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Lupus IgG V<sub>H</sub>4.34 Antibodies Bind to a 220-kDa Glycoform of CD45/B220 on the Surface of Human B Lymphocytes<sup>1</sup>

Amedeo J. Cappione, Aimee E. Pugh-Bernard, Jennifer H. Anolik, and Iñaki Sanz<sup>3</sup>

Anti-lymphocyte autoantibodies are a well-recognized component of the autoimmune repertoire in human systemic lupus erythematosus (SLE) and have been postulated to have pathogenic consequences. Early studies indicated that IgM anti-lymphocyte autoantibodies mainly recognized T cells and identified CD45, a protein tyrosine phosphatase of central significance in the modulation of lymphocyte function, as the main antigenic target on T cells. However, more recent work indicates that lupus autoantibodies can also recognize B cells and that CD45 may also represent their antigenic target. In particular, IgM Abs encoded by V<sub>H</sub>4.34 appear to have special tropism for B cells, and strong, but indirect evidence suggests that they may recognize a B cell-specific CD45 isoform. Because V<sub>H</sub>4.34 Abs are greatly expanded in SLE, in the present study we investigated the antigenic reactivity of lupus sera V<sub>H</sub>4.34 IgG Abs and addressed their contribution to the anti-lymphocyte autoantibody repertoire in this disease. Our biochemical studies conclusively demonstrate that lupus IgG V<sub>H</sub>4.34 Abs target a developmentally regulated B220-specific glycoform of CD45, and more specifically, an N-linked N-acetyllactosamine determinant preferentially expressed on naive B cells that is sterically masked by sialic acid on B220-positive memory B cells. Strikingly, our data also indicate that this reactivity in SLE sera is restricted to V<sub>H</sub>4.34 Abs and can be eliminated by depleting these Abs. Overall, our data indicate that V<sub>H</sub>4.34 Abs represent a major component of the lupus IgG autoantibody repertoire and suggest that the carbohydrate moiety they recognize may act as a selecting Ag in SLE. The Journal of Immunology, 2004, 172: 4298–4307.

Systemic lupus erythematosus (SLE)<sup>4</sup> is characterized by increased levels of serum autoantibodies directed against multiple self Ags, including determinants expressed on the surface of lymphocytes (1, 2). Indeed, it is well established that most patients with SLE develop IgM anti-lymphocyte autoantibodies (ALA) at some point in the course of the disease (1, 2). The best-characterized ALA are cold-reactive anti-T cell IgM Abs with lymphocytotoxic activity whose surface levels correlate with the degree of global peripheral lymphopenia and disease activity (3). Yet, warm-reactive IgG ALA have also been reported in SLE (4). Although ALA are most likely heterogeneous in terms of antigenic reactivity, IgM ALA appear to preferentially recognize different isoforms of CD45, a transmembrane protein tyrosine phosphatase expressed in the surface of both B and T cells that plays a central role in lymphocyte homeostasis (5, 6).

SLE anti-CD45 Abs have been reported to recognize nonsiallylated carbohydrate determinants in the highly O-glycosylated polymorphic domains of CD45 isoforms expressed by T cells (7–9). By and large, these Abs appear to preferentially bind T cells, but not B cells, suggesting that they recognize a T cell-specific CD45 glycoform (4, 7, 10, 11). Yet, the information summarized above needs to be reconciled with the observation that at least a subset of lupus autoantibodies has the ability to bind B cells possibly by recognizing a B cell-specific CD45 isoform (12–14). Such autoantibodies, termed V<sub>H</sub>4.34 Abs, owing to their expression of surface Ig encoded by the V<sub>H</sub>4.34 gene segment, are intrinsically autoreactive by virtue of their almost universal and largely L-chain-independent, recognition of the N-acetyllactosamine (NAL) antigenic determinant of the I<sub>i</sub>-blood group Ag (15–17). Strikingly, V<sub>H</sub>4.34 Abs make up the vast majority of pathogenic IgM anti-i cold agglutinin, and the V<sub>H</sub>4.34 gene segment seems to be mandatory for the generation of such autoantibodies (18, 19). Of note, NAL is also expressed on a 220-kDa CD45 B cell-specific isoform, which has been postulated to represent the antigenic target of V<sub>H</sub>4.34 IgM Abs derived either from patients with Wiskott-Aldrich syndrome or monoclonal cold agglutinin disease (13, 14, 20–22). However, in these studies, the V<sub>H</sub>4.34 Abs used failed to immunoprecipitate CD45, and therefore the actual nature of their antigenic target in B cells remains to be formally established.

Despite the abundance of V<sub>H</sub>4.34 B cells in normal individuals, V<sub>H</sub>4.34 Abs are virtually undetectable in healthy sera due to strict censoring of V<sub>H</sub>4.34 B cells (23, 24). However, circulating V<sub>H</sub>4.34 Abs are highly expressed in patients with SLE in whom they constitute a substantial fraction of anti-DNA Abs and highly correlate with overall disease activity, kidney, and CNS involvement (25–28). We have reported that censoring of V<sub>H</sub>4.34 B cells in healthy subjects is largely achieved by exclusion from participating in productive germinal center reactions (24). Our studies also show that this censoring mechanism is faulty in patients with SLE in whom V<sub>H</sub>4.34 B cells frequently form mature germinal centers and are abundantly expressed in the IgG memory and plasma cell repertoire (29). However, the actual antigenic reactivity of V<sub>H</sub>4.34 IgG Abs in SLE sera remains to be determined with a recent study suggesting that such Abs may not represent a major B cell-binding species (27).

Department of Medicine, Clinical Immunology and Rheumatology Unit, University of Rochester Medical Center, Rochester, NY 14642

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2 Current address: Department of Immunology, National Jewish Medical and Research Center, Denver, CO 80206.

3 Address correspondence and reprint requests to Dr. Iñaki Sanz, Department of Medicine, University of Rochester Medical Center, 601 Elmwood Avenue, Box 695, Rochester, NY 14642. E-mail address: Ignacio_Sanz@URMC.rockefeller.edu

4 Abbreviations used in this paper: SLE, systemic lupus erythematosus; ALA, anti-lymphocyte autoantibody; AntiSO<sub>2</sub>, ammonium sulfate; LCA, leukocyte common Ag; NAL, N-acetyllactosamine; PTPase, phosphotyrosine phosphatase.
In the present study, we have analyzed the contribution of IgG V_{H}4.34 Abs to the anti-lymphocyte repertoire in SLE and conclusively established the molecular basis for the reactivity of these Abs with human B cells. We demonstrate that V_{H}4.34 IgG Abs target a developmentally regulated B220-specific glycoform of CD45, and more specifically, an N-linked NAL determinant preferentially expressed on naive B cells. Strikingly, our data also indicate that the reactivity of SLE sera with this CD45 glycoform is dependent on V_{H}4.34 Abs and can be eliminated by depleting these Abs. To the best of our knowledge, our results also represent the first quantitative analysis of the abundance of V_{H}4.34 Abs in the SLE IgG repertoire. Our findings indicate that V_{H}4.34 Abs constitute a large fraction (10–50%) of all IgG in active SLE patients. The implications of our results regarding the antigenic selection and possible pathogenic roles of these autoantibodies in SLE are discussed.

Materials and Methods

Human samples

Peripheral blood (PBL) and tonsil samples were obtained from healthy donors, according to protocols approved by the University of Rochester Medical Center (URMC) Institutional Review Board. Tonsils were obtained as excess tissue from elective tonsillectomies from otherwise healthy patients aged 2–10 years. Only PBL was obtained from SLE patients. Patients were randomly selected from the URMC Lymph Clinic on the basis of their willingness to participate in the study if they had a clinical diagnosis of SLE, fulfilled ≥4 American College of Rheumatology criteria for the classification of SLE (30, 31), and had been only treated with antimalarials and/or low-dose prednisone (<10 mg/day) for at least 4 wk previous to venipuncture. Patients were classified as having nephritis based on the presence of an active urinary sediment, proteinuria >1000 mg/24 h, and/or a history of nephritis documented by kidney biopsy.

ELISA for detection of serum V_{H}4.34-encoded Abs

ELISA plates (Nunc, Naperville, CA) were coated with V_{H}4.34-specific anti-idiotypic mAb 9G4 (kindly provided by F. Stevenson, Tenevus Research Laboratories, Southampton, U.K.), or its isotype control (rat IgG2a; Sigma-Aldrich, St. Louis, MO), at 2 μg/ml and incubated for 1 h at 37°C (32). Plates were blocked with 2% nonfat dry milk/2% BSA for 1 h at 37°C, and then washed with 0.1% Tween 20 in PBS. Sera were serially diluted in HBSS (Life Technologies, Carlsbad, CA) and incubated for 30 min at 37°C. Plates were washed, then incubated with alkaline phosphatase-conjugated goat anti-human IgG (1:2000 dilution; BioSource International, Camarillo, CA) at 37°C for 1 h. After washing, plates were developed using the pNPP substrate system (Kirkegaard & Perry Laboratories, Gaithersburg, MD), according to manufacturer’s instructions, and OD at 405 nm was read on a microplate reader (model 3550-UV; Bio-Rad, Hercules, CA). Serum concentrations were determined using a V_{H}4.34 IgG standard represented by a V_{H}4.34 IgG mAb established in our laboratory by EBV immortalization of SLE PBL B cells. V_{H}4.34 IgG levels were corrected with respect to total serum IgG for all samples analyzed. The amount of total IgG in serum samples was determined by isotype-specific capture ELISA using goat anti-human IgG (5 μg/ml; Kirkegaard & Perry Laboratories) as the coating Ab and a human IgG standard (Sigma-Aldrich, St. Louis, MO) for quantitation.

B cell isolation

All protocols were conducted, as previously described, in our laboratory (24). Brieﬂy, mononuclear cells were isolated from heparinized peripheral blood (PBL) by gradient centrifugation at 4°C using Ficoll-Paque (Amer sham Pharmacia Biotech, Uppsala, Sweden). PBL B cells were obtained through magnetic positive selection using CD19 microbeads (MACS; Miltenyi Biotec, Auburn, CA) with a final purity of ≥98% CD19^+ as determined by FACS. Tonsillar cell suspensions were generated by mincing tissue in RPMI 1640 medium containing 10% FBS (Life Technologies), followed by one round of T cell depletion using 2-aminooethylisothiouronium bromide-SRBC (Colorado Serum, Denver, CO) and Ficoll-Paque centrifugation. The resulting cells (>97–99% CD19^+) were used directly for phenotypic analysis via flow cytometry.

Naive and Memory B cell isolation

For naive cell purification, 10^8 tonsillar B cells were labeled with anti-CD19 antibodies for 30 min at 4°C. After removing nonlabeled cells (either by washing three times in staining buffer (1× PBS, 1% BSA), cells were resuspended in degassed binding buffer (1× PBS, 2 mM EDTA, 0.5% BSA), incubated for 15 min at 4°C with anti-PE microbeads, and then negatively selected using an anti-CD27 MACS column (Miltenyi Biotec). When necessary, fractions were run over a second column to achieve >98% purity. The CD27^+ fraction thus obtained was labeled with IgD^+ FITC, washed, incubated with anti-FITC microbeads, and passed over a MACS column for positive selection. To obtain memory B cells, fractions were initially depleted of IgD^+ cells, followed by magnetic positive selection for CD27^−, as described above. The purity of the naive and memory fractions was verified by FACS.

Multiparameter FACS analysis

Single cell suspensions (10^6/sample) were labeled at 4°C for 30 min with predetermined optimal concentrations of fluorophore-conjugated mAbs, and pair-matched isotype controls, in combinations outlined in each figure legend. The following Abs were used: anti-CD19 allophycocyanin (SJ25C1), anti-CD27 PE (L128), streptavidin-PerCP, and rat IgG2a FITC (isotype control for 9G4) (BD Biosciences, San Diego, CA). V_{H}4.34 Abs were detected with the rat anti-idiotypic mAb 9G4. Control V_{H}^3 Abs were incubated with the avian anti-idiotypic mAb LI26 (kindly provided by G. Silverman, University of California at San Diego, La Jolla, CA) (33). For indirect staining, cells were washed three times in staining buffer after incubation with secondary Abs. All samples were analyzed via a FACS Calibur flow cytometer using CellQuest software (BD Biosciences). In total, 50,000–100,000 events, gated for live B cells based on forward and side scattering, were collected for each sample. Statistical significance was assessed using nonparametric Mann-Whitney U test with the GraphPad Prism software (GraphPad, San Diego, CA).

Detection of V_{H}4.34 Ab binding to B cells in vitro

Tonsillar B cells were incubated in heat-inactivated sera at 4°C for 30 min. Cells were washed three times in staining buffer, labeled with appropriate fluorophore-conjugated mAbs (isotype-matched controls), and analyzed via FACS. For blocking experiments, sera were preincubated with 50 μg of unlabelled 9G4 or (rg)2g2a, isotype control for 60 min at 4°C with constant rocking before binding reactions.

V_{H}4.34 Ig depletion and purification by affinity chromatography

SLE sera were fractionated by ammonium sulfate (AmSO4) precipitation, dialyzed, and applied to an affinity column of either agarose-9G4 or agarose-rg2g2a isotype control (Aminolink Immobilization Kit; Pierce-Endogen, Rockford, IL). After washing extensively with PBS, bound V_{H}4.34 Ig was eluted in 0.1 M glycine (pH 2.7). Positive fractions, as determined by absorbance at 280 nm, were pooled, neutralized with 1 M Tris (pH 9.5), and dialyzed against 1× PBS. V_{H}4.34-specific binding of depleted sera and eluates was determined by incubation and FACS, as previously described.

Immunoprecipitation of CD45

Purified B cell fractions (5 × 10^7 cells/ml) were lysed at room temperature with occasional vortexing in mammalian protection reaction extract reagent buffer (Pierce-Endogen) supplemented with 150 mM NaCl, 0.1 mM PMSF, and protease inhibitors (Sigma-Aldrich). Extracts were then cleared by ultracentrifugation. Lysates (1 × 10^7 cells/reaction) were precleared with protein A/G-Sepharose (Pierce-Endogen), then incubated with either anti-CD45/leukocyte common Ag (LCA) (F10-89-4), anti-CD45RA (F8-11), anti-CD45RB/B220 (RA3-6B2; e Bioscience, San Diego, CA). V_{H}4.34 Abs were detected with the appropriate dilutions of whole sera (either SLE derived or healthy control) or 9G4 affinity column-purified V_{H}4.34 Ab fractions, followed by goat anti-human IgG HRP (Sigma-Aldrich). Blots were developed using an ECL Plus detection kit (Amersham Pharmacia Biotech) for autoradiography with BIOMAX film (Eastman Kodak, Rochester, NY), according to the manufacturers’ instructions. Alternatively, precleared lysates were incubated with either whole sera, V_{H}4.34-depleted sera, or 9G4 affinity column eluates for 2 h at 4°C. Protein A/G-Sepharose was added,
and the incubation continued for 18 h. Immune complexes were resolved and blotted, as described above. Blots were probed with either anti-CD45/LCA or anti-CD45R/B220, followed by anti-mouse IgG HRP or anti-rat IgG HRP (Southern Biotechnology Associates), respectively, and developed, as previously described.

**Glycosidase treatment**

Immunoprecipitated CD45R/B220 was eluted from protein A/G beads under denaturing conditions (0.1% SDS, 0.5% 2-ME) by heating at 100°C for 3 min, then digested with either endo-β-galactosidase (Sigma-Aldrich), N-glycanase, O-glycanase, or neuraminidase (Glyko, Novato, CA) alone, or in combination, according to the manufacturer’s instructions. Deglycosylated and control samples (minus enzyme) were resolved by SDS-PAGE on 7% gels and transferred by electroblotting to nitrocellulose membrane. Immuno blotting with purified SLE VH4.34 Abs was performed, as previously described. Blots were probed with anti-CD45/LCA mAb in parallel to verify glycosidic digestion.

**Results**

**Identification of IgG V_H4.34 Abs in SLE sera**

Serum levels of VH4.34 Abs (whether IgM or IgG) have been consistently characterized in several reports as very low to undetectable in normal donors (23, 25–28). In contrast, elevated serum levels of IgG VH4.34 Abs have been highly associated with global disease activity in patients with SLE and with the presence of lupus nephritis and neuropsychiatric lupus (26–28). Therefore, we first sought to identify patients with elevated serum VH4.34 IgG Ab levels using 9G4 in a capture ELISA. Of 22 SLE patients analyzed, 16 subjects (72%) had significantly elevated Ab titers (defined as values greater than 3 SD over the mean observed in healthy sera). Consistent with previous studies, healthy controls had very low levels of serum IgG VH4.34 Abs (Fig. 1). We then classified the SLE patients into high and low VH4.34 IgG Ab cohorts (SLE_high and SLE_low, respectively) using an arbitrary cutoff point of 0.5 mg/ml, which represented a 4-fold increase over the normal mean. By this definition, 12 patients (55%) belonged in the SLE_high cohort and 10 patients in the SLE_low cohort (Fig. 1A). To assess the relative contribution of VH4.34 Abs to the SLE IgG Ab repertoire, we also determined the ratio of VH4.34 IgG to total IgG. As shown in Fig. 1B, the same 16 patients classified as having significantly elevated total levels of IgG VH4.34 Abs were also identified as having relatively increased values of IgG VH4.34 Abs (again defined as >3 SD over the normal mean). Of note, VH4.34 Abs contributed a remarkably high fraction (9–45%) of total IgG in SLE_high patients.

Consistent with published observations, only one-third of VH4.34 VH4.34 Abs (5 of 12) also expressed elevated levels of serum IgM VH4.34 Abs (data not shown) (27). Also in keeping with previous reports, this group had significantly higher anti-dsDNA titers (detected by ELISA, p = 0.02), and lower C3 levels (p = 0.006) than the VH4.34 VH4.34 Abs (data not shown). High serum VH4.34 Ab levels also correlated with the presence of nephritis (10 of 12 and 0 of 8, respectively, p = 0.0001). As shown in Table I, SLE_high patients were also characterized by significant lymphopenia affecting the naive B cell subset.

**SLE VH4.34 Abs preferentially bind autologous naive B cells in vivo**

We have previously shown that in normal subjects, VH4.34 B cells represent up to 10% of all naive B cells, but only ~1% of memory B cells (24). Therefore, it is rather remarkable that in VH4.34 VH4.34 SLE patients, a large fraction of their naive B cells (mean percentage ± SD: 63.3 ± 39.8) stains positive for the VH4.34 VH4.34-specific 9G4 Ab when analyzed by FACS directly ex vivo (Fig. 2A and Table II). In contrast, a significantly smaller fraction (9.6 ± 8.1%) of memory B cells was 9G4 positive in these patients. The corresponding values observed in our VH4.34 VH4.34 cohort were indistinguishable from healthy controls, as determined in this study and in our previous studies (Table II) (24). As opposed to VH4.34 VH4.34 cells, no significant differences in the relative frequency of control B cells expressing VH3 VH3-encoded Abs were observed between the different cohorts. To determine whether these results reflected the presence of an unlikely high number of VH4.34 B cells in the SLE repertoire or rather diverse B cells painted by absorbed serum VH4.34 Abs, we repeated the 9G4-staining experiments after extensive washing in PBS, followed by incubation in complement-inactivated FCS at 37°C for 60 min, a protocol previously used by others to elute cytotoxic Abs (27, 35). After elution, the number of naive B cells that stained positive with 9G4 returned to values close to those observed in healthy donors and in VH4.34 VH4.34 patients (Fig. 2). These results indicate that in VH4.34 VH4.34 SLE patients, the vast majority of 9G4+ naive B cells represent cells bearing exogenously bound VH4.34 Abs.

**SLE VH4.34 Abs preferentially bind healthy naive B cells in vitro**

Ex vivo studies were expanded by determining the ability of SLE-derived VH4.34 Abs to stain normal tonsil B cells in vitro (Fig. 3). Thus, incubation with VH4.34 VH4.34 sera resulted in the staining of a very large percentage of naive B cells (72.0 ± 15.6%) as compared with VH4.34 VH4.34 low sera (13.8 ± 4.9%) or normal sera (7.8 ± 1.2%). Binding was concentration dependent as serum dilution gradually eliminated reactivity of VH4.34 VH4.34 sera (data not shown). In contrast, incubation with VH4.34 VH4.34 low produced only a modest staining of memory B cells as compared with VH4.34 VH4.34 high or normal sera (10.0 ± 2.7, 2.0 ± 0.8, and 1.2 ± 0.5%, respectively). It should be noted that preincubation of target B cells

![FIGURE 1. Determination of serum levels of VH4.34 IgG Abs. Serum samples were obtained from SLE patients and normal controls and assayed by capture ELISA using the VH4.34-specific 9G4 mAb. Results are presented as total levels of VH4.34 IgG (A) or as the relative level of VH4.34 IgG compared with total IgG (B). The values shown for each group represent the mean ± SD. Patients with total levels greater than 3 SD above the normal mean were classified as VH4.34 VH4.34 high, and the remainder SLE patients were classified as VH4.34 VH4.34 low. Four patients in the SLE VH4.34 high cohort had significantly increased total and relative levels of IgG VH4.34 Abs as compared with normal values (denoted with an asterisk).](http://www.jimmunol.org/)
with unlabeled 9G4 Ab completely blocked V_{H4.34} Ab binding in a dose-dependent fashion (data not shown). As opposed to V_{H4.34}, the relative frequency of B cells stained with anti-V_{H3} Abs was unaffected by incubation with any sera analyzed (Fig. 3, A–D, right panel). The later result strongly suggests that V_{H3} Abs expressed in SLE sera do not bind B cells and that in contrast, V_{H4.34} Abs seem to contribute the majority of anti-B cell Abs in SLE sera. To confirm that V_{H4.34} Abs were indeed responsible for the B cell binding observed, V_{H4.34} Abs were preabsorbed on 9G4 affinity columns before assaying for B cell binding. In each case, the V_{H4.34}-depleted fraction was devoid of binding activity, while the V_{H4.34}-enriched fraction recovered in the eluate possessed the same binding characteristics as the original sera (Fig. 4). In contrast, fractions absorbed on either rIgG2a (9G4 isotype control) or LJ26 (data not shown) columns showed no loss in binding activity (data not shown).

V_{H4–34} Abs bind specifically to an N-linked carbohydrate moiety of CD45R/B220, a unique glycoform of CD45

Previous studies have suggested that at least some V_{H4.34} mAbs may cross-react with an isoform of CD45 expressed on the surface of B cells (21). Albeit this reactivity was not formally demonstrated, the expression of NAL oligosaccharides in CD45 and the frequent presence of anti-CD45 autoantibodies in SLE sera lend credence to this hypothesis (9, 20, 22). To identify the antigenic target(s) of anti-B cell V_{H4.34} Abs, sera from SLE patients and healthy controls were initially examined by immunoblotting for reactivity to CD45 fractions purified from bulk tonsil B cell lysates by immunoprecipitation using LCA, a pan-CD45 mAb (Fig. 5A). From the control LCA lane, it is apparent that CD45 expression is unaffected by incubation with any sera analyzed (Fig. 3, A–D, right panel). V_{H4.34} Abs following precipitation by LCA was eliminated by prior extract depletion with either CD45RA or B220 (RA3-6B2) Abs (lanes 4 and 5, respectively), but not a CD45RO-restricted mAb that specifically recognizes the smaller 180-kDa isoform (lane 3). V_{H4.34} reactivity was also abolished if extracts were preabsorbed with LCA before precipitation with anti-CD45R/B220, thus confirming that the 220-kDa protein recognized represents a CD45R full-length isoform bearing the B220 epitope (lanes 6 and 7).

### Table 1. Peripheral blood B cell subsets in SLE and healthy controls

<table>
<thead>
<tr>
<th>PBL Source</th>
<th>Total Cell Count/μl</th>
<th>Relative Percentage of CD19⁺ B Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Naive IgD⁻ Memory</td>
<td>IgD⁺ Memory</td>
</tr>
<tr>
<td></td>
<td>Naive IgD⁺ Memory</td>
<td></td>
</tr>
<tr>
<td>SLE_{high} n = 12</td>
<td>12.7 ± 9.2[^a^]</td>
<td>9.1 ± 5.3</td>
</tr>
<tr>
<td>SLE_{low} n = 10</td>
<td>55.7 ± 28.4</td>
<td>11.5 ± 9.7</td>
</tr>
<tr>
<td>Normals n = 8</td>
<td>ND</td>
<td>3.2 ± 2.2</td>
</tr>
</tbody>
</table>

[^a^]: CD19⁺ PBL B cells were fractionated into naive (IgD⁺/CD27⁻) and memory (IgD⁺/CD27⁺ and IgD⁺/CD27⁺) via multiparameter FACS. For each group, the values shown represent the mean ± SD.

[^b^]: p = 0.003 between SLE_{high} and SLE_{low}.

[^c^]: p = 0.01 between SLE_{high} and SLE_{low}.

[^d^]: p < 0.05 between SLE_{high} and SLE_{low} or normals.

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**FIGURE 2.** Most naive 9G4⁺ B cells in SLE_{high} patients represent cells with bound V_{H4.34} Abs. Peripheral blood CD19⁺ B cells were purified from SLE patients and analyzed by FACS to determine the frequency of 9G4⁺ B cells in the naive and memory subsets. The experiments were conducted directly ex vivo (baseline) or after elution of exogenously acquired Abs. Representative examples obtained with SLE_{high} (A) and SLE_{low} (B) patients are shown.
We further investigated whether V\textsubscript{H} 4.34 Abs bound to different B cell fractions segregated according to their expression of B220 using a B220 glycoform-specific mAb, RA3-6B2 (37). As shown in Fig. 7, V\textsubscript{H} 4.34 Abs bind to >90% of B220\textsuperscript{+} naive B cells, whereas no significant staining of B220\textsuperscript{−} B cells was observed. However, V\textsubscript{H} 4.34 Abs only recognize a rather small fraction (\~10%) of B220\textsuperscript{+} memory B cells. Together, the above experiments strongly suggest that while V\textsubscript{H} 4.34 Abs recognize a full-length CD45R isoform that contains the B220 epitope, the determinant recognized by these Abs is distinct from B220 and is not expressed or exposed in memory B cells.

To further characterize the reactive ligand, CD45R/B220 fractions, immunoprecipitated from either naive or memory B cells, were deglycosylated, and the ability of VH 4.34 Abs to bind these modified fractions was examined via immunoblot. Although binding to naive samples was unaffected by O-glycosylation, reactivity was completely removed following digestion with N-glycanase, an enzyme, which releases N-linked sugars (Fig. 8A, lanes 5 and 3, respectively). Treatment with endo-β-galactosidase (an enzyme that specifically cleaves the β1–4 linkage of NAL) also abolished V\textsubscript{H} 4.34 recognition (lane 4). This is in accordance with previous reports of V\textsubscript{H} 4.34 Abs displaying sensitivity to endo-β-galactosidase (38). Removal of O-linked sugars with O-glycanase in naive B cells did not eliminate binding of V\textsubscript{H} 4.34 Abs, but resulted in a decreased molecular mass of the Ag recognized. This finding is consistent with the fact that multiple sites of O-linked glycosylation are encoded by exons A, B, and C present in the larger CD45RA isoform, and indicates that the epitope recognized by VH 4.34 Abs is not created by O-linked glycosylation (39). Interestingly, removal of sialic acid by neuraminidase treatment restored the ability of VH 4.34 Abs to recognize the 220-kDa CD45 isoform in memory B cells, and this reactivity was not altered by...
subsequent treatment with O-glycanase (Fig. 8C, lanes 1, 2, and 5). As it was the case for naive fractions, V_H 4.34 binding was completely eliminated by digestion with N-glycanase (Fig. 8C, lane 3).

Discussion

Anti-lymphocyte Abs are part of the autoantibody repertoire in patients with SLE. It had been previously established that at least some of these Abs are directed against O-linked carbohydrate determinants expressed by CD45 on T cells. It has also been shown that V_H 4.34 IgM Abs, whether mAbs derived from individuals or from patients with Wiskott-Aldrich syndrome or polyclonal Abs

FIGURE 4. Binding of SLE V_H 4.34 high sera to tonsil B cells is V_H 4.34 dependent. Purified tonsil B cells were incubated at 4°C for 30 min with V_H 4.34 high sera (A), V_H 4.34-depleted fractions (B), or 9G4 affinity-purified fractions (C). Staining and FACS analysis for V_H 4.34 detection were performed, as previously described in Fig. 3. In each case, histograms depict the frequency of 9G4 cells within the total population or each subset.

FIGURE 5. CD45 reactivity of serum IgG derived from SLE patients. A, CD45 was purified from total tonsil B cells by immunoprecipitation with LCA (a human pan-CD45 mAb), and blotted with SLE V_H 4.34 high (4 patients), SLE V_H 4.34 low (2 patients), or healthy control sera (3 subjects), followed by anti-human IgG-HRP. The LCA lane demonstrates probing of CD45 precipitates with LCA. For B, proteins precipitated with AmSO_4-fractionated sera were immunoblotted with LCA. Sera derived from the same patients were used for both A and B.

FIGURE 6. Binding of SLE Abs to CD45R/B220 is due to the presence of V_H 4.34 Abs. A, Total B cell lysates were precipitated with V_H 4.34 high sera (lane 1), AmSO_4-fractionated V_H 4.34 high (lane 2), and the following fractions derived from V_H 4.34 high sera: rIgG2a affinity column (9G4 isotype)-purified (lane 3), rIgG2a column-depleted (lane 4), 9G4 affinity column-purified (lane 5), and 9G4 column-depleted V_H 4.34 high (lane 6), or LCA (lane 7). Samples were separated via SDS-PAGE and probed with LCA. For B, total B cell lysates were precipitated with either a mouse IgG CD45 isotype control (lane 1), LCA (lane 2), LCA following preadsorption of cell extracts with either CD45RO (lane 3), CD45RA (lane 4), or CD45R/B220 (lane 5), CD45R/B220 (lane 6), and CD45R/B220 following preadsorption with LCA (lane 7). Samples were separated as described and probed with the V_H 4.34 Ab fraction recovered from V_H 4.34 high patient 2, followed by anti-human IgG Abs. Lane 8, Positive control for CD45. The weaker intensity of the bands in lanes 2 and 3, as compared with lanes 6 and 8, most likely reflects the relative abundance of the B220 isoform precipitated by the pan-CD45 LCA Ab and the B220-specific RA3-6B2 Ab, respectively.
obtained from SLE sera, frequently possess anti-lymphocyte reactivity (13, 14, 21, 27, 38). In SLE, in which $V_{\gamma}^{4.34}$ Abs are specifically and substantially expanded, these Abs are capable of binding autologous B cells in vivo (27). Our results confirm and expand such observations and demonstrate that SLE $V_{\gamma}^{4.34}$ Abs preferentially target naive B cells defined by a conventional CD19$^+$, CD27$^-$, IgD$^+$ surface phenotype (40, 41). This result is consistent with the observation that $V_{\gamma}^{4.34}$ IgM mAbs preferentially recognize IgD$^+$ follicular mantle B cells (13). In our studies, both autologous SLE peripheral blood naive B cells and heterologous healthy tonsil naive B cells were equally targeted by these Abs.

This is the first conclusive identification of the antigenic target of anti-lymphocyte $V_{\gamma}^{4.34}$ Abs and provides a molecular explanation for their preferential recognition of naive B cells. Previous work had suggested that these Abs might recognize a B cell-restricted isoform of CD45. Such suggestion was based on the observation that B cell binding paralleled the anti-i reactivity typical of IgM $V_{\gamma}^{4.34}$ Abs and could be abolished by endo-$\beta$-galactosidase, a treatment that degrades the NAL units present in CD45 (13, 14, 20, 22, 27). Yet, the final proof remained elusive as the mAbs used failed to immunoprecipitate this molecule. Using polyclonal SLE $V_{\gamma}^{4.34}$ Abs, however, we were able to consistently immunoprecipitate a 220-kDa CD45 species from naive B cells and demonstrate that IgG $V_{\gamma}^{4.34}$ Abs strongly bind this antigenic target. Enzymatic treatments designed to modify glycosylation of surface glycoproteins indicate that the differential recognition of CD45 220 kDa in naive vs memory B cells is dependent on the presence in the former cell subset of a CD45 220-kDa glycoform containing an N-linked carbohydrate moiety that is masked in memory B cells by the developmentally regulated addition of sialic acid residues (42–44). The chemical nature of the determinant recognized and the fact that 9G4 mAbs block this interaction confirm that the structure recognized is an N-linked carbohydrate epitope structurally similar to the NAL determinant of the i Ag.

CD45 is expressed as a complex set of several isoforms ranging in size from 180 to 220 kDa, which are generated by alternative splicing of exons A, B, and C. Human and murine mature T cells express different CD45 isoforms in a pattern that depends on function, differentiation state, and previous antigenic engagement. Thus, naive T cells express the higher molecular mass isoforms containing the A exon (CD45RA, 205–220 kDa), whereas activated memory T cells express the smaller 180-kDa CD45RO isoform, which contains none of the A, B, and C exons (45). CD45/B220 represents a CD45R full-length isoform containing the A, B, and C exons and is specifically defined by the RA3-6B2 Ab (43, 44). Although the majority of murine B cells express B220, this molecule had been previously thought not to be present on human B cells. This notion, however, has been corrected by a report published during the preparation of this manuscript in which the authors demonstrate that B220 is actually expressed by the majority of human naive B cells and that its expression is down-regulated on CD27$^+$ memory B cells (46). In this study, we confirm this report and show that CD45/B220 is expressed in >90% of all human naive B cells, but in only ~20% of memory B cells. Furthermore, we show that while $V_{\gamma}^{4.34}$ Abs bind all B220$^+$ naive B cells, they only bind ~10% of B220$^+$ memory B cells. Together, we postulate that a B220 glycoform is recognized by $V_{\gamma}^{4.34}$ Abs present in high abundance in SLE sera and that the corresponding epitope is sterically masked by sialylated carbohydrate chains (43, 44).

Our data also show that while SLE sera contain a diversity of anti-lymphocyte and anti-CD45 Abs, anti-CD45R/B220 Abs are essentially restricted to the $V_{\gamma}^{4.34}$ Ab fraction. This finding indicates that the remarkable $V_{\gamma}^{4.34}$ restriction of the anti-i/i
response is maintained in SLE and suggests that this Ag or similar Ags may play a significant role in the activation and/or selection of a large fraction of the autoimmune IgG Ab repertoire in SLE (18, 19). The pathophysiological significance and the pathogenic implications of this observation are underscored by the magnitude of the V_{\text{H}4.34} serum Ab levels illustrated in this study. Indeed, our data provide a first quantitative appraisal of the magnitude of the V_{\text{H}4.34} IgG Ab response in SLE. As shown in Fig. 1, V_{\text{H}4.34} Abs contributed up to 45% of total serum IgG (mean, 21%; range, 9–45%) in SLE^{\text{naive}} patients (representing >50% of all SLE patients analyzed and a large majority of active patients). Along these lines, it is noteworthy that the V_{\text{H}4.34} Ab may be expressed in oxidized apoptotic cells and that B220 is expressed by preapoptotic T cells (43, 47, 48). These findings may explain our observation that V_{\text{H}4.34} Abs (both monclonal and polyclonal) bind apoptotic cells (49). Given the proposed role of autoantigen-bearing apoptotic cells in the pathogenesis of SLE, it is tempting to speculate that apoptotic bodies could contribute to the expansion of V_{\text{H}4.34} B cells in this disease (50, 51).

At least a subset of V_{\text{H}4.34} Abs may also bind DNA, and serum V_{\text{H}4.34} Abs have been shown to make up a substantial fraction of anti-dsDNA Abs in patients with SLE (52). Therefore, it is apparent that V_{\text{H}4.34} Abs could play a role in the disease process through their participation in this pathogenic Ab response (53). However, it is also plausible that V_{\text{H}4.34} Abs could exert a pathogenic role through anti-CD45 effects either by enhancing or damping CD45 activity. Indeed, CD45 is a transmembrane phosphotyrosine phosphatase (PTPase) with the ability to modulate Ag receptor-mediated B and T cell responses both positively and negatively through its conventional PTPase activity and a recently described Janus kinase phosphatase activity (54). It has been proposed that the activity of CD45 may be dependent on the balance between monomeric and dimeric forms because dimerization results in inhibition of the PTPase activity of the CD45 cytoplasmic domain and negative regulation of Ag receptor signaling. In turn, the interaction between the extracellular domains of the different CD45 isoforms may determine the extent of homodimerization with the larger isoforms such as B220 being less prone to dimerize (55). It is therefore conceivable that anti-CD45 Abs could interfere with the dimerization process and consequently enhance CD45 function. As demonstrated by the wedge mutation model, unabated CD45 activity may result in polyclonal T and B cell activation and severe autoimmune nephritis with autoantibody production (56, 57).

The reactivity of V_{\text{H}4.34} Abs and the correlation with lower naive B cell levels described in this work (Table II) suggest that these Abs could also contribute to the naive B cell lymphopenia observed in patients with active SLE (34). Naive lymphopenia could be induced by V_{\text{H}4.34} Abs whether through their reported lymphocytotoxic activity or by alternative mechanisms (38, 60). Thus, while costimulatory signaling through the Ag receptor and CD45, in particular B220, is essential both for B cell activation and proliferation, ligation of CD45 alone promotes apoptosis of both T and B lymphocytes (61–64).Therefore, V_{\text{H}4.34} Abs could induce apoptosis of virgin naive B cells upon ligation of CD45 alone while promoting activation and expansion of autoreactive naive B cells actively costimulated by self Ag through the B cell receptor. In turn, lymphocyte apoptosis induced by V_{\text{H}4.34} Abs would contribute to the availability of exposed intracellular autoantigens that could in turn amplify the autoimmune response possibly through the induction of IFN-α production by PBMC. This mechanism would be consistent with the recently reported ability of lupus IgG-apoptotic cell complexes to activate IFN-α-producing cells, a phenomenon that could bear significant pathogenic potential in SLE, and the ability of IFN-α to induce B cell lymphopenia (51, 65–67). It is also plausible that anti-CD45 V_{\text{H}4.34} Abs could contribute to naive lymphopenia by inducing naïve B cell differentiation and isotype switch, as previously postulated by others on the basis of in vitro experiments (21, 68). This mechanism could also help explain the expansion of peripheral blood plasmablasts observed in patients with active SLE (34, 69).

Additional studies, currently underway in our laboratory, will be required to dissect the mechanisms and the actual consequences of the overexpression of V_{\text{H}4.34} Abs in SLE.

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**FIGURE 8.** The ligand bound by V_{\text{H}4.34} Abs is an N-linked carbohydrate moiety of CD45R/B220. CD45R/B220 was precipitated using the RA3-6B2 mAb from either naive (A and B) or memory (C) B cells, deglycosylated, subjected to SDS-PAGE, then probed with either V_{\text{H}4.34} Abs (A and C) or CD45/LCA (B) to verify digestion. For naive samples, the following digests were performed: no enzyme control (lane 1), neuraminidase (lane 2), N-glycanase (lane 3), endo-β-galactosidase (lane 4), O-glycanase (lane 5), neuraminidase, then O-glycanase (lane 6). For memory fractions: no enzyme control (lane 1), neuraminidase (lane 2), N-glycanase (lane 3), O-glycanase (lane 4), neuraminidase, then O-glycanase (lane 5).
References


