A SINGLE AMINO ACID SUBSTITUTION IN THE HUMAN
HISTOCOMPATIBILITY LEUKOCYTE ANTIGEN DR3
β CHAIN SELECTIVELY ALTERS ANTIGEN PRESENTATION

BY ELIZABETH MELLINS,* BENJAMIN ARP,* BARBARA OCHS,*
HENRY ERLICH,4 AND DONALD PIOUS*1

FROM THE DEPARTMENTS OF *PEDiatrics AND 4GENETICS, UNIVERSITY OF WASHINGTON, SEATTLE, WASHINGTON 98195; AND THE 4CETUS CORPORATION, EMERYVILLE, CALIFORNIA 94608

Activation of antigen-specific helper/inducer T cells requires that antigen be presented by APC in association with self MHC class II molecules (1). Recent evidence indicates that APC accomplish this by degrading exogenous soluble proteins to peptide fragments, which become bound to class II molecules (2, 3). The amino acid residues of human class II molecules that interact with immunogenic peptides, with the TCR or with accessory molecules such as CD4, are for the most part unknown. As an approach to mapping such residues, we are studying structure-function relationships in immunoselected mutant B lymphoblastoid cell lines (B-LCLs)1 that express altered HLA-DR3 molecules. B-LCLs present soluble antigens to antigen-specific, HLA class II-restricted T cells (4), making it possible to assay the functional effects of mutational alterations in class II molecules. Mutational analysis has proved useful for mapping serologic epitopes and T cell restriction sites on human class I molecules (5) and murine class I and II molecules (5, 6). However, single amino acid substitutions that affect antigen presentation in human cells have not previously been reported.

To generate class I mutants in a human APC line, we mutagenized an HLA-DR3-expressing B-LCL with ethyl methane sulfonate. To simplify the analysis, we used as the progenitor line 8.1.6, a deletion mutant that lacks all DR and DQ genes of one haplotype, but expresses the class II loci of the other haplotype, DR3, normally (referred to in reference 6a). Immunoselection of mutagenized 8.1.6 with an anti-DR3-specific mAb, 16.23, yielded several types of mutants (7). Here, we describe one immunoselected mutant, 7.13.6, that expresses a structurally altered DR3 molecule and has a selective loss in DR3-restricted antigen presentation compared with its progenitor, 8.1.6. The mutation 7.13.6 maps to the first hypervariable region of the DR3 β chain.

MATERIALS AND METHODS

APC LINES. With the exception of mutant clones 7.13.6 and 7.25.6, the B-LCLs have been reported. 8.1.6 is derived from T5-1 progenitor line (7); 9.22.3 is a homozygous DRα dele-
AN AMINO ACID SUBSTITUTION ALTERS ANTIGEN PRESENTATION

tion mutant derived from 8.1.6 (6a); 9.4.3 is an 8.1.6-derived mutant that lacks DRβ chain mRNA (7); 6.1.6 is a class II-negative regulatory mutant derived from T5-1 (7). 7.13.6 and 7.25.6 are DR3 mutants isolated by a described protocol (7). Mutant 7.25.6 expresses a DRβ chain with a more acidic isoelectric point (pI) than that of 8.1.6 (not shown). 7.25.6 binds 45 ± 4% of 8.1.6 levels of anti-DR mAb VI.15, 35 ± 4% of anti-DR3 mAb 16.23, and 48 ± 6% of anti-DR3 mAb CD6B1.

**Two-dimensional Gel Analysis.** ^35^S-labeled DR molecules were immunoprecipitated with anti-DR mAb VI.15 (7). Immunoprecipitates, with or without prior digestion with Endo F, were subjected to electrophoresis on two-dimensional (2-D) gels, as described (Cotner, T., submitted for publication).

**Radioimmune Binding Assays.** For binding assays, mAbs 16.23, anti-DR3 specific (8); CD6B1, anti-DR3 specific (9); 7.3.19, anti-DRβ52 specific (10); VI.15, anti-DR monomorphic (7) were used. Cells were assayed with saturating amounts of mAb and ^125^I protein A or ^125^I-rat anti-mouse κ chain as a second reagent, as described (7).

**T Cell Proliferation Assays.** Human T cell lines specific for soluble protein antigen were generated as described (4). Antigens tetanus toxoid (TT), PPD, and *Candida albicans* extract were used as described (4); recombinant hepatitis B surface antigen (HBsAg), the generous gift of Merck Sharp & Dohme (West Point, PA) was used at 10 μg/ml. T cell clones (ND-PPD1, ND-PPD2, CT-TT, BJ-HBsAg) are designated by donor-antigen and were obtained by limiting dilution cloning in the presence of antigen, exogenous IL-2, and irradiated PBMC as APC. ND-PPD1 and ND-PPD2 are PPD-specific clones with different reactivity patterns; they are likely to recognize different peptides derived from PPD, which is a mixture of proteins. 1.5 × 10^6^ T cell blasts were cocultured with 10^5^ mitomycin C-treated B-LCLs as APC in the presence or absence of soluble antigen; stimulation was measured by the incorporation of ^3H^thymidine into DNA, as described (4).

**Polymerase Chain Reaction (PCR) Amplification and Sequence Analysis.** cDNAs prepared from poly(A)^+^ RNA from 8.1.6 and 7.13.6 were size selected (>0.7 kb) on an agarose gel and subjected to PCR amplification using Taq I polymerase (11). DRα primers were selected based on published sequences (12). DRβ primers were selected based on the sequence of a DR3β clone from 8.1.6 (B. Arp, unpublished results). All primer sequences are available on request. Size-selected double-stranded PCR DNA was subjected to dideoxy sequencing using modified T7 DNA polymerase (Sequenase, U.S. Biochemical Corp., Cleveland, OH). The PCR primers and additional oligonucleotide primers covering 21 bp segments of the coding regions were used to generate overlapping 100–250 base segments of sequence information.

**Results and Discussion**

We initially analyzed DR molecules from mutant 7.13.6 and its progenitor 8.1.6, by 2-D SDS-PAGE electrophoresis (Fig. 1). 8.1.6, like other cells bearing the DR3 haplotype, expresses a single DRα chain and two DRβ chains, βi and βIII, each of which forms a heterodimer with DRα. Comparison of the 7.13.6 and 8.1.6 2-D gel patterns reveals that mutant 7.13.6 expresses an altered DRβ chain, whose pI is two charges more basic than that of 8.1.6 (see Fig. 1, legend).

To evaluate the level of cell surface expression of the mutant DR3 molecule expressed by 7.13.6, we compared cell surface binding with 7.13.6 and 8.1.6 by a panel of four mAbs that bind to DR3 molecules (Table I). On the basis of their different fine specificities (see Materials and Methods) and inability to crossinhibit each other (not shown), these antibodies are likely to react with distinct epitopes on DR3 molecules. At antibody concentrations that are saturating for 8.1.6, the binding of each antibody to 7.13.6 is moderately reduced (40–70%) from 8.1.6 levels. For both the DR3-specific mAb 16.23 and the monomorphic anti-DR mAb VI.15, binding to 7.13.6 saturates at 50% of the concentration required to saturate 8.1.6 (not shown). These data suggest that the mutant molecules in 7.13.6 are expressed in decreased
FIGURE 1. (A) 2-D SDS-PAGE analysis of Endo F-treated HLA-DR molecules from parent line 8.1.6 and mutant 7.13.6. The designations of 8.1.6 β chains as βⅠ and βⅢ are based on comparisons of limited NH2-terminal amino acid sequencing with the published DR3βⅠ and βⅢ gene sequences (14 and T. Cotner, unpublished results). In both 7.13.6 and 8.1.6 gels, the βⅠ spot is more abundant than the βⅢ spot; the βⅠ spots are also marked by a weaker spot of the same pI but lower molecular weight, which most likely represents a proteolytic breakdown product. In the 8.1.6 gel, the βⅠ spot obscures the more basic βⅢ spot. To compare the 7.13.6 and 8.1.6 patterns, the β chain spots are aligned by the βⅢ spots, which cofocus in the 8.1.6/7.13.6 mixture. The different positions of the DRα spots in the different gels are due to differential stretching of the gels. However, the 8.1.6/7.13.6 mixture, being internally controlled for stretching, demonstrates that the DRα species from 7.13.6 cofocuses with that of 8.1.6, whereas the 7.13.6 βⅠ chain is more basic than that of 8.1.6, α, parental; m, mutant. (B) 2-D SDS-PAGE analysis of non-Endo F-treated HLA-DR molecules from 8.1.6 and 7.13.6. The βⅠ chain pattern from 8.1.6 includes the prominent, nonsialated βⅠ spot and a more acidic glycosylation ladder consisting of three spots of increasing acidity. A fifth spot, the nonsialated βⅢ chain, is visualized to the basic side of the βⅠ spot; its glycosylation ladder is obscured by the βⅠ spots. In 7.13.6, the nonsialated βⅠ chain and its glycosylation ladder are shifted to the basic side (relative to 8.1.6) and overlap the βⅢ spots. In the 8.1.6/7.13.6 mixture the nonsialated βⅠ chain of 7.13.6 and a single glycosylation intermediate are visualized on the basic side of the nonsialated 8.1.6 βⅠ chain. Because each sialation contributes 1 acidic charge, this pattern suggests that the 7.13.6 βⅠ chain has undergone a 2 charge basic shift in pI compared with 8.1.6.

amounts on the cell surface, possibly because the mutant βⅠ chains associate less efficiently than 8.1.6 βⅠ chains with the DRα chain.

To evaluate DR3-restricted antigen presentation in 7.13.6, we tested the ability of 7.13.6 to stimulate proliferation of antigen-specific DR3βⅠ-restricted T cells derived from normal DR3 donors. DR3βⅠ-restricted T cells were identified as cells that respond to antigen presentation by 8.1.6 but not by an 8.1.6-derived mutant that has lost DRβⅠ expression (mutant 9.4.3). As shown on Table II, mutant 7.13.6 is unable to stimulate ND-PPD1, a DR3βⅠ-restricted T cell clone specific for PPD. However, the mutant DR3 molecules of 7.13.6 function as effectively as those of 8.1.6 in stimulating a DR3βⅠ-restricted TT-specific clone CT-TT, a second DR3βⅠ-restricted PPD-specific clone, ND-PPD2, and DR3βⅠ-restricted T cells specific for
AN AMINO ACID SUBSTITUTION ALTERS ANTIGEN PRESENTATION

Table I

| Antibody | Cell line | CD6B1 | 7.3.19 | VI.15 |
|----------|-----------|-------|--------|-------|
| 8.1.6    | 100*      | 100   | 100    | 100   |
| 7.13.6   | 29 ± 4    | 45 ± 4| 66 ± 2 | 47 ± 6|

* Binding ratio is calculated as (cpm bound by mutant - cpm bound by negative control)/(cpm bound by 8.1.6 - cpm bound by negative control). Data represent medians ± SEM from four or more experiments. Negative control was the DR null mutant, 9.22.3. cpm bound by 9.22.3 ranged from 2 to 9% of cpm bound by 8.1.6.

C. albicans (JN-CA). Stimulation by 7.13.6 of a hepatitis B surface antigen-specific clone, which is restricted by non-DR-restricting elements (BJ-HBsAg) is also equivalent to 8.1.6 levels (Table II). These data indicate that the mutation in 7.13.6 specifically affects the presentation of PPD to clone ND-PPD1 and does not result in a generalized abnormality of antigen processing or presentation.

The 7.13.6 defect in stimulation of ND-PPD1 appears to result from the structural change in HLA-DR3 molecules rather than the change in the level of HLA-DR3 molecules on the cell surface based on the following observations. Doubling the number of 7.13.6 cells used as APC does not overcome the defect (data not shown). In addition, a different 8.1.6-derived DR3β1 structural gene mutant, 7.25.6, which, like 7.13.6, expresses ~50% of 8.1.6 levels of DR3 (see Materials and Methods), stimulates ND-PPD1 at a level equivalent to 8.1.6 (Table II). This indicates that reductions in HLA-DR3 expression of the magnitude seen in 7.25.6 and 7.13.6 do not of themselves result in reduced stimulation of ND-PPD2 T cells. These data, as well as the ability of 7.13.6 to stimulate other DRβ1-restricted T cells normally, suggest

Table II

| APC       | [3H]TdT incorporation | ND-PPD1 | ND-PPD2 | CT-TT | JN-CA | BJ-HBsAg |
|-----------|-----------------------|---------|---------|-------|-------|----------|
|           | cpm × 10⁻³             |         |         |       |       |          |
| 8.1.6     | 25.5                  | 14.1    | 5.5     | 28.2  | 61.7  |          |
| 7.13.6    | 0                     | 20.4    | 5.3     | 30.3  | 65.4  |          |
| 7.25.6    | 24.0                  | 18.4    | ND      | 34.7  | ND    |          |
| 9.4.3     | 0                     | 0       | 0       | 19.0  | ND    |          |
| 9.22.3    | 0                     | 0       | 0       | 2.6   | 62.0  |          |
| 6.1.6     | ND                    | ND      | ND      | 0     | 0.4   |          |

Data are net antigen-specific cpm from the median of triplicate assays from a representative experiment. SEM <10%. Relative responses (response to mutant / response to 8.1.6) were comparable (SEM < 10%) in 2-4 independent experiments.

* JN-CA is a polyclonal T cell line, specific for C. albicans; as shown, its response is primarily DR3 restricted when assayed with 8.1.6 as APC.
that the functional alteration in mutant 7.13.6 derives from the structural change in its DRβ1 chain.

To more precisely identify the structural basis for the cell surface antibody binding and functional changes observed in 7.13.6, we determined the site of the mutational lesion in its DRβ1 gene. We used the PCR to amplify the entire DRA and DRβ coding region of cDNAs from 7.13.6 and 8.1.6 and subjected the PCR products to dideoxy sequence analysis. The DRA gene from 7.13.6 is identical to that of 8.1.6 (data not shown). However, as shown on Fig. 2, the DRβ1 gene differs from that of 8.1.6 by a single base change, a guanine → adenine transition in the first nucleotide of the codon for amino acid 9. The mutation changes the encoded residue from glutamic acid to lysine which is consistent with the two charge basic shift in pI of the mutant β1 chain observed on 2-D gel analysis. Thus, it appears that a single amino acid change underlies the functional alterations in the 7.13.6 mutant. The location of this mutation in the NH2-terminal domain of β chain (the β1 domain) is not surprising; this domain contains most allelic variant amino acid positions in the HLA-DR molecule (13), and 7.13.6 was selected for altered reactivity with a DR3-specific antibody.

The evidence from mutant 7.13.6 implicates the first hypervariable region (amino acid positions 9–13) of the β1 domain of the DRβ1 chain as important for the stimulation of some DR3-restricted T cells. The third hypervariable region (62–78) is also involved in presentation of soluble antigens (6). Recently, a model of the binding domain of the class II molecule has been proposed, based on the crystal structure of HLA class I molecule A2 and on shared features of primary structure of class I and II molecules (6). In this model, the NH2-terminal portions of the α1 and β1 domains (including the first hypervariable region) are folded into β-pleated sheets and form the bottom of an antigen-binding cleft. The side chains of polymorphic residues 9, 11, and 13 of the first hypervariable region point into the antigen-binding site. The COOH-terminal portions of the α1 and β1 domains (including the third hypervariable region) are α helical structures that form the sides of the cleft. Side chains of some residues in the helices point out and are available for interaction with antibodies and TCRs. Position 9, which is altered in 7.13.6, is on the floor of the cleft in this model, but its side chain is also in close proximity to the presumed α-helical portion of the DRA chain. This model suggests at least three alternative mechanisms for the functional alteration in 7.13.6. The glutamic acid at position 9 in normal DR3 molecules may interact directly with an immunogenic peptide derived from PPD. Mutations at this site might therefore interfere with antigen binding. Alternatively, the substitution at this site may induce a local conformational change in the

8 9 10
Leu Glu Tyr

8.1.6 TTG GAG TAC
7.13.6 --- A-C ---
Leu Lys Tyr

Figure 2. The DRβ1 nucleotide coding sequence of 7.13.6. The numbers refer to the amino acid positions. 7.13.6 differs from 8.1.6 by a G → A transition in codon 9 of the β1 chain. Independent evidence verifying this result was obtained by amplifying and sequencing a segment of genomic DNA spanning the second exon of the DRβ1 genes of 7.13.6 and 8.1.6 (data not shown). The DRβ1 gene of the DRw9 specificity also has a lysine at position 9, but differs from mutant 7.13.6 at positions 10–13 (15).
AN AMINO ACID SUBSTITUTION ALTERS ANTIGEN PRESENTATION

α helix of the DRα chain affecting a contact residue for particular TCRs. Thirdly, the 7.13.6 mutation in the DRβ1 chain may perturb its interaction with the NH2-terminal region of the DRα chain, changing the tertiary structure of the mutant dimer. These changes might ablate either peptide binding or T cell recognition. Evidence obtained in binding studies of appropriate peptides to purified mutant DR3 molecules from 7.13.6 should help distinguish among these hypotheses.

Summary

Activation of T lymphocytes by immunogenic peptides bound to HLA molecules is a central event in the generation of an immune response. To determine the sites on HLA molecules involved in this process, we isolated mutant EBV-transformed B cell clones that express altered HLA-DR3 molecules. One mutant has lost the ability to stimulate a T cell clone specific for a mycobacterial protein, but retains the ability to stimulate other antigen-specific T cells. The DNA sequence of the complete DRα and β coding regions revealed a single nucleotide change resulting in a glutamic acid to lysine substitution at amino acid 9 in the first hypervariable region of the DRβ chain. These results are discussed in relation to a recently proposed model of class II molecule structure.

We thank R. Johnson for isolation of the 8.1.6 DRβ cDNA clone; S. Scharff for assistance in cloning a genomic DRβ1 second exon region; Dr. Y. Lee of the Howard Hughes Medical Institute, University of Washington, for PCR and sequencing primers; J. Johnson for the generous gift of mAb 16.23; Dr. D. Wiley for helpful discussions; Drs. T. Cotner and R. Perlmutter for review of the manuscript; D. Singh, C. Bozich, and L. Smith for technical assistance; and D. Hill for preparation of the manuscript.

Received for publication 10 June 1988 and in revised form 8 August 1988.

References

1. Benacerraf, B. 1981. Role of MHC gene products in immune regulation. Science (Wash. DC). 212:1299.
2. Shimonkevitz, R. J., J. W. Kappler, P. Marrack, and H. Grey. 1983. Antigen recognition by H-2-restricted T cells. I. Cell-free antigen processing. J. Exp. Med. 158:303.
3. Babbitt, B., P. Allen, G. Matsueda, E. Haber, and E. Unanue. 1985. Binding of immunogenic peptides to Ia histocompatibility molecules. Nature (Lond.). 317:359.
4. Mellins, E., D. Pious, and M. Woelfel. 1987. Importance of HLA-DQ and -DP restriction elements in T-cell responses to soluble antigens: Mutational analysis. Hum. Immunol. 18:211.
5. Bjorkman, P. J., M. A. Saper, B. Samraoui, W. S. Bennett, J. L. Strominger, and D. C. Wiley. 1987. The foreign antigen binding site and T cell recognition regions of class I histocompatibility antigens. Nature (Lond.). 329:512.
6. Brown, J., T. Jardetsky, M. Saper, B. Samraoui, P. Bjorkman, and D. Wiley. 1988. A hypothetical model of the foreign antigen binding site of class II histocompatibility molecules. Nature (Lond.). 332:845.
6a. Levine, F., H. Erlich, B. Mach, R. Leach, R. White, and D. Pious. 1985. Deletion mapping of HLA and chromosome 6p genes. Proc. Natl. Acad. Sci. USA. 82:3741.
7. Pious, D., L. Dixon, F. Levine, T. Cotner, and R. Johnson. 1985. HLA class II regulation and structure. Analysis with HLA-DR3 and HLA-DP point mutants. J. Exp. Med. 162:1193.
8. Johnson, J., T. Meo, G. Riethmüller, D. J. Schendel, and R. Wank. 1982. Direct demonstration of an HLA-DR allotypic determinant on the low molecular weight (β) subunit using a mouse monoclonal antibody specific for DR3. *J. Exp. Med.* 156:104.

9. Sachs, J. A., N. Fernandez, M. Kurpisz, R. Okoye, J. Ogilvie, J. Awad, M. Labeta, and H. Festenstein. 1986. Serological biochemical and functional characterization of three different HLA-DR monoclonal antibodies derived from C57BL6 mice. *Tissue Antigens.* 28:199.

10. Koning, F., I. Schreuder, M. Giphart, and H. Bruning. 1984. A mouse monoclonal antibody detecting a DR-related MT2-like specificity: serology and biochemistry. *Hum. Immunol.* 9:221.

11. Wong, C., D. Dowling, R. Saiki, R. Higuchi, H. Erlich, and H. Kazazian. 1987. Characterization of β-thalassemia mutations using direct genomic sequencing of amplified single copy DNA. *Nature (Lond.)* 330:384.

12. Schamboeck, A., A. Korman, A. Kamb, and J. Strominger. 1983. Organization of the transcriptional unit of a human class II histocompatibility antigen: HLA-DR heavy chain. *Nucleic Acids Res.* 11:8663.

13. Figueroa, F., and J. Klein. 1986. The evolution of MHC class II genes. *Immunol. Today.* 7:78.

14. Gorski, J., and B. Mach. 1986. Polymorphism of human Ia antigens: gene conversion between two DRβ loci results in a new HLA-D/DR specificity. *Nature (Lond.)* 322:67.

15. Bell, J. I., D. Denney, L. Foster, T. Belt, J. A. Todd, and H. O. McDevitt. 1987. Allelic variation in the DR subregion of the human major histocompatibility complex. *Proc. Natl. Acad. Sci. USA.* 84:6234.