schrodinger LLC).

Mice. HHD mice were donated by Immunocore Ltd. or purchased from the Weatherall Institute of Molecular Medicine at the University of Oxford (Oxford, United Kingdom). These mice express a hybrid HLA-A2 transgene comprising the human α1/α2 domains and β2-microglobulin fused with a murine α3 domain (H-2Dp) (59, 60). The HHD background strain was either C57BL/6J (subcutaneous experiments) or albino C57BL/6J Tyr-31 (oral experiments). Mice were housed throughout the study under specific pathogen-free conditions.

Immunization, organ harvest, and influenza infection. HHD mice were primed in the ventral inguinal area by injection with 200 μl of a PBS preparation containing 100 μg peptide (GILGFVFTL, gp160/105npp, or ELAGIGILTV) and 100 μl IFA (Sigma-Aldrich). The same preparation was used to boost on the contralateral side 14 days later. Care was taken to ensure the formation of a raised area at
the injection site, indicating that the vaccine was delivered subcutaneously rather than intraperitoneally. For experiments involving organ harvest, mice were euthanized 7 days after the last immunization, and the peripheral lymph nodes (inguinal, axillary, brachial, and submandibular) were prepared as single-cell suspensions. For challenge experiments, mice were infected intranasally with influenza A virus strain PR8 obtained from the National Institute for Medical Research (London, United Kingdom). On the basis of dose optimization experiments, male mice received 100 PFU and female mice received 50 PFU PR8 in 50 μl sterile PBS under light anesthesia. Body weight was recorded daily after infection. Mice were classified as nonsurvivors and euthanized if their body weight fell by 20% or more. All other mice were euthanized 8 days after infection.

**Mouse and human IFN-γ ELispot.** IFN-γ-producing cells were quantified using a mouse or human IFN-γ kit (MabTech). Briefly, ELispot multiscreen filter plates (Millipore) were coated with capture antibody for 4 hours at 37°C, and then washed with PBS and blocked with R10 for 1 hour at room temperature. For mouse samples, 0.5 × 10^5 or 2 × 10^5 cells were added per well in the presence of peptide at a final concentration of 10 μM. For human samples, 250 clonal T cells and 100,000 CIR WT or HLA-A2–transgenic cells were used per well. Medium alone was used as a negative control, and phytohemagglutinin (PHA) (1 μg/ml) was used as a positive control. Assays were incubated overnight at 37°C, and the plates were developed per the manufacturer’s instructions (MabTech). Spot-forming units (SFUs) were counted using an AID ELispot Reader v5 (AID Diagnostika GmbH).

**Statistics.** For the pro tease and simulated gastric acid assays, data in percentages were square-root transformed for all assays. Statistical analyses were conducted using unpaired t tests (I per time point) corrected for multiple comparisons using the Holm-Sidak method (Alpha 0.05; Prism 6, GraphPad Software). For the human ELISPOT assay, we used the unpaired, 1-tailed t test (Excel, Microsoft). For the HHD influenza survival curve, we used the unpaired, 2-tailed t test (Excel). P ≤ 0.05 was considered significant. Clonotype composition was compared using the Mann-Whitney U test (Prism 6, GraphPad Software).

**Study approval.** In vivo experiments were performed under United Kingdom Home Office approved projects (licenses 30/2355, 30/2635 and 30/3188) and conducted in compliance with the United Kingdom Home Office Guidance on the Operation of the Animals (Scientific Procedures) Act 1986. The use of human blood was approved by the School of Medicine Research Ethics Committee (Cardiff University School of Medicine, Cardiff, United Kingdom), project title: Comprehensive Analysis of T-cell Receptor Degeneracy and T-cell Reactivity (reference 12/09). Blood was sourced from local donors and the Welsh Blood Service (Ponycunh, United Kingdom). All human blood was procured and handled in accordance with the guidelines of Cardiff University’s Human Tissue Act compliance team, to conform to the United Kingdom Human Tissue Act 2004.

**Author contributions**

JJM and AKS conceived and planned the project. JJM, MPT, GD, ESJE, SAEG, SG, BL, MC, JM, KL, KKM, TSW, KT, YW, HSL, RJC, JMP, MA, AL, AA, AG, PJR, JR, DKC, and DAP designed and performed experiments. JJM, MPT, SRB, DAP, and AKS drafted and critically revised the manuscript.

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