Common Genetic Variations Associated with the Persistence of Immunity following Childhood Immunization

Graphical Abstract

Highlights
- Signal-regulatory proteins locus associated with the persistence of MenC immunity
- SNPs within the HLA locus associated with persistence of TT-specific immunity
- Classical HLA alleles associated with TT-specific immunity, independently of lead SNPs

In Brief
Genetic variants impact immune responses to antigenic stimuli. O’Connor et al. show that variants within the human leukocyte antigen (HLA) and signal-regulatory proteins loci are associated with persistence of immunity following immunization, suggesting these genes are involved in regulating immune responses to routine childhood immunization.

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O’Connor et al., 2019, Cell Reports 27, 3241–3253
June 11, 2019 © 2019 The Author(s).
https://doi.org/10.1016/j.celrep.2019.05.053
Common Genetic Variations Associated with the Persistence of Immunity following Childhood Immunization

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https://doi.org/10.1016/j.celrep.2019.05.053

SUMMARY

Vaccines have revolutionized public health, preventing millions of deaths each year, particularly in childhood. Yet, there is considerable variability in the magnitude and persistence of vaccine-induced immunity. Maintenance of specific antibody is essential for continuity of vaccine-induced serological protection. We conducted a genome-wide association study into the persistence of immunity to three childhood vaccines: capsular group C meningococcal (MenC), Haemophilus influenzae type b, and tetanus toxoid (TT) vaccines. We detail associations between variants in a locus containing a family of signal-regulatory proteins and the persistence MenC immunity. We postulate a regulatory role for the lead SNP, with supporting epigenetic and expression quantitative trait loci data. Furthermore, we define associations between SNPs in the human leukocyte antigen (HLA) locus and the persistence of TT-specific immunity. Moreover, we describe four classical HLA alleles, HLA DRB1*0301, HLA DQB1*0201, HLA DQB1*0602, and HLA DRB1*1501, associated with TT-specific immunity, independent of the lead SNP association.

INTRODUCTION

Vaccination will prevent an estimated 23.3 million deaths this decade (2011–2020) (Lee et al., 2013). Globally, polysaccharide-encapsulated organisms are the leading cause of bacterial meningitis and pneumonia in children. Haemophilus influenzae type b (Hib) and Neisseria meningitidis are estimated to cause 8.13 million and 500,000 serious illnesses worldwide each year, respectively (Watt et al., 2009; Wilder-Smith and Memish, 2003). Over 150,000 Hib and 50,000 meningococcal cases result in death each year (GBD 2013 Mortality and Causes of Death Collaborators, 2015). Tetanus is an acute and life-threatening disease, caused by the bacterium Clostridium tetani. An estimated 61,000 deaths resulted from neonatal tetanus in the year 2011 alone (World Health Organization, 2017).

Unlike plain polysaccharide vaccines, conjugate vaccines (i.e., polysaccharides chemically conjugated to carrier proteins such as tetanus toxoid [TT]) are T cell-dependent antigens that are immunogenic from early infancy (Pollard et al., 2009; Black et al., 1991). In the United Kingdom, introduction of national immunization programs with the Hib conjugate vaccine (1992—) and the capsular group C meningococcal (MenC) conjugate vaccine (1999—) resulted in the virtual disappearance of invasive disease caused by these organisms (Miller et al., 2001; Salisbury et al., 2014). However, persistence of serum antibody to encapsulated bacteria such as Hib and MenC is essential for direct protection against these rapidly invading pathogens (McVernon et al., 2003; Snape et al., 2006). During a resurgence of Hib disease in the United Kingdom, Hib was found to be still colonizing older healthy children, and invasive disease was observed in some preschool children despite demonstrable immunological memory, indicating the failure of B cell memory to confer direct protection or block transmission (McVernon et al., 2003; Oh et al., 2008).

Unfortunately, following immunization with Hib conjugate and MenC conjugate vaccines in early infancy, antibody levels rapidly wane. By 1 year of age, >25% and >50% of children have antibody levels below the putative threshold of protection for Hib conjugate and MenC organisms, respectively (Trotter et al., 2003; Pace et al., 2015). In the United Kingdom, booster doses of Hib and MenC vaccines were introduced for all children at 1 year of age in 2003 and 2006, respectively (McVernon et al., 2003). Yet, the majority of older children were found to lack protective antibodies levels after the 12-month booster dose of MenC vaccine, prompting the recent introduction of an
adolescent dose of MenC (in the form of a quadrivalent Men-ACWY vaccine) to induce herd immunity and prevent transmission to younger children (Perrett et al., 2010; Pace et al., 2015; Public Health England, 2014). The mechanisms underlying the persistence of antibody are of major interest, because effectiveness and acceptability of vaccines would be improved if protection were sustained after infant immunization without the need for repeated boosting through childhood.

A number of factors have been implicated in determining vaccine responses and the persistence of immunity: age, sex, ethnicity, microbiota, nutritional status, and infectious diseases (Siegrist and Aspinall, 2009; Klein et al., 2015; Kollmann, 2013; Savy et al., 2009; Brodin et al., 2015; Nguyen et al., 2016). Importantly, twin studies have also shown vaccine-induced immunity to be highly heritable, and recent studies have started to unpick the genetic components underlying this complex trait (Newport et al., 2004; O’Connor and Pollard, 2013; Mentzer et al., 2015; O’Connor et al., 2014; Davila et al., 2010; Png et al., 2011). The genome-wide association study (GWAS) approach has already provided considerable insight into the genetic basis of a number of complex immune-related diseases (Parkes et al., 2007; Snape et al., 2006, 2008a, 2008b, 2010; Waddington et al., 2013; de Voer et al., 2010; Khatami et al., 2011, 2014; Pace et al., 2007; Visscher et al., 2017). Here we used a two-stage GWAS approach to evaluate the genetic determinants of the persistence of immunity to three routine childhood immunizations: MenC conjugate vaccine, Hib conjugate vaccine, and tetanus vaccine.

RESULTS

Participants and Study Design

DNA was available from 3,602 children from nine vaccine studies conducted in Oxford, United Kingdom, and one vaccine study conducted in Bilthoven, the Netherlands (Blanchard-Rohner et al., 2013; de Voer et al., 2010; Khatami et al., 2011, 2014; Pace et al., 2007; Snape et al., 2006, 2008a, 2008b, 2010; Waddington et al., 2010). Median age at last vaccination was 1,966 days (interquartile range [IQR], 125–3,701.5), and median time since vaccination was 1,478 days (IQR, 287–1,769). Participant demographics are shown in Table S1. The two-stage GWAS design is illustrated in Figure 1. The discovery cohort (n = 2,061) was genotyped using the Illumina Omniexpress-12v1 or Omniexpress-12v1.1 microarray. Genotypes were further imputed using the 1000 Genomes Phase I integrated variant set release (March 2012) as the variant reference set (1000 Genomes Project Consortium et al., 2012). Approximately 6.7 million SNPs were included in quantitative trait association analyses of four log10 normalized vaccine-induced immunological measures: MenC-specific immunoglobulin G (IgG) concentrations, MenC-specific serum bactericidal antibody (SBA) titers (functional antibody), Hib polyribosylribitol phosphate (PRP)-specific IgG concentrations, and TT-specific IgG concentrations.

The genomic control (λGC) inflation factors for MenC-specific IgG, MenC-specific SBA, PRP-specific IgG, and TT-specific IgG were 1.013, 1.010, 1.002, and 1.019, respectively (Figures S1A–S1D). The percentage of overall variance, in each of the immunological measures, explained by genetic information captured on the genotyping microarray (i.e., heritability) varied from 14% to 81% (Table 1). On the basis of the discovery stage, we selected 276 SNPs for replication-stage genotyping (Table S2). Replication SNPs were genotyped using either Sequenom or TaqMan assays on both the discovery (n = 2,061) and replication (n = 1,541) cohorts. A genome-wide significance threshold of p < 5 × 10−8 was set, and two independent loci were found to surpass this threshold in combined (discovery + replication) analysis (Tables 2 and 3).

MenC Conjugate Vaccine

Manhattan plots of the results of the discovery stage association analyses are displayed in Figure 2. Twenty-four SNPs had suggestive statistical associations (p < 1 × 10−6) with the persistence of MenC-specific IgG concentrations, 13 of which were within six genes: SERP2, NBEA, LRFN5, MCTP2, GALR1, and GGT75 (Table S3). Seventy-four SNPs had suggestive association with the persistence of MenC-specific SBA titers, of which 50 resided within nine genes: ALK, CNTN6, FAM124B, LINC00285, NPAS3, PDLIM1, PTPRD, SIRPG, and SLCL1A3 (Table S3).

A subset of SNPs from the discovery stage were selected for genotyping in the replication cohort; these were selected to capture the most credible association signals in a parsimonious manner (as described in the STAR Methods). A total of 69 and 57 SNPs were selected to capture the association signals of MenC-specific IgG concentrations and SBA titers, respectively. Nine and 12 of these SNPs failed Sequenom iPLEX design, leaving 60 and 45 SNPs for MenC-specific IgG and SBA replication analyses, respectively (Table S3).

A single locus was found to contain SNPs that were significantly (p < 5 × 10−8) associated with the persistence of MenC-specific SBA titers in combined analysis of discovery and replication data (Table 2; Table S4). The SNP most significantly associated with MenC-specific SBA titers was rs6135736 (p = 6.0 × 10−8, dominant model), which lies within LOC105368219 (gene of unknown function) and <50 kb from the transcription start site of SIRPG. The meta-analysis of summary data from discovery and replication cohorts is shown in Table S5. Results of the combined analysis (i.e., mega-analysis) and meta-analysis were highly correlated (Pearson’s correlation coefficient > 0.98; Figures S1E and S1F).

The SNPs associated with the persistence of MenC-specific SBA titers were within a genomic region containing a family of signal-regulatory proteins: SIRPA, SIRPB, and SIRPG. Using the densely genotyped discovery dataset, the association signal appears to be confined to a region incorporating SIRPG, but separated from the other two signal-regulatory proteins (SIRPs) by recombination hotspots (Figure S2). The HaploReg tool (http://www.broadinstitute.org/mammals/haploreg) was used to systematically mine the Roadmap Epigenomics Consortium dataset, finding several variants to reside within putative promoter and enhancer regions, in a number of tissues including blood cells, thymus, and spleen (Romanoski et al., 2015; Ward and Kellis, 2012). Moreover, the lead SNP at this locus (i.e., most statistically associated with MenC SBA titers), rs6135736, was predicted to substantially alter the motifs of four TFs: serum response factor (SRF), zinc-finger protein 410 (ZNF410), retinoic acid receptor gamma (RARγ), and RAR-related orphan receptor alpha (RORα).
Moreover, this SNP is an expression quantitative trait locus (eQTL) for \textit{SIRPG} and \textit{SIRPB1} (Figures S1J and S1K).

**Hib Conjugate Vaccine**

A total of 122 SNPs had regression p values suggestive of association (p < $1 \times 10^{-8}$) with the persistence of PRP-specific IgG concentrations (Figure 2C). These SNPs were within five annotated genes: \textit{FOXP1}, \textit{PDSS2}, \textit{MLXIPL}, \textit{CSMD3}, and \textit{IGL} (immunoglobulin lambda locus). Seventy-five variants were selected for replication analysis following the SNP pruning algorithm (https://github.com/dan-scholar/LD_pruning). Six of these SNPs failed Sequenom iPLEX design; none of the remaining 69 SNPs surpassed the level of genome-wide significance in the combined analysis of discovery and replication cohorts (Table S4).

**TT Vaccine**

In the discovery stage, 111 SNPs in eight genes surpassed the level of suggestive association with TT-specific IgG concentrations: \textit{CDH9}, \textit{MICB}, \textit{HLA-DQA1}, \textit{DOCK4}, \textit{DENND1A}, \textit{LHPP}, \textit{TMEM135}, and \textit{RBFOX3} (Figure 2D). Furthermore, five SNPs in an intergenic region of chromosome 10 surpassed the level of genome-wide significance (p < $5 \times 10^{-8}$); the closest gene (<250 kb) to these associations was \textit{TCERG1L}. Seventy-seven SNPs were selected for replication. Twenty-two of these SNPs failed Sequenom iPLEX design, leaving 55 SNPs for genotyping. As anticipated, the replication SNPs selected within the human leukocyte antigen (HLA) locus failed Sequenom iPLEX design; due to the polymorphic nature of this locus, iPLEX primer design is problematic. Therefore, conditional linear regression analysis was used to select five HLA SNPs for genotyping using the TaqMan SNP genotyping methodology.

None of the Sequenom genotyped SNPs surpassed the level of genome-wide significance in combined analysis (Table S4). The lead SNP (rs75727401) in the intergenic region of chromosome 10 that reached the genome-wide significance threshold in the discovery stage was not assessed because it failed Sequenom quality control (QC). However, this locus was tagged by rs79697632 ($r^2$ of 0.88 with rs75727401), which was not found to substantiate the initial GWAS finding. A SNP in HLA
(rs2523650), typed on the TaqMan platform, did surpass the level of genome-wide significance in the combined analysis and (rs2523650), typed on the TaqMan platform, did surpass the level of genome-wide significance in the combined analysis and

Classical Human Leukocyte Antigen Alleles

The discovery GWAS dataset was used to impute 168 classical HLA alleles (Table S7). Four alleles, HLA-DQB1*0201, HLA-DRB1*0301, HLA-DQB1*0602, and HLA DRB1*1501, were significantly associated with TT-specific IgG concentrations, after correction for multiple testing (i.e., by number of HLA alleles tested; p < 0.05/168) (Table 4). In silico epitope mapping predicted DRB1*0301 to have the fewest strong and weak binding affinity to TT epitopes of the panel of HLA-DRB1 alleles assessed (Figure S3). Conditional analysis, by including HLA DRB1*0301, HLA DQB1*0201, HLA DQB1*0602, or HLA DRB1*1501 as covariates in the linear regression model, implied the lead SNP asso-

Pleiotropic Loci Associated with Immunity to Childhood Immunizations

A total of 301 genes contained SNPs with a regression (additive model) p < 1 × 10⁻⁴, with one or more vaccine-induced serological measures (Figure 3). Nine of these genes were shared with more than one vaccine-induced IgG concentrations measure (Figure 3). Two genes, SRSF7 and RP11-115H18.1, shared the same SNPs between these serological measures and were therefore correlated and concordant (Table S10).

DISCUSSION

Evolving robust and sustained vaccine-induced immunity from early life is a crucial component of global health initiatives to combat the humanitarian burden of infectious disease. Here we provide a GWAS of persistence of immunity following three routine childhood vaccines: MenC conjugate vaccine, Hib conjugate vaccine, and TT vaccine. We describe two genetic loci associated (p < 5 × 10⁻⁸) with the persistence of vaccine-induced immunity following childhood immunization.

First, we present a statistical association between SNPs within a genomic region containing a family of signal-regulatory pro-
Table 2. Top 10 SNPs, Ranked by p Value, Associated with the Persistence of MenC-Specific SBA Titers following Vaccination, in Combined Analysis (Discovery + Replication Cohort)

| CHR | SNP | Gene Symbol | Cohort | N | Additive Model β | Additive Model p | Dominant Model β | Dominant Model p |
|-----|-----|-------------|--------|---|------------------|-----------------|-----------------|-----------------|
| 20  | rs6135736 LOC105369219 | discovery | 1,436 | 0.19 (0.12, 0.26) | 3.2 × 10⁻⁷ | 0.24 (0.15, 0.33) | 1.2 × 10⁻⁷ |
|     |    | replication | 915 | 0.06 (0.01, 0.17) | 0.09 | 0.12 (0.01, 0.22) | 0.03 |
|     |    | combineda | 2,351 | 0.16 (0.10, 0.22) | 6.4 × 10⁻⁶ | 0.20 (0.14, 0.28) | 6.0 × 10⁻⁹b |
| 20  | rs4814511 | discovery | 1,443 | 0.19 (0.11, 0.26) | 3.5 × 10⁻⁷ | 0.24 (0.15, 0.33) | 1.7 × 10⁻⁷ |
|     |    | replication | 920 | 0.05 (0.04, 0.13) | 0.27 | 0.09 (0.01, 0.20) | 0.08 |
|     |    | combineda | 2,363 | 0.14 (0.09, 0.20) | 3.7 × 10⁻⁷ | 0.20 (0.12, 0.27) | 1.8 × 10⁻⁸b |
| 20  | rs3818168 SIRPG | discovery | 1,441 | 0.19 (0.12, 0.27) | 2.7 × 10⁻⁷ | 0.23 (0.14, 0.32) | 4.1 × 10⁻⁷ |
|     |    | replication | 919 | 0.06 (0.03, 0.14) | 0.20 | 0.11 (0.01, 0.22) | 0.04 |
|     |    | combineda | 2,360 | 0.15 (0.09, 0.20) | 5.9E–7 | 0.19 (0.12, 0.26) | 6.2 × 10⁻⁸ |
| 20  | rs17770331 SIRPG-AS1, SIRPG | discovery | 1,443 | 0.19 (0.11, 0.26) | 5.6 × 10⁻⁷ | 0.22 (0.13, 0.31) | 1.8 × 10⁻⁶ |
|     |    | replication | 919 | 0.06 (0.03, 0.14) | 0.21 | 0.09 (0.01, 0.20) | 0.07 |
|     |    | combineda | 2,362 | 0.14 (0.09, 0.20) | 7.3 × 10⁻⁷ | 0.17 (0.11, 0.25) | 4.9 × 10⁻⁷ |
| 4   | rs10517505 | discovery | 1,444 | 0.33 (0.49, 0.17) | 7.2 × 10⁻⁵ | 0.36 (0.53, 0.20) | 2.3 × 10⁻⁵ |
|     |    | replication | 920 | 0.239 (0.42, 0.05) | 0.01 | 0.24 (0.43, 0.05) | 0.01 |
|     |    | combineda | 2,364 | 0.30 (0.42, 0.17) | 3.4 × 10⁻⁶ | 0.32 (0.44, 0.19) | 1.2 × 10⁻⁶ |
| 20  | rs4813191 SIRPG-AS1, SIRPG | discovery | 1,444 | 0.15 (0.08, 0.22) | 1.7 × 10⁻⁵ | 0.17 (0.09, 0.27) | 7.3 × 10⁻⁵ |
|     |    | replication | 918 | 0.06 (0.02, 0.14) | 0.17 | 0.10 (0.00, 0.21) | 0.04 |
|     |    | combineda | 2,362 | 0.12 (0.07, 0.17) | 7.8 × 10⁻⁶ | 0.16 (0.09, 0.228) | 4.9 × 10⁻⁶ |
| 2   | rs1467180 | discovery | 1,431 | 0.30 (0.48, 0.14) | 4.8 × 10⁻⁴ | 0.32 (0.50, 0.15) | 3.5 × 10⁻⁴ |
|     |    | replication | 920 | 0.18 (0.40, 0.05) | 0.13 | 0.18 (0.40, 0.05) | 0.13 |
|     |    | combineda | 2,351 | 0.27 (0.41, 0.13) | 1.5 × 10⁻⁴ | 0.27 (0.42, 0.14) | 1.2 × 10⁻⁴ |
| 6   | rs551216 ADGRB3 | discovery | 1,429 | 0.12 (0.19, 0.05) | 2.6 × 10⁻⁴ | 0.16 (0.25, 0.07) | 3.3 × 10⁻⁴ |
|     |    | replication | 920 | 0.03 (0.11, 0.05) | 0.48 | 0.10 (0.21, 0.00) | 0.05 |
|     |    | combineda | 2,349 | 0.08 (0.13, 0.03) | 2.7 × 10⁻³ | 0.13 (0.20, 0.06) | 2.0 × 10⁻⁴ |
| 12  | rs1358274 | discovery | 1,444 | 0.17 (0.26, 0.09) | 9.2 × 10⁻⁵ | 0.18 (0.28, 0.09) | 1.8 × 10⁻⁴ |
|     |    | replication | 919 | 0.04 (0.15, 0.06) | 0.43 | 0.07 (0.18, 0.05) | 0.28 |
|     |    | combineda | 2,363 | 0.13 (0.20, 0.06) | 2.3 × 10⁻⁴ | 0.14 (0.22, 0.07) | 2.2 × 10⁻⁴ |
| 2   | rs2042086 | discovery | 1,444 | 0.15 (0.23, 0.07) | 1.7 × 10⁻⁴ | 0.18 (0.28, 0.09) | 9.6 × 10⁻⁵ |
|     |    | replication | 918 | 0.03 (0.13, 0.05) | 0.43 | 0.04 (0.16, 0.06) | 0.4 |
|     |    | combineda | 2,362 | 0.11 (0.17, 0.04) | 6.8 × 10⁻⁴ | 0.13 (0.21, 0.06) | 2.4 × 10⁻⁴ |

CHR, chromosome; N, number of participants included in the analysis.

*aResults from combining all individual-level data into a single analysis.

*p values <5 × 10⁻⁸ are genome-wide significant.

Differences between the half-life of serum antibody to different vaccines (e.g., >200 years for measles and mumps compared with ~10 years for TT) suggest these features are programmed into plasma cells during their maturation in the GC (Amanna et al., 2007). We postulate that the lead SNP described here is causally involved in the generation of competent and competitive (i.e., for long-term survival niches) high-affinity LLPCs, via an altered TF-binding motif within a hypothetical enhancer region in antigen-stimulated T cells.

We also identified a region within the HLA gene complex that contained SNPs associated with the persistence of TT-specific IgG. HLA molecules present peptides to T cells, which in turn induce B cells to produce antibodies (Murphy et al., 2008). Given their role, HLA genes have frequently been candidates in studies exploring the genetic determinants of vaccine responses (O'Connor and Pollard, 2013; Mentzer et al., 2015). Moreover, a GWAS of hepatitis B surface antigen (HBsAg) vaccine-induced immunity found independent signals across the HLA region that were associated with HBsAg-specific IgG concentrations following vaccination (Png et al., 2011). Furthermore, variants with the HLA-DRB1 locus have been linked to rubella neutralization antibody titers following measles-mumps-rubella vaccine, albeit the association did not reach the customary threshold of genome-wide significance (lead SNP p = 8.62 × 10⁻⁸) (Lambert et al., 2015). Interestingly, HLA has been estimated to account for only a minority of the total heritability associated with humoral immunity to TT, rubella, and HBV. Yet, to date, no genes outside the HLA region have been implicated, at the level of genome-wide significance, with responses to these vaccines. One explanation for this could be a modest individual effect size for these putative non-HLA loci. Previous studies of immune-related diseases have shown a relationship between the number of loci...
reaching genome-wide significance and sample size, and it is likely that the study of larger vaccinee cohorts will yield more loci associated with immunity to vaccine antigens (Parkes et al., 2013). In our study, we estimated the heritability of vaccine-induced immunity to vary from 14% to 81%; TT immunity was estimated to be the most heritable of these measures. Interestingly, analysis of TT immunity required 10 principal components (PCs) to regress out genomic inflation, compared with 3 PCs for the other vaccine responses. There are a number of potential explanations for this finding, including trait heritability, sample size, linkage disequilibrium structure, and number of causal variants, which have all been shown to influence genomic inflation (Yang et al., 2011b).

The identification of causal variants within the HLA region is intrinsically difficult due to its complex and long-range linkage disequilibrium structure. The association signals may originate from differing abilities of classical HLA alleles to bind peptide. However, it may also be the case that cis-regulatory elements underlie these associations. To explore this further, we imputed classical HLA alleles using the discovery stage GWAS dataset (Dilthey et al., 2011). This analysis suggested HLA-DOB1*0201, HLA-DRB1*0301, HLA-DOB1*0602, and HLA DRB1*1501 were associated with TT-IgG concentrations. Intriguingly, HLA-DRB1*0301 is distinct from the other major HLA-DRB1 alleles both genetically and immunologically, recognizing a peptide motif that is dissimilar from that recognized by the other major HLA-DRB1 alleles (Sidney et al., 1992). This allele has also been associated with increased susceptibility to several autoimmune and allergic phenotypes, as well as lower HBsAg-specific IgG concentrations following hepatitis B vaccine, supporting a generalized difference in the peptide-binding preferences (Alper et al., 1989; Li et al., 2009; Handunnetthi et al., 2010).

Table 3. The Results of Combined Analysis for the Five HLA SNPs Selected for Replication Analysis with TT-Specific IgG Concentrations

| CHR SNP | Cohort N | Additive Model β (95% CI) | Additive Model p | Dominant Model β (95% CI) | Dominant Model p |
|---------|----------|---------------------------|-----------------|---------------------------|-----------------|
| 6       | rs2523650 | discovery 638 0.12 (0.06, 0.18) 4.1 × 10⁻⁵ 0.15 (0.07, 0.22) 9.9 × 10⁻⁵ |
|         | replication 1,151 0.10 (0.05, 0.14) 2.1 × 10⁻⁵ 0.12 (0.05, 0.16) 0.0003 |
|         | combined 1,789 0.12 (0.08, 0.15) 2.6 × 10⁻¹⁰ 0.14 (0.09, 0.18) 6.5 × 10⁻⁹ |
| 6       | rs6903608 | discovery 625 0.12 (0.06, 0.18) 4.7 × 10⁻⁵ 0.18 (0.10, 0.25) 5.4 × 10⁻⁶ |
|         | replication 1,096 0.03 (−0.02, 0.07) 0.21 0.03 (−0.02, 0.09) 0.24 |
|         | combined 1,721 0.06 (0.03, 0.10) 2.4 × 10⁻⁴ 0.09 (0.04, 0.14) 1.3 × 10⁻⁴ |
| 6       | rs3094188 | discovery 621 0.11 (0.05, 0.16) 2.1 × 10⁻⁴ 0.12 (0.04, 0.19) 0.0031 |
|         | replication 1,108 0.03 (−0.01, 0.08) 0.11 0.07 (0.01, 0.13) 0.01 |
|         | combined 1,729 0.06 (0.03, 0.10) 4.6 × 10⁻⁴ 0.08 (0.04, 0.14) 2.6 × 10⁻⁴ |
| 6       | rs9268877 | discovery 602 0.10 (0.05, 0.16) 1.1 × 10⁻⁴ 0.13 (0.05, 0.22) 6.2 × 10⁻⁴ |
|         | replication 1,094 0.03 (−0.01, 0.07) 0.17 0.04 (−0.02, 0.10) 0.17 |
|         | combined 1,696 0.06 (0.02, 0.10) 0.0012 0.07 (0.02, 0.12) 0.0043 |
| 6       | rs2523663 | discovery 593 0.06 (0.00, 0.12) 0.03 0.08 (0.00, 0.16) 0.04 |
|         | replication 1,065 0.02 (−0.01, 0.07) 0.19 0.01 (−0.05, 0.07) 0.67 |
|         | combined 1,658 0.04 (0.01, 0.08) 0.0151 0.04 (−0.01, 0.09) 0.1178 |

CHR, chromosome; CI, confidence interval; N, number of participants included in the analysis.

aResults from combining all of the data into a single analysis.
bp < 5 × 10⁻⁸ are genome-wide significant.

effective T cell responses to different class II alleles contributing to the quantitative differences in humoral responses to TT.

The index HLA SNP (rs2523650) remained significantly associated with TT-IgG concentrations after conditioning for HLA DRB1*0301, HLA DQB1*0201, HLA DQB1*0602, or HLA DRB1*1501, suggesting this association is independent of these classical alleles. Moreover, rs2523650 has been annotated as an expression-trait quantitative locus for HLA-DRB1 and HLA-DRB5 (Zeller et al., 2010). Therefore, these data support the mechanism underlying this association to be regulatory, rather than classical, HLA allele dependent.

Previous studies have shown considerable correlation in immune responses to a number of childhood vaccines (Newport et al., 2004; Finn et al., 2000; Goldblatt et al., 1999). There was some thought that this could be largely because of age-dependent immunological maturation. However, disparities in the correlations between vaccine antigens contradict a simple “responsiveness” trait (Finn et al., 2000). Nevertheless, it is not known whether there are pleiotropic loci that are involved in “vaccine responsiveness” in a generic sense. Here, analysis for pleiotropic loci identified nine genes, at a liberal p value cutoff of 10⁻⁴, which were shared between two or more measures of vaccine-induced immunity. Intriguingly, PTPRD was associated with both MenC-specific SBA titers and PRP-specific IgG concentrations, and has previously been associated with rubella-specific IFN-γ responses following measles, mumps, and rubella (MMR) vaccination (Kennedy et al., 2014). Interestingly, we did not find any overlap in genes containing the most statistically associated (p < 1 × 10⁻⁵) SNPs between the vaccine-induced serological measures. This finding is consistent with data from the large study into pleiotropic loci among immune-related diseases, which suggested SNPs with the largest effect sizes tended to be phenotype specific (Parkes et al., 2013).
Table 4. Top 10 Imputed Human Leukocyte Antigen Alleles, Based upon p Values, in Association Analysis with TT-Specific IgG Concentrations in Discovery Stage

| CHR  | SNP             | N     | Additive Model β (95% CI) | Additive Model p | Dominant Model β (95% CI) | Dominant Model p |
|------|-----------------|-------|--------------------------|-----------------|--------------------------|-----------------|
| 6    | HLA_DRB1_03     | 535   | –0.19 (–0.28, –0.11)     | 1.42 × 10⁻⁵ ⁵a  | –0.18 (–0.28, –0.09)     | 1.75 × 10⁻⁴ ⁴a  |
| 6    | HLA_DRB1_0301   | 535   | –0.19 (–0.28, –0.11)     | 1.42 × 10⁻⁵ ⁵a  | –0.18 (–0.28, –0.09)     | 1.75 × 10⁻⁴ ⁴a  |
| 6    | HLA_DQB1_0201   | 535   | –0.18 (–0.27, –0.09)     | 5.46 × 10⁻⁶ ⁵a  | –0.17 (–0.27, –0.07)     | 6.35 × 10⁻⁴ ⁴   |
| 6    | HLA_DQB1_02     | 535   | –0.14 (–0.21, –0.07)     | 5.91 × 10⁻⁶ ⁵a  | –0.17 (–0.26, –0.08)     | 1.10 × 10⁻⁴ ⁴   |
| 6    | HLA_DQB1_1501   | 535   | 0.15 (0.07, 0.24)        | 5.31 × 10⁻⁴     | 0.20 (0.10, 0.30)        | 9.02 × 10⁻⁵     |
| 6    | HLA_DQB1_01     | 535   | 0.14 (0.06, 0.23)        | 8.87 × 10⁻⁴     | 0.19 (0.10, 0.29)        | 1.08 × 10⁻⁴     |
| 6    | HLA_DQB1_0602   | 535   | 0.15 (0.06, 0.23)        | 1.08 × 10⁻³     | 0.18 (0.08, 0.28)        | 2.88 × 10⁻⁴     |
| 6    | HLA_A_0201      | 535   | 0.11 (0.01, 0.21)        | 1.26 × 10⁻³     | 0.13 (0.02, 0.043)       | 3.32 × 10⁻³     |
| 6    | HLA_DQA1_01     | 535   | 0.10 (0.04, 0.16)        | 1.58 × 10⁻³     | 0.10 (0.01, 0.19)        | 2.50 × 10⁻²     |
| 6    | HLA_A_24        | 535   | 0.19 (0.07, 0.32)        | 2.32 × 10⁻³     | 0.18 (0.04, 0.31)        | 8.88 × 10⁻³     |

CHR, chromosome; CI, confidence interval; N, number of participants included in the analysis.

* p < 3 × 10⁻³ (0.05/168).

In this study, participants were included from 10 sub-studies, which differed in terms of age of vaccination, time since vaccination, immunological assay protocols, vaccine schedules and compositions, and concomitant vaccines administered. Although these factors were included as covariates in the linear models, this heterogeneity will have been detrimental to statistical power (Ioannidis et al., 2009). Of note, there was considerable heterogeneity, between the discovery and replication cohorts, in the effect size estimates for the SNPs with the most statistical evidence for association with persistence of MenC-specific SBA titers. Here we report two SNPs associated with MenC-specific SBA titers, at the level of genome-wide significance, based on combining individual-level data from all cohorts; although this results in increased power (compared with meta-analysis), the caveat is that this approach is more susceptible to inflated error rates or loss of power when there is heterogeneity between cohorts (Skol et al., 2006). Nevertheless, the SNP with the most statistical evidence for association with the persistence of MenC-specific SBA titers showed evidence of replication (p value < 0.05) in the replication cohort and a meta-analysis p value of 5.1 × 10⁻⁸.

No SNPs were found to be associated with PRP-specific IgG concentrations at the level of genome-wide significance, an observation that could have a number of possible explanations. The statistical power to identify SNPs associated with quantitative traits is influenced by variant effect size, the number and frequency of causal variants, sample size, as well as the robustness of the phenotypic measure (Manchia et al., 2013; Shin and Lee, 2015). Of note, the PRP-specific IgG assessments described here were made in several laboratories, and problems with inter-assay standardization of PRP-specific IgG quantification have been described (Kelly et al., 2004). Moreover, although Hib carriage rates have been extremely low in the United Kingdom for the last decade among preschool children, older participants, in particular, may have been exposed to Hib colonization in the pre-vaccine era, when carriage rates in young children were up to 8% (McVernon et al., 2004). Equally, polysaccharides cross-reactive with the Hib polysaccharide, PRP, are present on several bacterial species, such that the rate of immunizing exposures (Hib or cross-reactive bacteria) is estimated to be 1.2 per year per child, even in the post-vaccination era (Leino et al., 2002). Phenotypical variance introduced by measurement variability and immunological boosting, because of natural exposure, may have severely diminished statistical power to detect genetic variants associated with the persistence of PRP-specific IgG.

Because these data were limited to Caucasians from the United Kingdom and the Netherlands, it is unclear how these would relate to other ethnic populations, especially considering the allelic frequency of the lead SNP proximal to SIRPG varies drastically between HapMap populations: European ancestry (CEU) minor allele frequency (MAF) ~20% and Sub-Saharan Africans (YRI) MAF ~1%. Conversely, the future use of trans-ethnic vaccine cohorts, such as those described by Mentzer et al. (2015), may leverage different linkage equilibrium patterns to help fine-map causal variants. Even though GWAS captures common variation adequately, it does not capture rare variants efficiently (i.e., MAF < 1%). This may be particularly relevant because rare variants of large effect sizes may conceivably contribute to the “extremes” of vaccine responsiveness (e.g., vaccine failure). Next-generation sequencing approaches are more conducive to the description of rare variants; however, the cost of these approaches often precludes their use. In this study, we described genetic variants associated with the persistence of immunity following immunization. However, the absence of data from the acute vaccine response (peaking at about 1 month post-vaccination) meant we could not differentiate individuals who responded poorly (“primary vaccine failures”) from those who failed to maintain serological immunity (“secondary vaccine failures”).

Currently, we are not aware of any implemented healthcare system to identify children whose vaccine-induced immunity has waned and would benefit from additional immunizations. In fact, the additional healthcare provision required for such a system might make it unfeasible in many settings. Conversely, we envisage genetic markers of vaccine responses could soon prove their clinical utility. Although the cost of whole-genome sequencing is constantly decreasing, our understanding of these data and their clinical utility has been rapidly rising (Khera et al., 2018). It is realistic to conceive that neonatal screening...
approaches will soon incorporate a number of genetic risk factors (potentially derived the whole-genome sequencing at birth) (Howard et al., 2015). Therefore, it is feasible that in the near future that the persistence of immunity could be predicted and vaccine regimens personalized to maximize vaccine effectiveness.

The modest effect size of the genetic associations described in this study are consistent with the hypothesis that the genetic variants most strongly associated with complex phenotypes typically account for only a small fraction of the genetic variance; many additional causal loci, with small effect sizes, explain much of the trait heritability (Manolio et al., 2009; Yang et al., 2013). Also, a number of other host factors such as age, nutritional status, microbiota, and infectious diseases have been shown to influence immune responses (Kampmann and Jones, 2015). For example, some acute viral infections have been shown to have profound immunomodulatory effects, long after symptomatic recovery (Mina et al., 2015; Huang and Hong, 1973). Naturally acquired immunity, and immunological boosting through natural exposure, may also strongly influence immunity to organisms against which children are vaccinated (Andrews et al., 2015; Wilson et al., 2017; Voysey et al., 2017). However, this is not likely to have played a major role in immunity to the vaccines studied here; during the time frame of this study, carriage rates for Hib and MenC were very low in young children, and tetanus is non-communicable (McVernon et al., 2004; Maiden et al., 2008). Age at vaccination is known to influence vaccine responses; although we included this in linear regression analysis, heterogeneity in age of vaccination will have been detrimental to study power (Snape et al., 2008a; Tang et al., 2015). Moreover, twin-twin variability in a number of immune system parameters has been shown to increase with age, suggesting GWAS studies focused on vaccine responses early in life may have the greatest statistical power (Brodin et al., 2015). Here we assessed genetics factors with generalizable effects on vaccine responses, notwithstanding there may also be sex-dependent factors that influence immune responses to vaccines (Klein et al., 2015).

In conclusion, we describe a GWAS of the persistence of immunity to three routine childhood vaccines. We detail two loci that were associated with the persistence of vaccine-induced immunity, at the level of genome-wide significance. Although these variants inevitably account for only a small portion of the total genetically determined contribution to persistence of vaccine-induced immunity, this study demonstrates the utility of applying this “hypothesis-free” approach in generating candidates for future functional and mechanistic investigations, the description of which may ultimately influence vaccine development and implementation.

**STAR METHODS**

Detailed methods are provided in the online version of this paper and include the following:

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**SUPPLEMENTAL INFORMATION**

Supplemental Information can be found online at https://doi.org/10.1016/j.celrep.2019.05.053.
ACKNOWLEDGMENTS

We thank all the children and families who participated in the study, as well as the research nurses and doctors and laboratory scientists of Oxford Vaccine Group (University of Oxford, Oxford, UK). We also acknowledge Vaccine Evaluation Unit (Public Health England, Manchester, UK) and GlaxoSmithKline Biologicals (GSK Biologicals, Belgium) for the serological data incorporated into this manuscript. This work received funding from the European Union’s Seventh Framework Programme under EC-GA no. 279185 (EUCLIDS). GlaxoSmithKline Biologicals was provided the opportunity to review a preliminary version of this manuscript for factual accuracy, but the authors are solely responsible for final content and interpretation. A.J.P. is a Jenner Investigator and James Martin senior fellow. The authors received no financial support or other form of compensation related to the development of the manuscript.

AUTHOR CONTRIBUTIONS

Conceptualization, D.O., M.L.H., C.C.K., and A.J.P.; Methodology, D.O., E.P., C.C.K., and C.H.; Investigation, D.O. and E.P.; Resources, M.D.S., A.V.S.H., F.v.d.K., M.L.H., and A.J.P.; Writing – Original Draft, D.O.; Writing – Review & Editing, D.O., E.P., C.C.K., M.D.S., A.V.S.H., F.v.d.K., C.H., M.L., M.L.H., and A.J.P.; Funding Acquisition, M.L., M.L.H., and A.J.P.; Supervision, A.V.S.H., M.L., M.L.H., and A.J.P.

DECLARATION OF INTERESTS

The authors declare no competing interests.
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## STAR★METHODS

### KEY RESOURCES TABLE

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---------------------|--------|------------|
| **Biological Samples** | | |
| 1000 Genomes variant reference set | [http://www.internationalgenome.org/](http://www.internationalgenome.org/) data#download | 1000 Genomes Phase I integrated variant set release (March 2012) as the variant reference set |
| Type 1 Diabetes Genetics Consortium reference panel | Wellcome Centre for Human genetics | Consortium reference panel (5225 unrelated individuals) |
| **Critical Commercial Assays** | | |
| Illumina OmniExpress12v1 | Illumina®, California, United States | Cat#WG-311-1125 |
| Illumina OmniExpress12v1.1 | Illumina®, California, United States | Cat#WG-312-1120 |
| Illumina® scanner with Illumina®BeadStudio software | Illumina®, California, United States | Cat#SY-101-1001 |
| **Oligonucleotides** | | |
| Custom TaqMan SNP Genotyping Assays rs2523650 | [https://www.thermofisher.com/us/en/home/life-science/pcr/real-time-pcr/real-time-pcr-assays/snp-genotyping-taqman-assays.html](https://www.thermofisher.com/us/en/home/life-science/pcr/real-time-pcr/real-time-pcr-assays/snp-genotyping-taqman-assays.html) | Cat#4331349 |
| Custom TaqMan SNP Genotyping Assays rs6903608 | [https://www.thermofisher.com/us/en/home/life-science/pcr/real-time-pcr/real-time-pcr-assays/snp-genotyping-taqman-assays.html](https://www.thermofisher.com/us/en/home/life-science/pcr/real-time-pcr/real-time-pcr-assays/snp-genotyping-taqman-assays.html) | Cat#4331349 |
| Custom TaqMan SNP Genotyping Assays rs3094188 | [https://www.thermofisher.com/us/en/home/life-science/pcr/real-time-pcr/real-time-pcr-assays/snp-genotyping-taqman-assays.html](https://www.thermofisher.com/us/en/home/life-science/pcr/real-time-pcr/real-time-pcr-assays/snp-genotyping-taqman-assays.html) | Cat#4331349 |
| Custom TaqMan SNP Genotyping Assays rs9268877 | [https://www.thermofisher.com/us/en/home/life-science/pcr/real-time-pcr/real-time-pcr-assays/snp-genotyping-taqman-assays.html](https://www.thermofisher.com/us/en/home/life-science/pcr/real-time-pcr/real-time-pcr-assays/snp-genotyping-taqman-assays.html) | Cat#4331349 |
| Custom TaqMan SNP Genotyping Assays rs2523663 | [https://www.thermofisher.com/us/en/home/life-science/pcr/real-time-pcr/real-time-pcr-assays/snp-genotyping-taqman-assays.html](https://www.thermofisher.com/us/en/home/life-science/pcr/real-time-pcr/real-time-pcr-assays/snp-genotyping-taqman-assays.html) | Cat#4331349 |
| **Software and Algorithms** | | |
| PLINK whole genome association analysis toolset | [http://zzz.bwh.harvard.edu/plink/](http://zzz.bwh.harvard.edu/plink/) | PLINK version 1.9 |
| SMARTPCA software | [https://www.hsph.harvard.edu/alkes-price/software/](https://www.hsph.harvard.edu/alkes-price/software/) | EIGENSOFT version 4.2 |
| Segmented HAPlotype Estimation and Imputation Tool | Delaneau et al., 2013 | SHAPEIT version 2 |
| IMPUTE | Howie et al., 2009 | IMPUTE version 2 |
| SNP2HLA | [http://software.broadinstitute.org/mpg/snp2hla/](http://software.broadinstitute.org/mpg/snp2hla/) | SNP2HLA version 1.0.1 |
| NetMHCIIpan | [http://www.cbs.dtu.dk/services/NetMHCIIpan/](http://www.cbs.dtu.dk/services/NetMHCIIpan/) | NetMHCIIpan version 3.1 |
| SNPTEST | [https://mathgen.stats.ox.ac.uk/genetics_software/snptest/snptest.html](https://mathgen.stats.ox.ac.uk/genetics_software/snptest/snptest.html) | SNPTEST version 2.4.0 |
| Genome-wide SNPs for complex traits (the GREML method) | [https://cnsgenomics.com/software/gcta/#Overview](https://cnsgenomics.com/software/gcta/#Overview) | GCTA version 1.91.7 (beta) |
| **Deposited Data** | | |
| Raw genotyping data, meta-data and analysis script | [https://data.mendeley.com](https://data.mendeley.com) | O’Connor, Daniel (2019), “Common genetic variations associated with the persistence of immunity following childhood immunisation,” Mendeley Data, V1 (https://doi.org/10.17632/d7y6jhc36b.1) |
| R code algorithm devised to select SNPs for stage 2 | [https://github.com](https://github.com) | [https://github.com/dan-scholar/LD_pruning](https://github.com/dan-scholar/LD_pruning) |

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Cell Reports 27, 3241–3253.e1–e4, June 11, 2019
CONTACT FOR REAGENT AND RESOURCE SHARING

Further information and requests for resources and data should be directed to and will be fulfilled by the Lead Contact, Daniel O’Connor (daniel.oconnor@pediatrics.ox.ac.uk).

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Study participants and vaccines

Healthy children and adolescents were included from nine studies conducted in Oxford, United Kingdom and one study conducted in Bilthoven, Netherlands (1634 males and 1795 females; demographics are shown in Table S1). In accordance with national guidelines (UK and Netherlands) immunisations were not delayed for minor illnesses but were deferred during acute illness (with fever above 38°C) until recovery. Regional research ethics committees approved these studies and the genetic analysis presented in this work (CO2.328, 07/Q1605/34, 09/H0604/107, 10/H0604/07, 04/Q1604/28, 06/Q1604/67, Stichting Therapeutische Evaluatie Geneesmiddelen [R05-044], B07/Q1605/41,10/H0504/25).

In brief, cohorts 1 and 2 were studies to examine the persistence serological of immunity to MenC in adolescents aged 11-20 years; 3-5 years after immunisation with a single dose of MenC vaccine, as part of the UK MenC catch-up immunisation program (Snape et al., 2006, 2008a). Participants received one of three vaccines administered during the UK MenC vaccine campaign: two of which contained MenC capsular polysaccharide conjugated to CRM197 and the other was conjugated to TT. These vaccines were Menjugate (Novartis Vaccines and Diagnostics, Siena), Meningitec (Wyeth Vaccines, New York), and NeisVac-C (Baxter Vaccines, Maryland). While Hib vaccination status was recorded for these participants, the vaccine formulation was not noted.

Cohort 3 was a group of infants from a study assessing the immunogenicity of the Hib-MenC conjugate vaccine (Pace et al., 2007). Study participants received 3-doses of Hib-MenC (Menitorix, GSK Biologicals), which is conjugated to TT, or Meningitec, at 2, 3, and 4 months of age. Persistence of immunity to MenC, Hib and TT was assessed at 1 year of age. Cohorts 5 and 7 were infants enrolled into studies evaluating the immunogenicity of immunisation with 2- or 3-doses of capsular group A, C, W and Y quadrivalent meningococcal CRM-conjugated vaccine Menveo (Novartis Vaccines and Diagnostics, Siena) at 2, 3, 4 months or 2 and 4 months of age (Blanchard-Rohner et al., 2013; Snape et al., 2008b). Participants also received their routine infant immunisation, in accordance with the UK schedule, of relevance Pediacel (DTaP-Hib-IPV, Sanofi-Pasteur-MSD, Maidenhead, United Kingdom) was administered at 2, 3, 4 months of age; persistence of MenC and Hib immunity was measured at 1 year of age. Cohort 4 comprised of infants recruited into a study evaluating immunological memory following infant MenC conjugate vaccine (Menjugate or NeisVac-C) in consistent or alternating limbs. Participants received either a single dose of Menjugate or NeisVac-C at 3 months of age or a 2-dose schedule of Menjugate at 3 and 4 months of age; administered concomitantly with routine immunisations including Pediacel at 2, 3, 4 months of age (Khatami et al., 2014). Persistence of immunity to MenC and Hib was measured at 1 year of age.

Cohort 6 entailed a study evaluating the immunogenicity of the 2009 pandemic H1N1 influenza vaccine, in children 6 months to 12 years of age; data were also collected on routine childhood immunisations and sera were assessed to determine immunity to MenC, Hib and TT vaccines (Waddington et al., 2010). Cohort 8 was a study assessing the immunogenicity of the 7- and 13-valent pneumococcal conjugate vaccine alongside routine infant immunisations. As part of this study participants received NeisVac-C at 2 and 4 months of age and Pediacel at 2, 3, and 4 months of age. Persistence of vaccine-induced immunity was measured at 1 year of age (Snape et al., 2010). Cohort 9 was a longitudinal study assessing kinetics of the decline in MenC-specific antibody following early childhood (1-4 years of age) MenC immunisation, as part of the UK MenC catch-up immunisation program (Khatami et al., 2011). All of these children received a single dose of a licensed MenC conjugate vaccine of Menjugate, Meningitec or NeisVac-C. Cohort 10 examined the persistence of serological immunity to MenC in adolescents aged 9-20 years; 3-5 years after immunisation with a single dose of NeisVac-C, as part of the Dutch national MenC catch-up immunisation program (de Voer et al., 2010). These participants received their last dose of Hib containing vaccine (Pediacel) at 11 months of age; and their last dose of TT containing vaccine (assuming only routine immunisation) at 9 years of age or as a carrier protein to the MenC vaccine in year 2002.

METHOD DETAILS

Serum bactericidal assays

The Vaccine Evaluation Unit (VEU), Public Health England (Manchester), performed MenC-specific SBAs for study cohorts 2, 8 and 9 using rabbit complement (rSBA), and using human complement (hSBA) for cohorts 4 and 6. Novartis Vaccines, Germany (Marburg), performed MenC-specific SBAs using human complement for cohorts 1, 5 and 7 (Snape et al., 2006). GSK Biologicals, Belgium, performed MenC-specific hSBA titers using human complement for cohort 3 (Pace et al., 2007). Rijksinstituut voor Volksgezondheid en Milieu (RIVM), Bilthoven, measured MenC-specific rSBA titers using rabbit complement for cohort 10 (Maslanka et al., 1997). The lower limit of quantification (LLQ) for the hSBA assays was a reciprocal titer of 4 and for the rSBA assay this was 8, sera without detectable bactericidal antibody were assigned an arbitrary value of two.
MenC-specific IgG concentrations
Novartis Vaccines, Germany (Marburg), performed MenC-specific IgG for Cohort 1, by a standardized enzyme-linked immunosorbent assay (ELISA) with a LLQ of 0.3 μg/mL (Snape et al., 2006). MenC-specific IgG concentrations were measured by ELISA in-house for cohorts 2 and 7, with a LLQ of 0.00167 μg/mL (Blanchard-Rohner et al., 2013). MenC-specific IgG concentrations were measured using ELISA at GlaxoSmithKline Biologicals, Belgium, for Cohort 3, with a LLQ of 0.3 μg/mL (32). MenC-specific IgG concentrations were measured at the Vaccine Evaluation Unit (VEU), Public Health England (Manchester) by ELISA for Cohort 4 and 6, with a LLQ of 0.12 μg/mL (Gheesling et al., 1994). MenC-specific IgG concentrations were measured at the RIVM, Bilthoven, by multiplexed immune assay (Bioplex) for Cohort 10, with a LLQ of 0.01 μg/mL (de Voer et al., 2009). For the purposes of analysis MenC-specific IgG concentrations below the LLQ were assigned of half the respective assay LLQ.

Hib-specific IgG concentrations
An in-house ELISA was performed to measure Hib-specific IgG concentrations for cohort 2, with a LLQ of 100ng/mL (Booy et al., 1992). Hib-specific IgG concentrations were measured at Public Health England (Manchester), by Bioplex PHE for Cohort 4 and 6, with a LLQ of 46 ng/mL (Pickering et al., 2002). GlaxoSmithKline Biologicals, Belgium, performed Hib-specific IgG quantification for Cohort 3, by ELISA with a LLQ of 150ng/mL (Pace et al., 2007). Hib-specific IgG concentrations for Cohort 10 were assessed at RIVM, Bilthoven, by multiplexed immune assay, with a LLQ of 0.01 μg/mL (Pickering et al., 2002).

TT-specific IgG concentrations
TT-specific IgG concentrations were measured using ELISA at GlaxoSmithKline Biologicals, Belgium, for Cohort 3, the LLQ for this assay was 0.1IU/ml (Pace et al., 2007). Vaccine Evaluation Unit (VEU), Public Health England (Manchester) performed TT-specific IgG quantification using Bioplex PHE for Cohort 4 and 6, with a LLQ of 2 (IU × 1000/ml) (Pickering et al., 2002). Aventis Pasteur, Toronto, measured TT-specific IgG Cohort 9, using an ELISA with an in-house reference standard, the LLQ for this assay was 0.1 IU/ml (Collins et al., 2004). TT-specific IgG concentrations were measured using ELISA at Novartis Vaccines, Germany (Marburg) for Cohort 5, with a LLQ of 0.1 IU/ml (Snape et al., 2008b). RIVM, Bilthoven, measured TT-specific IgG concentrations using multiplexed immune assay, for Cohort 10, with a LLQ of 0.001 IU/ml (Pickering et al., 2002).

DNA extraction and genotyping
DNA was extracted either extracted from whole blood collected in EDTA tubes or from clotted whole blood samples. In the case of clotted samples, 1ml of blood clots (remaining from serum separated peripheral blood) were placed in a Clotspin® basket (QIAGEN, Hilden, Germany) and centrifuged at 2000 × g₀ for 5 minutes to disperse the clot. Then, 5 mL of red blood cell lysis solution (16.52 g NH₄Cl, 2 g KHCO₃ and 0.074 g DNA in 2L of H₂O) was added, samples were vortexed for 3 s, and shaken for 5 minutes on an orbital mixer at 120-200 rpm. Samples were vortexed for 3 s and centrifuged at 2000 × g₀ for 5 minutes. Supernatant was discarded and an additional 5 mL of red blood cell lysis solution was added, vortexed for 3 s, before repeating the orbital mixer step. Samples were centrifuged at 2000 × g₀, supernatant discarded and vortexed. Next, 1 mL of Cell Lysis solution (1 mL nuclei lysis solution [Promega, Wisconsin, United States]; 25 μL Protease K [QIAGEN, Hilden, Germany]; and 250 μL 0.5 M ethylenediaminetetraacetic acid). Following this incubation, DNA was extracted according to the standard spin protocol for whole blood, using the Qiamp® midi kit (QIAGEN, Hilden, Germany). For blood samples collected directed into EDTA blood tubes (anticoagulant), the pre-extraction process was skipped and DNA was extracted according to the standard spin protocol for whole blood, using the Qiamp® midi kit (QIAGEN, Hilden, Germany).

Genotyping of the discovery cohort (n = 2,061) was performed using either Illumina OmniExpress12v1 or OmniExpress-12v1.1 genotyping microarrays (Illumina®, California, United States), at the Genome Institute of Singapore as according to manufacturers protocol. In brief, DNA samples were whole-genome amplified and enzymatically cleaved into 300-600bp fragments. Samples were then purified using isopropyl precipitation and re-suspended in hybridization buffer. Samples were hybridized to the microarray and an allele-specific enzymatic single-base extension step was performed, to add a biotin-labeled (guanine or cytosine) or dinitrophenol-labeled (adenine or thymine) base. Sequential rounds of staining were performed with green-fluorescent streptavidin and biotin-labeled antibodies, and red-fluorescent anti-dinitrophenol antibodies and dinitrophenol-labeled antibodies. Following staining, the arrays were read on an Illumina® scanner and genotypes were called using Illumina® BeadStudio software.

A number of quality control (QC) checks were undertaken on the genotyping data before statistical association testing, the QC pipeline utilized was similar to that described by Anderson et al., 2010, using the PLINK whole genome association analysis toolset (http://zzz.bwh.harvard.edu/plink/) (Anderson et al., 2010; Purcell et al., 2007). Participants with discrepancies between the sexes (n = 81) reported on participant information data and those deduced from the genotyping data were removed. Participants with genotype heterozygosity greater than two standard deviations from the cohort mean heterozygosity rate (n = 28), or with a missing genotyping proportion > 0.03 were removed (n = 16). First- and second-degree relatives were identified identity-by-descent (IBD) analysis, and all but the best-performing participant (in terms of genotype call-rate) were removed (n = 212). SMARTPCA software was used to identify ancestral outliers, and population outliers were removed (n = 132) using the metrics described by Anderson et al., 2010 (Anderson et al., 2010; Price et al., 2006). SNPs with minor allele frequencies (MAF) of < 0.01 (n = 77991), genotype call rate < 0.95 (n = 1984) and/or Hardy-Weinberg equilibrium (HWE) p values < 1 × 10⁻⁵ (n = 16305) were eliminated.
Imputation
The post quality filtered dataset from the GWAS array was used for genotype imputation, Segmented HAPlotype Estimation and Imputation Tool (SHAPEIT) version 2 was used to pre-phase each chromosome of the genotype data individually (Delaneau et al., 2013). Imputation was performed using IMPUTE version 2 on 5 Mb chunks of this pre-phased data, applying the 1000 Genomes Phase I integrated variant set release (March 2012) as the variant reference set (Howie et al., 2009). Imputed data were filtered for MAF > 0.02, HWE p values > 1 x 10^{-3} and information scores > 0.8.

Imputation of classical HLA alleles
The SNP2HLA framework was used to impute classical human leucocyte antigen alleles from the genotype data, using the Type 1 Diabetes Genetics Consortium reference panel (5225 unrelated individuals) (Jia et al., 2013; Wellcome Trust Case Control Consortium, 2007). Classical HLA alleles were annotated as present or absent, and a linear regression analysis was conducted using PLINK 1.9 (Purcell et al., 2007). Conditional analysis of the five replication HLA SNPs including HLA DRB1*0301, HLA DQB1*0201, HLA DQB1*0602 or HLA DRB1*1501, as covariate in the linear regression model was undertaken.

In silico epitope mapping
Clostridium tetani tetanus toxin protein sequence was retrieved from UniProt (https://www.uniprot.org/). Tetanus toxin 20-mer, overlapping 19 amino acids, peptides were assessed against a panel of HLA-DRB1 alleles, using NetMHCIIpan 3.1 (http://www.cbs.dtu.dk/services/NetMHCIIpan/), pan-specific MHC class II prediction tool.

QUANTIFICATION AND STATISTICAL ANALYSIS

Association analysis
A linear regression model was used to assess the relationship between SNP allele dosage and the persistence (> 120 days post-vaccination) of log10 vaccine-specific measures. Analysis was conducted using SNPTEST version 2.4.0: incorporating age at vaccination, time since vaccination, study enrolled in, complement source (for SBA analysis) and the first three principal components (PCs) as covariates (Marchini and Howie, 2010). Post-association QC was also conducted to check for inflation, lambda gc (λgc), of test-statistics, using the ‘GenABEL’ R package, under the assumption that the vast majority of the genetic markers assessed would not be associated with the phenotype (Aulchenko et al., 2007). Genomic inflation was observed for regression analysis of TT-specific IgG concentration (λgc = 2.30); however, this was ameliorated by the inclusion of the first 10 PCs into the regression model.

Heritability analysis
The GREML method was used to estimate the phenotypic variance explained by all SNPs, as described by Yang et al., 2011a (Yang et al., 2011a). Heritability analysis used only the genome-wide genotyping data generated from the discovery cohort.

Replication SNP selection
The R code for the algorithm devised to select SNPs for stage 2 is deposited on Github (https://github.com/dan-scholar/LD_pruning). In brief, genotyped SNPs from stage 1 with association p values < 1 x 10^{-4}, as well as imputed SNPs with p values < 1 x 10^{-5}, in the regression models of MenC-specific IgG concentrations or SBA titers were selected. A different statistical cut-off for genotyped and imputed SNPs was imposed as imputed SNPs have an inevitable reduced certainty. These SNPs were separated into 500kb chromosomal windows and windows with < 3 SNPs were eliminated as these are more likely to represent genotyping and/or imputation errors. Next, to avoid redundant genotyping of markers in high LD the SNP list was pruned by filtering SNPs with an R^2 > 0.95 with the lead SNP within each 500kb window. Then, the next most significant SNP remaining in each window was selected and LD filtering repeated iteratively, until all SNPs had been interrogated. We carried out combined analysis of the individual level discovery- and replication-stage data in a single analysis, for both additive and dominant genetic models, using PLINK 1.9 (Purcell et al., 2007). Meta-analysis of the discovery- and replication-stage cohorts was conducted by the inverse variance method, without adjusting for principal components, using PLINK 1.9 (Purcell et al., 2007).

Pleiotropic loci analysis
SNPs associated with the persistence of serological immunity to MenC, Hib or TT at a p < 1 x 10^{-4} were collapsed into genetic loci by gene boundaries. Genes linked with more than one measure of vaccine immunity were interpreted as pleiotropic.

Transcription factor motif prediction
Sequences surrounding SNPs were evaluated for potential transcription factor (TF) binding sites and the allelic variants were considered for their impact on TF motifs, using the R package ‘motifbreakR’ (Coetzee et al., 2015).