HLA-DM Recognizes the Flexible Conformation of Major Histocompatibility Complex Class II

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Abstract

DM facilitates formation of high affinity complexes of peptide-major histocompatibility complex (MHC) by release of class II MHC-associated invariant chain peptide (CLIP). This has been proposed to occur through discrimination of complex stability. By probing kinetic and conformational intermediates of the wild-type and mutant human histocompatibility leukocyte antigen (HLA)-DR1–peptide complexes, and examining their reactivities with DM, we propose that DM interacts with the flexible hydrophobic pocket 1 of DR1 and converts the molecule into a conformation that is highly peptide receptive. A more rigid conformation, generated upon filling of pocket 1, is less susceptible to DM effects. Thus, DM edits peptide–MHC by recognition of the flexibility rather than stability of the complex.

Key words: antigen processing • molecular conformation • HLA-DR antigens • surface plasmon resonance • fluorometry

Introduction

HLA-DM or H2-M in mice, a nonclassical HLA molecule, has been shown to play a critical role in loading antigenic peptides to newly synthesized MHC class II molecules. The significance of DM function is exemplified by the finding that MHC class II molecules isolated from DM-negative cells were largely occupied with class II MHC-associated invariant chain peptide (CLIP) (1). Consequently, DR molecules isolated from these mutant cells were prone to SDS denaturation at room temperature (2). Since its discovery, several other functions have been attributed to DM, including stabilization of empty class II molecules (3, 4) and peptide editing for selection of peptides that form stable complexes with MHC class II (5) by an enzyme-like mechanism (6, 7). Nevertheless, although DM accelerates dissociation of some peptide–MHC complexes, other complexes remain resistant to DM-induced dissociation (5, 7–11). Furthermore, a chaperone-like function for DM has also been proposed (5). The crystal structures of HLA-DM (12) and H2-M (13) have been resolved and they do not exhibit a groove to accommodate a peptide. Thus, the mechanism of DM reactivity remains unsolved.

It is now established that conformational changes in the structure of MHC molecules are associated with peptide binding (14–21). Class II molecules that are empty or have lost their peptide are less rigid (floppy conformation) and migrate with a larger apparent molecular mass or fall apart on SDS-PAGE. Stable peptide–class II complexes migrate faster than the floppy conformation, indicating their more compact and rigid conformation (compact dimer [14–17, 22]). Recently, we demonstrated that the SDS stability of DR1 complexes correlates with the burial of hydrophobic residues in pocket 1. DR1 molecules in complex with peptides that lack anchor residue in corresponding pocket 1 form floppy conformations and fall apart in SDS gels (23). When a peptide like influenza virus hemagglutinin (HA) 306–318, which has a tyrosine anchor fitting in pocket 1, binds DR1, the complex becomes compact and resists SDS-induced denaturation (17, 24).

The rate-limiting step in formation of stable peptide–MHC complexes occurs in generation of a receptive class II conformation (19, 20). A receptive conformation is created when a resident peptide dissociates. At this time, a second peptide can bind class II almost spontaneously and stochiometrically (19, 20). This receptive molecule has a flexible conformation with a very short half-life. In the absence of any free peptide, this flexible molecule rapidly reverts to a “closed” conformation that binds slowly to the subsequently offered peptide (20). A mutant DR1, DR1 G86V, that remains permanently in receptive or “open” form was designed by introducing a single site-specific mutation.
β86G was changed to tyrosine presumably to fill pocket 1 and rescue the flexible pocket from collapsing (23, 24). Thus, the conformation of mutant DR1 partially resembles wild-type (wt)DR1 in complex with a peptide that has tyrosine as the main anchor. The molecule is rigid and open, and thus can bind and dissociate peptides efficiently.

In accord with these in vitro findings, the process of synthesis, maturation, and export of class II molecules through the endocytic pathway involves conformational changes in the structure of MHC (25, 26). A class II invariant chain peptide, CLIP, acts as a surrogate short-lived peptide for shaping of MHC class II (27). In peptide-loading compartments, CLIP dissociates, leaving a receptive groove “open” for efficient peptide binding. Similar to empty soluble DR1 molecules that aggregate in the absence of peptides (22), class II molecules tend to aggregate in the absence of invariant chains (28).

As DM seems to be involved in class II peptide–loading processes, we considered different conformations of MHC as potential ligands for DM. By probing conformational changes that exist between wt and DR1 (86G→Y) and their reactivities with DM, we propose the following mechanism for DM function: through hydrophobic interactions around pocket 1, DM recognizes a flexible conformation of pocket 1 of DR1 and accelerates dissociation of CLIP or a peptide that lacks the pocket 1 anchor. This interaction converts the molecule into a highly receptive conformation for peptide binding. A compact class II that is generated upon binding of a peptide with a large hydrophobic side chain at corresponding pocket 1 yields a rigid conformation that is less responsive to DM.

Materials and Methods

Production of Recombinant Soluble DR1 and DM Proteins. Soluble DR1 proteins were expressed and purified as described (23). DM, expressed and isolated as described previously (8), was further purified by gel filtration (Superdex 200; Amersham Pharma- ceutics Biotech) and ion–exchange chromatography (Mono-Q Sepharose; Amersham Pharma- ceutics Biotech [12]).

Peptide Synthesis and Labeling. HA peptides, CKPKVK-QNKTKLAT, HAHHY86G, and several variants, HAY86A (CPKAVQNTKLAT), and Cy5-HA2 (CPKAVKANGAK-AAT) were purified to apparent homogeneity of >95% by reverse-phase preparative HPLC and their identities were confirmed by mass spectrometry. Then, 0.15 mM HAHHY86G or HA2, containing a single cysteine in 10 ml PBS, was incubated with 25 μl of 75 mM fluorescein-5-maleimide (Molecular Probes) in 0.15 M citrate/phosphate buffer at pH 6.0, for 7 min. Amino groups were generated by injection of ethylendiamine hydrochloride (1 M, pH 6.0) for 8 min at a flow rate of 10 μl/min for 7 min. Amino groups were generated by injection of ethylendiamine hydrochloride (1 M, pH 6.0) for 8 min at a flow rate of 10 μl/min. To introduce maleimido groups, a solution of the heterobifunctional reagent, Sulfo-succinimidyl 4-(p-maleimidophenyl)-butyrate (SMBP; Pierce Chemical Co.), was pumped over the surface for 10 min. Cysteine peptides (100–200 μM) were injected to desired levels.

All binding experiments with use of biosensor were performed in 0.15 M citrate/phosphate buffer at pH 6.0. The pH 6.0 was chosen because the optimal activity of DM is shown to be at the pH range of 3.5–6. However, at pH levels <6.0, the Biacore dextran chip undergoes some changes that lead to a false increase in the resonance unit (RU) levels. Thus, we tested the above pH range for our Biacore experiments, and selected pH 6.0 because the observed bindings were real, and complexes formed associated within the expected dissociation rates for different pairs of peptide–MHC. On the contrary, at pH ≤ 5.8 the nonspecific effects were apparent. Soluble DR1 was incubated with 200 μM HAHHY86G at 37°C for 36 h. Size-exclusion HPLC (Superdex 200 gel filtration column; Amersham Pharmacia Biotech) was then used to isolate the sDR1-HAHHY86G complexes. The complexes were further concentrated by centrifugal filter devices (Millipore). The concentration of the complex was determined by absorbance at 280 nm with the extinction coefficient of 77,000 M–1 cm–1. The complex was incubated at 37°C for 20 min with or without 1 μM DM and injected to the peptide surfaces. For dissociation experiments, 9 μM DM in citrate buffer, pH 6.0, was injected over the preformed complexes, wtDR1–
HA_{306–318}. WtDR1–HA Anchorless and DR1_{\beta G86Y}–HA Anchorless, and dissociation sensograms were collected. DR1_{\beta G86Y}–HA_{306–318} surface was used as a control surface for establishing the background signal levels due to injection of DM.

For biosensor experiments with extended contact time, a BIAcore X instrument was used in the external injection mode. Samples were delivered by an externally computer-controlled syringe pump (model 402; Gilson) in a configuration similar to that described previously (29), modified to allow the use of smaller sample volumes. Because of the temperature, 37°C, and long duration (3 h), microscopic bubbles formed that caused the unusual appearance of the sensogram. For other experiments, we used a BIAcore 2000.

Results

DR1_{\beta G86Y} Molecules That Have a Shallow Pocket 1. HA Anchorless and HA_{Y308A} are short-lived peptides that dissociate from DR1 with $t_{1/2}$ of 30–120 min and thus leave DR1 that is receptive to peptide binding. Experimental evidence has shown that alanine substitution for threonine at pocket 6 of HA_{306–318} sequence improved binding by threefold (30). To design a true HA Anchorless peptide, we made a threonine to glycine substitution at position 313 (20, 23).

To generate DR1 molecules that would not bind peptides stably and would mimic kinetic and structural intermediates, we designed a mutant DR1 molecule with a shallow pocket 1 that would not allow fitting of a large anchor residue. A single site-specific mutation for glycine at position 86 to tyrosine was introduced. Residue 86 was chosen because DR alleles exhibit glycine-valine dimorphism at that position, suggesting that a bigger sidechain would not cause gross structural changes in the protein. In support of this, I-E\k has a phenylalanine for \beta 86 (31). \beta G86 was changed to a tyrosine because HA_{306–318} is both the best binding and best characterized peptide of DR1, has a tyrosine at that position as seen from the DR1–HA_{306–318} crystal structure (32).

As predicted, DR1_{\beta G86Y}–HA Anchorless complexes dissociated with rates similar to that of wtDR1–HA Anchorless (Fig. 1) and exhibited a more rigid and compact structure resistant to denaturation by SDS and heat, even in the absence of peptides (23, 24; Table I). DR1_{\beta G86Y} binds effectively to peptides that contain alanine at the corresponding pocket 1 position via a kinetic on rate that fits a single exponential equation (Fig. 2 a). This is in contrast to empty sDR1 that binds the same peptide slowly via biphasic kinetics, and maximal binding was not obtained even after 24 h of incubation in the presence of 100 μM peptide (Fig. 2 b). The binding of wtDR1 that has just lost tenant peptide, and is in receptive form, follows a single exponential rate (Fig. 2 c). The biphasic kinetic relation in Fig. 2 b might be due to heterogeneity of DR1 molecules, some binding peptide rapidly and others that bind slowly. The fast phase might be because of DR1 molecules in complex with unknown short-lived peptides that dissociate rapidly.

Effect of DM on Peptide Release from Wt and DR1_{\beta G86Y}. Previous work has shown that DM enhances dissociation of short-lived peptide–class II complexes (5, 8, 33–35). To determine if DM affects the wt and DR1_{\beta G86Y} in different ways, we examined the molar ratio of DM necessary to facilitate dissociation of wtDR1 in complex with FITC-HA Anchorless. At the lowest tested DM to wtDR1 ratio of 1:5, >40% of the complexes dissociated within 20 min incubation (Fig. 3 a). However, after 40 min incubation, >90% of complexes had dissociated (Fig. 3 b). In contrast, DM did not affect dissociation of DR1_{\beta G86Y}–HA Anchorless at this molar ratio. Furthermore, upon a 20-min incubation (Fig. 3 a), only 10–15% of complexes dissociated at the highest molar ratio. However, at the maximum ratio of ~1:1 of DM to DR1_{\beta G86Y}–HA Anchorless only 50% of complexes dissociated within 40 min (Fig. 3 b). For maximum difference in dissociation of complexes of the wt and DR1_{\beta G86Y} upon DM effects, we chose the DM/DR ratio of 1:2.5, and an incubation time of 20 min for future experiments.

Table I. DR1_{\beta G86Y} Has a More Rigid Conformation than WtDR1

| MHC protein | Pocket 1 | SDS stability* | $T_m$ ‡ |
|-------------|----------|----------------|--------|
| DR1 (-P)    | Deep     | Unstable       | 67     |
| DR1_{\beta G86Y} (-P) | Shallow | Stable         | 72     |
| DR1–HA_{306–318} | –        | Stable         | 84     |

*From references 23 and 24.
‡$T_m$ midpoint temperature of thermal denaturation of a protein (reference 24); –P, without peptide.
We compared the formation of FITC-peptide–MHC complexes for the DR1<sub>G86Y</sub> and wtDR1 in the presence of 1 μM DM. Fig. 2, a and b, show comparison of association rates of the DR1<sub>G86Y</sub> and wtDR1 interacting with HA<sub>Anchorless</sub> in the absence and after addition of DM. In the absence of DM, a clear difference in the shape and the rates of wt and DR1<sub>G86Y</sub> binding to HA<sub>Anchorless</sub> established the receptive conformation of the DR1<sub>G86Y</sub>. Remarkably, DM converted the biphasic peptide-binding pattern of wtDR1 to the monophasic-binding pattern of DR1<sub>G86Y</sub>. A small (10–15%) increase in the plateau level might be due to further stabilization of the DR1<sub>G86Y</sub> by DM.

**Peptide Binding of DR1 Assisted by DM in Real Time.** To determine the effects of DM on binding of receptive DR1 to peptides and dissociation of complexes formed in real time, we developed a peptide-binding assay by BIA-

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**Figure 2.** The effects of DM on the generation of receptive DR1. (a and b) The effects of DM on the binding of HA<sub>Anchorless</sub> peptide to wt and DR1<sub>G86Y</sub>. 2.4 μM DR1<sub>G86Y</sub> (a) and wt (b) were incubated with 100 μM FITC-HA<sub>Anchorless</sub> peptide for various times in the absence (c) and presence (■) of DM (1 μM, 0.15 M citrate phosphate buffer, pH 6.0, at 37°C). The calculated rates for peptide binding to DR1<sub>G86Y</sub> in the absence and presence of DM, to wtDR1 in the presence of DM, and to the receptive wtDR1, were all very similar and ranged between 0.47 and 0.61 s<sup>-1</sup> μM<sup>-1</sup>. (c) The kinetics of HA peptide binding to dissociating DR1-HA<sub>Anchorless</sub> complex. 50 μM FITC-HA was incubated with 2.4 μM DR1–AMCA–HA<sub>Anchorless</sub> complex (isolated by size-exclusion chromatography, citrate buffer, pH 6.0) for various times at 37°C. The unbound peptides were then removed by Sephadex G-50 spin columns in PBS. Samples were read at two wavelengths of 345 (AMCA) and 514 nm (fluorescein). The dissociation data (■) were fit to a single exponential decay curve. The HA association (■) data were fit to a single exponential binding curve.

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**Figure 3.** The effects of DM on dissociation of DR1–peptide complex in pH 6.0. 2.4 μM wtDR1 (black bars) and DR1<sub>G86Y</sub> (white bars) in complex with FITC–HA<sub>Anchorless</sub> were incubated with DM (citrate buffer, pH 6.0) for 20 min (a) or 40 min (b), and dissociation of the complexes was measured. At the physiological ratio of 1:5 DM/DR (reference 45), DM did not affect dissociation of the DR1<sub>G86Y</sub>–HA<sub>Anchorless</sub> complexes, whereas at higher molar ratios, up to 50% of the complexes dissociated after 40 min of incubation.
core surface plasmon resonance (SPR), as the fluorescence assay does not allow accurate measurement of very rapid interactions. We took advantage of the fact that prior association with low affinity peptides induces a receptive conformation in class II (19, 20). First, DR1<sub>BGS6Y</sub> was used to establish the assay because it binds peptide more efficiently and stays in receptive form once the peptide is dissociated (20; Fig. 2 a). The peptide surfaces were generated first by Cys coupling to the CM5 chip. Fig. 4 a shows a sensogram of DR1<sub>BGS6Y</sub> binding to the HA<sub>Anchorless</sub> surface. As the steady-state binding can be reached 9,000 s after protein injection, in the following experiments only the early binding curves were generated. The estimated dissociation rate was $5.6 \times 10^{-5}$ s<sup>-1</sup>, and the $t_{1/2} \sim 3.4$ h. This is in agreement with the rates measured by the use of conventional fluorescence assays (23; Fig. 1).

To examine formation of DR1–peptide complexes in real time, HA<sub>306–318</sub>, HA<sub>Anchorless</sub>, and a non–DR1-binding peptide, CLSPFPFDL, were conjugated to different surfaces of a CM5 chip. Wt or DR1<sub>BGS6Y</sub> was shaped to be receptive by incubating with short-lived HA<sub>Y308A</sub> peptide (see details in Materials and Methods) before it was injected over the surface and binding was monitored. Fig. 4 b shows wtDR1 binding to HA<sub>A</sub> and HA<sub>306–318</sub> surfaces in the presence and the absence of DM. Binding was significantly higher if DM was preincubated with wtDR1 and was present in the sample mix during the injection. DM enhanced binding of wtDR1 to the peptide surface, perhaps by increasing the dissociation of HA<sub>Y308A</sub> from DR1 and by maintaining the receptive conformation of the empty protein once the bound peptide was dissociated. 

The binding of DR1<sub>BGS6Y</sub> to HA<sub>Anchorless</sub> was visualized by injecting DR1<sub>BGS6Y</sub>–HA<sub>Y308A</sub> complexes (citrate buffer, pH 6.0). The long-term experiments were performed in a BIAcore X instrument (for details, see Materials and Methods). The binding curve is expressed as RU as a function of time. The DR1<sub>BGS6Y</sub>–HA<sub>Y308A</sub> complexes were prepared by preincubation of DR1<sub>BGS6Y</sub> and HA<sub>Y308A</sub> peptide followed by size-exclusion purification. Running buffer was citrate buffer plus 0.01% Tween 20, pH 6.0. One out of two experiments is shown. (b and c) The effects of DM on binding of the wtDR1 (b) and DR1<sub>BGS6Y</sub> (c) to the peptide surfaces; 2.4 μM wtDR1 or DR1<sub>BGS6Y</sub> in complex with HA<sub>Y308A</sub> peptide, was isolated by the procedure described in the legend to Fig. 1, and then was incubated at 37°C with or without 1 μM DM for 20 min. Samples (citrate buffer, pH 6.0) were injected over three different peptide surfaces (cys-HA, cys-HA<sub>Anchorless</sub> and the control peptide) of BIAcore 2000 at a flow rate of 4 μl/min for 7 min followed by washout (citrate buffer plus 0.01% Tween 20, pH 6.0) at a flow rate of 5 μl/min. Sensograms of DR1 binding are shown in different colors: in the absence of DM (blue), presence of DM (red), and DM plus soluble peptide for blocking (green). One out of three experiments is shown.

In contrast to wtDR1 that bound to peptide surface poorly in the absence of DM, DR1<sub>BGS6Y</sub> bound to HA<sub>Anchorless</sub> surface efficiently. Preincubation with DM increased peptide binding by only 10–15%. Again, the resultant DR1<sub>BGS6Y</sub> when in complex with soluble peptide failed to bind to the immobilized peptide surface. Accessibility of immobilized peptides for efficient binding might be a limitation in this assay. Also, the competition between the dissociated peptides (from DR1–HA<sub>Y308A</sub> under the DM influence) present in the sample mixture together with DM that enhances their binding as well might generate binding profiles that represent slower rates than those that might be obtained by solution studies. Nonetheless, the strength of this assay is in measurement of fast dissociation rates such as those shown in Fig. 5.
Dissociation of the WtDR1 and DR1<sub>G86Y</sub> from HA<sub>Anchorless</sub> Surface by DM. The observation that DM did not act on DR1<sub>G86Y</sub> efficiently suggested that DM recognized conformations of empty pocket 1 of wtDR1. In the previous experiment in Fig. 4, wtDR1 formed complexes with HA<sub>306–318</sub> and HA<sub>Anchorless</sub> peptide surfaces, and DR1<sub>G86Y</sub> formed complexes with HA<sub>Anchorless</sub> peptide on the biosensor chip. Fig. 5 depicts the effects of injected DM on the dissociation of these complexes. Only the wtDR1–HA<sub>Anchorless</sub> surface showed a significant decrease (40 RU) after DM injection (t₁/₂ ~ 3 min). The half-time for dissociation of DR1<sub>G86Y</sub>–HA<sub>Anchorless</sub> complexes in the presence of DM was 135 min; thus, the presence of DM accelerated dissociation of the wtDR1–HA<sub>Anchorless</sub> complexes compared with the DR1<sub>G86Y</sub>–HA<sub>Anchorless</sub> complexes by 45-fold. The HA<sub>306–318</sub> complexes dissociated within a t₁/₂ ~ 344 h that is consistent with long-term solution studies, and was not accelerated upon DM effects. The data clearly demonstrate that DM effectively enhanced dissociation of wtDR1 in complex with a peptide with alanine at pocket 1 position but that the wtDR1–HA<sub>306–318</sub> and DR1<sub>G86Y</sub>–HA<sub>Anchorless</sub> surfaces were resistant to DM dissociation.

Measurements of Tryptophan Fluorescence upon DR1 and DM Interaction. Wiley’s group (12) has suggested that two tryptophan residues, α62 and B120, located on the lateral surface of DM, are partially exposed and are candidates for binding to DR. Moreover, a glycosylation mutant of DR that interfered with DM effects was suggestive of the NH₂-terminal side of DR1 as a target for DM (36). We examined this possibility by detecting intrinsic tryptophan fluorescence of wtDR1 and DR1<sub>G86Y</sub> and DM. The intrinsic tryptophan of each sample was excited at 295 nm to minimize the interference of tyrosine fluorescence, and the emission spectra were obtained from 310 to 500 nm. The fluorescence spectra of DM and empty wtDR1 alone have intensity maxima ~340 nm (Fig. 6 a). These two spectra can be additive if the DM and DR1 do not interact with each other. However, if the DM and DR interact, causing the exposed tryptophans to be buried at their interface, tryptophan fluorescence should increase. In accord with this, when DM and empty wtDR1 were mixed, the intensity maxima of the emission fluorescence spectra increased by 10–12% (Fig. 6 b). Moreover, in agreement with the above data that DR1<sub>G86Y</sub> is not an optimal ligand for DM, empty DR1<sub>G86Y</sub> and DM did not yield increased fluorescence (Fig. 6 c). In addition, no fluorescence increase was observed when DM was mixed with the wtDR1–HA<sub>306–318</sub> complex, suggesting lack of interactions that would bury exposed tryptophans (Fig. 6 d). Overall, these observations support the notion that DM interacts with empty and flexible pocket 1 of DR1 and that the interaction causes burial of exposed tryptophans present in DR1 and DM.

Discussion

In this paper, we show that DM may function through conformational recognition. Several observations support this model. Previously published results have proposed that the stability of peptide–MHC complexes is the determinant of DM reactivity. Our results here oppose this view by providing evidence that the conformational differences in an empty/flexible hydrophobic pocket 1 of DR1 is what is recognized by DM.

Formation of peptide–MHC kinetic and structural intermediate complexes leads to shaping of the peptide-binding site of class II to a conformation that is highly receptive to stable peptide binding. The rate-limiting step in the forma-
tion of stable peptide binding is therefore the generation of this peptide-receptive conformation. In this study, we have used several experimental approaches and generated a mutant DR1 with a single amino acid substitution inside its pocket 1 to reduce the depth and hydrophobicity of this pocket. The peptide-binding characteristics of DR1\textsubscript{BG68Y} resemble that of wtDR1 in a peptide-receptive conformation (Fig. 2). The receptive characteristics of this mutant might be due to the presence of tyrosine that partially fills the pocket and prohibits the protein from stable peptide binding. In addition, the presence of tyrosine induces rigidity of pocket 1 as shown by resistance to SDS and an increase in melting temperature (\(T_m\)) by 5°C (Table 1). This rigidity may render empty DR1\textsubscript{BG68Y} less susceptible to collapsing. We show that DM recognizes an intermediate flexible conformation of wtDR1 that is characteristic of empty DR1, or DR1 that is occupied with peptides lacking the main anchor. This interaction generates and maintains a peptide-receptive form of the protein.

DR1\textsubscript{BG68Y} forms only short-lived complexes with peptides yet serves as a poor substrate for DM function. As the conformations of DR1\textsubscript{BG68Y} and wtDR1 in complex with short-lived peptides are different, and DM can distinguish these complexes, we propose that DM recognizes its substrate via structural differences. In the absence of DM, a clear difference in the shape and the rates of wt and DR1\textsubscript{BG68Y} binding to HA\textsubscript{Anchored} documents the receptive conformation of the DR1\textsubscript{BG68Y} (Fig. 2).

It is remarkable that DM converts the biphasic peptide-binding pattern of wtDR1 to the monophasic-binding pattern of DR1\textsubscript{BG68Y}. A small (10–15%) increase in the plateau level from the DM interaction might be the result of further stabilization of the DR1\textsubscript{BG68Y} by DM. The earlier phase in binding of wtDR1 in the presence of DM may represent...
binding of a cohort of the wtDR1 that is in receptive form and binds peptide rapidly, whereas the second phase represents HLA-DR1 that binds peptide slowly (20). Similar biphasic binding patterns have previously been observed for DR1 molecules binding peptides in acidic, but not neutral pH (19). Rabinowitz et al. also demonstrated that at acidic pH, pre-shaped wtDR1 binding to HA306–318 peptide is monophasic (19). Interestingly, adding DM to the empty wtDR1 and peptide samples converts biphasic binding to monophasic binding. The monophasic peptide-binding rate is very similar to the binding rate of the DR1bG86Y and pre-shaped wtDR1. This dramatic change in peptide-binding pattern marks an important and novel function of DM: that is, generation of a homogeneous population of MHC proteins capable of binding peptides rapidly.

To further elucidate the mechanism catalyzed by DM, we developed a real time peptide-binding assay. Although the BIAcore SPR assay for binding of the MHC class I to immobilized peptides has been successful (37, 38), this approach has failed for class II peptide binding, presumably because the peptide-binding grooves of class II molecules are either occupied, or collapse after peptide release (17). As we and others now have established that class II molecules can be shaped to a peptide-receptive conformation that exhibits accelerated peptide association, it was likely that direct MHC class II binding to peptides could be measured in real time. Using BIAcore SPR, we show that DM assists peptide exchange more efficiently for wtDR1 than for DR1bG86Y. A three- to fourfold increase in binding of the DR1bG86Y (rate $\approx 119 \times 10^{-3} \text{ s}^{-1}$) versus wtDR1 (rate $\approx 35 \times 10^{-3} \text{ s}^{-1}$) in binding to HAAnchorless surface in the absence of DM was observed. A reason for a difference in efficiency of DR1bG86Y in binding to the peptide surface relative to the wt protein is the extreme susceptibility of the wtDR1 in receptive form to partial denaturation unless stabilized by loose binding to another peptide or DM. In contrast, DR1bG86Y is mostly in receptive conformation with little need for stabilization by either peptide or DM. As preparations of wtDR1 had been incubated in the absence of DM for a minimum of 20 min before injection over immobilized peptide surfaces, up to 50% of them (20) have already converted to the low binding conformation during this time. We also demonstrate, for the first time, using SPR, that acceleration of peptide release with addition of DM only occurs with the wtDR1 in complex with peptides that contain alanine instead of tyrosine at the corresponding pocket 1 position. Our SPR assay establishes that analysis of the behavior of class II molecules can be monitored in real time. Because of great sensitivity, interactions of MHC II with peptides and other accessory molecules, such as DO with DM, can be studied in a more controlled environment.

Can DM select its substrate by distinguishing the class II–peptide complex stability? Our results show that the wt and DR1bG86Y molecules that follow the same dissociation rates for HAAnchorless or HA308A are differentially recognized by DM. This strongly suggests that DM recognizes a specific and flexible conformation of class II rather than the previously proposed unstable MHC–peptide. The interaction may resemble a chaperone function for DM. Just like a chaperone that is required for proper folding and/or assembly of another protein or protein complex, DM binds to a partially folded flexible class II (18) that is either empty or loosely bound to peptides. Because class II without a bound peptide is prone to denaturation and peptide binding prevents this process, DM facilitates binding and release of loosely binding peptides until a peptide that can complete the folding of the nascent protein is encountered (18). Once a stable peptide–MHC complex is formed, the conformation of the complex is no longer suitable for DM binding. At this point, class II is free to move to the cell surface. This mechanism can also explain the suitability of the DR1–CLIP complex as a DM substrate. Methionine, which fits in pocket 1 of DR, has a distinctive flexible side chain (39) that would not induce rigidity around pocket 1. This pattern of recognition for DM is also consistent with lack of recognition of I-Ek, which has a shallow pocket 1 (31) very similar to that of the DR1bG86Y (11, 40). Moreover, effects of H2-M on selection of immunodominant epitopes of hen egg white lysozyme may reflect its preference for more rigid ligand structures (41).

Intrinsic fluorescence assay showed that DM–DR interaction may involve the pocket 1 of DR1. An increase in intrinsic fluorescence was observed when DM was mixed with the wtDR1, whereas addition of DR1bG86Y or empty wtDR1 in complex with HA306–318 peptide did not enhance fluorescence. The observed 10–12% change in tryptophan fluorescence is significant because of minimal changes in the control groups, i.e., complexes of wtDR1–HA306–318 or DR1bG86Y–HAAnchorless, and the reproducibility of these results. Thus, such a response pattern suggests that the tryptophan–rich lateral surface of DM may be buried by interactions with empty wtDR1. This is consistent with predictions that Trp 62 on the lateral face of DM makes contact with Phe 51 of DR around pocket 1 (12). Although it has been shown that when DM and DR were mixed, the nonpolar dye, anilinonaphthalene sulfonic acid (ANS), which binds to hydrophobic patches of proteins, emitted reduced fluorescence (42), the specific interaction sites were not defined. Our findings substantiate that the hydrophobic pocket 1 of DR1 is the main target for the DM-induced conformational changes in this system.

The observations in this paper point to a central role for conformational changes that take place upon peptide binding to MHC class II. These conformational adjustments regulate class II peptide loading, trafficking to the proper vesicular compartments, and cell surface expression. They monitor interactions with DM and selection of peptides that ultimately exit to the cell membrane and stimulate T cells. It is likely that in class I presentation, a chaperone/editor protein, tapasin, also plays similar roles (43, 44). It will be fascinating to find out if tapasin also functions through mechanisms similar to those of DM.

We thank Drs. Peter Schuck for Fig. 4 a, Lydia Mosyak, Efstratios Stratikos, and Don Wiley for DM, Dennis Zaller for the DM cell
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