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Molecular Mimicry: Structural and Physiological Investigations

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Introduction

Independent molecules are expected to possess distinct three-dimensional structures. However, it is becoming increasingly evident that diverse biological molecules, particularly proteins, do not have entirely unrelated structural architectures, even when their functions are independent. It is apparent that the protein structural repertoire is generated from a finite number of structural modules which are used again and again in different contexts and combinations [Chothia and Finkelstein, 1990; Murzin and Chothia, 1992; Chavali et al., 2001]. Many such structural modules have been identified and many more might emerge [Efimov, 1997; Chavali et al., 1997]. Nevertheless, it is likely to be still a finite number. The structural redundancy associated with the protein architecture on one hand and the commonality in the nature of interactions defining specificity of recognition on the other, could lead to the failure in the specificity of molecular communication. Molecular mimicry, in essence, is a consequence of such a failure in the specificity of molecular recognition.

In the physiological context, molecular mimicry is manifested in a variety of ways. The accidental structural resemblances between unrelated molecules can have functional implications [Baum et al., 1993]. Molecular mimicry also occurs by design in various regulatory mechanisms [Bode and Huber, 1992; Kobe and Deisenhofer, 1996]. It has implications in rational drug design as well [Beeley, 1994; Tian et al., 1998]. Focus of research in this laboratory, over past several years, has been to exploit x-ray crystallography along with biochemical approaches towards understanding the structural basis of molecular mimicry.

Manifestations of molecular mimicry in the immune response

Vaccines could be described as the non-infectious mimics of the corresponding infectious agents. The typically successful reductionist approach in modern biology led to the consideration that in terms of specificity and immunogenicity peptides can be suitable candidates for rational design of vaccines [Arnon and Howitz, 1992; Brown, 1992].

However, in the majority of cases, peptides and the peptide-like molecules have had limited success as they suffer from serious disadvantages like short half-life and poor bioavailability. To overcome these obstacles the ideal next generation vaccine could be nonpeptidyl mimic of the peptide B-cell and T-cell epitopes that are either obtained by random screening or by rational design. Our studies involving peptide-carbohydrate mimicry provided interesting insights as to how the immune system would respond when subjected to such molecular mimics.

Concanavalin A (ConA) recognizes a dodecapeptide, DVFYPYPYASGS, and a sugar, methyl α -D-mannopyranoside [Lis and Sharon, 1998; Oldenberg et al., 1992]. We had earlier shown that these molecules exhibit mimicry, expressed in terms of polyclonal antibody cross-reactivity. The polyclonal antibodies raised against sugar exhibited cross-reactivity with peptide and its various analogs and the antibodies against the peptide showed cross-reactivity with the sugar [Kaur et al., 1997]. The ConA binding activities of various analogs were found to have direct correlation with the topological relationship between the peptide and the carbohydrate ligands. It was shown that the binding of these peptides could be competitively inhibited by methyl α -D-mannopyranoside implying that the peptides and the sugars could share the binding site on ConA. Functional analysis of the mimicry showed that ConA-induced T-cell proliferation can be inhibited by the 12mer implying that the peptide binding sites incorporated the extended carbohydrate binding site on ConA (Jain et al., 2000b)

Since, the antibody response against an antigen is expected to recognize its three-dimensional shape, we had first exploited polyclonal antibodies for identifying the structural distinctions between these molecular mimics [Kaur et al., 1997]. The antipeptide polyclonal antibodies showed cross-reactivity with sugar and vice-versa. Further, attempts were made to assess the molecular mimicry between peptide and sugar as a function of progression of the immune response for understanding the course of maturation of the mimicry and also to comprehend various factors affecting it. Thus, we have analyzed the induction and subsequent progression of the mimicry at different levels of antibody maturation [Kaur et al., 2001]. Also, the anti-sugar antibodies could be boosted using a carbohydrate mimicking peptide on cross-immunization. Thus, the carbohydrate-peptide mimicry appears to be a topological quasi-equivalence reflected differently in terms of antibody response during maturation.

Structural basis of molecular mimicry

The mannosylated-specific lectin, ConA, was also exploited as a template receptor while addressing structural basis of molecular mimicry. It enabled establishing the topological correlation between diverse ligands that included a peptide, a porphyrin and a carbohydrate moiety. The crystallographic studies involving complexes of these ligands with ConA provided rich insights into various structure and interaction aspects of molecular mimicry.

Initially, crystal structure of the 12-mer peptide bound to ConA was determined [Jain et al., 2000a] which helped to demonstrate direct topological correlation of the peptide with a trimannose moiety. Although the functional mimicry was observed between the peptide and the carbohydrate moieties, the crystal structure of the ConA-peptide complex revealed that the two peptide binding sites are independent of the methyl α -D-mannopyranoside binding site. The topological correlation of 12-residue peptide with different carbohydrate ligands of ConA showed similarity between trimannose and the YPY region of the peptide establishing structural mimicry [Jain et al., 2000a]. Molecular docking of trimannose and the YPY motif on the reciprocal binding sites revealed equivalent interactions and energetics implying that the peptide-binding sites may constitute additional sugar-binding subsites of ConA. The binding of a mannose-rich neoglycoprotein with significantly higher affinity compared with that of the methyl α -D-mannopyranoside is consistent with this interpretation.

We have also determined structures of several other carbohydrate-mimicking peptide molecules bound to ConA and highlighted the role of conformational flexibility and interaction plasticity in the binding of various peptide ligands to ConA. The structures of ConA in complex with 10-mer (MYWYPYASGS) and 15-mer (RVWYPYGSYLTASGS) were determined [Jain et al., 2001a]. In both the crystal structures four independent peptide molecules bind to each of the crystallographically independent subunits of ConA tetramer. The peptides exhibit small but significant variability in conformations and interactions while binding to ConA. Comparison of these two structures with that of ConA-12mer complex shows that the peptides bind to ConA at a common binding site, using different contacting residues and interactions depending on their sequence and the local environment at the binding site. The binding is also optimized by corresponding plasticity of the peptide binding site on ConA. The adaptability of peptide-ConA interactions may also be correlated with the carbohydrate-mimicking property of these peptides.

We have also designed another peptide ligand of ConA with enhanced binding and showed that the affinity increase arises from improved geometrical complementarity [Jain et al., 2001b]. The structural basis of affinity enhancement was addressed by analyzing the interactions between ConA and the carbohydrate-mimicking peptide ligands. It is apparent that the deletion of the structurally variable region of the larger peptides has led to an improved complementarity and increased buried surface area in the case of the designed peptide. The crystal structure also showed the formation of two backbone hydrogen bonds between the ligand and the ligate which were not present in the complexes of the precursor peptides. The observed structural features adequately explain the enhanced binding of the designed analogue.

The crystal structure of yet another ligand, *meso*-tetrasulphonatophenylporphyrin, complexed with ConA provided an interesting example of functional mimicry without any explicit structural similarity [Goel et al., 2001]. The crystal structure of *meso*-tetrasulfonatophenylporphyrin complexed with ConA was determined at 1.9 Å resolution. While comparing the binding of porphyrin to ConA with that of mannose, we demonstrated that the functional equality could exist between two ligands even in the absence of structural similarity, unlike in the case of peptide-carbohydrate mimicry, providing an added dimension to molecular mimicry. Comparison of this structure with that of ConA bound to methyl α -D-mannopyranoside provided direct structural evidence of molecular mimicry in the context of ligand receptor binding (Figure 1). The sulfonatophenyl group of *meso*-tetrasulfonatophenylporphyrin occupies the same binding site on ConA as that of methyl α -D-mannopyranoside, a natural ligand. A pair of stacked porphyrin molecules stabilizes the crystal structure by end-to-end cross-linking with ConA resulting in a network similar to that observed upon agglutination of cells by lectins. The porphyrin binds to ConA predominantly through hydrogen bonds and water-mediated interactions. Thus, the similarity in chemical interactions was manifested in terms of functional mimicry despite the obvious structural dissimilarity between the sugar and the porphyrin.

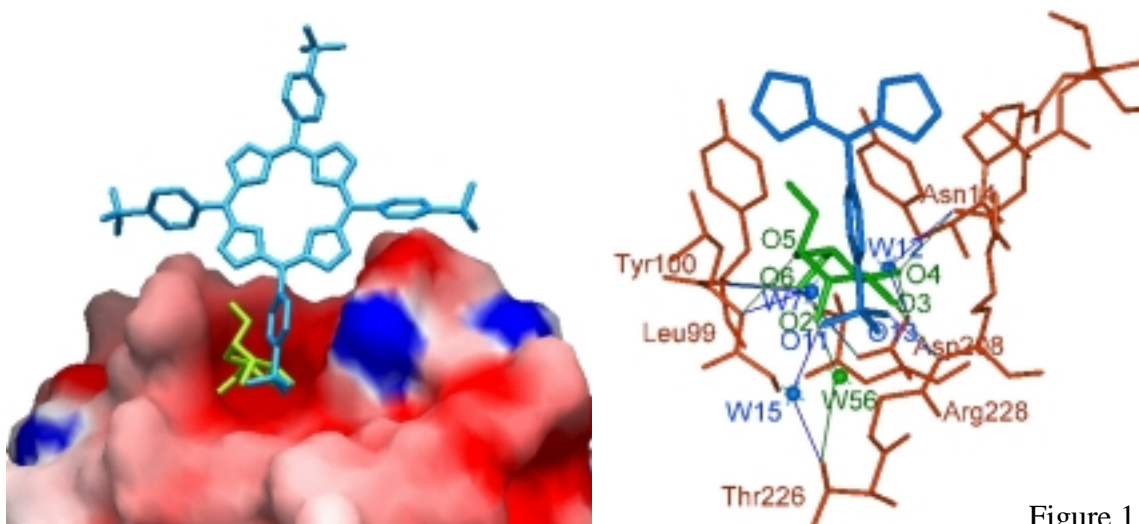


Figure 1

Antigen mimetics: designer immune epitopes

The success in understanding the structural rules of molecular mimicry between peptide and non-peptide ligands, encouraged us to explore possibilities of designing mimics that would resemble native peptide immune epitopes. In this context, first attempts were made to exploit retro-inverso (ri) analogs which have been considered to resemble native peptides in terms of side chain juxtapositions [Van Regenmortel and Muller, 1998]. We were successful in designing a couple of MHC class I specific T cell epitopes using this approach but were unable to design mimic for an immunodominant B cell epitope [Nair et al., 2003]. The ri analogs of model T cell and B cell epitopes were designed *in silico* as mimics and then assayed for activity. The ri versions of two MHC class I binding peptide epitopes, one from a vesicular stomatitis virus glycoprotein (VSVp) and another from OVA (OVAp), exhibit structural as well as functional mimicry of their native counterparts. In contrast, the ri version of an immunodominant B cell peptide epitope from a hepatitis B virus protein, PS1, exhibits no structural or functional correlation with its native counterpart. PS1 and its ri analog do not exhibit similar conformational propensities. PS1 is less flexible relative to its ri version. While the designed retro-inverso analog of T cell epitopes showed activity, the corresponding analog of the B cell epitope did not. The detailed comparative analysis of these epitope mimics suggested that the inherent structural properties of the individual peptide ligands are critical determinants of possible retro-inverso mimicry. Thus, it is evident that the correlation of conformational and interaction propensities of native L-peptides and their

ri counterparts depends both on their inherent structural properties and on their mode of recognition.

The most appropriate basis for designing a B cell epitope would be, first to define the invariant structural properties of an immunodominant region of the antigen while it interacts with a finite number of independent monoclonal antibodies. That would enable defining the structural features that may be critical for its 'immunogenicity' which could then be used in computer-aided design of a non-peptide mimic. Such a design is yet to be achieved, but several interesting insights in to the structural basis of antibody recognition of a molecule that keeps changing shape have been gained based on the crystallographic experiments that were designed towards understanding the structural basis of the antibody recognition of the immunodominant peptide epitope [Nair et al., 2000; Nair et al., 2002].

The crystal structures of three distinct monoclonal antibodies recognizing a common epitope of a peptide antigen in the unbound and bound forms were determined. Elaborate crystallographic studies involving this surface antigen and diverse monoclonal antibodies in antigen bound and antigen-free form provided interesting insights in to the immune response. These antibodies display dissimilar binding site structures in the absence of the antigen. The dissimilarity is primarily expressed in the conformations of complementarity-determining region H3, which is responsible for defining the epitope specificity. Interestingly, however, the three antibodies exhibit similar complementarity-determining region conformations in the antigen binding site while recognizing the common epitope, indicating that different pathways of binding are used for antigen recognition. The epitope also exhibits conformational similarity when bound to each of these antibodies, although the peptide antigen was otherwise flexible.

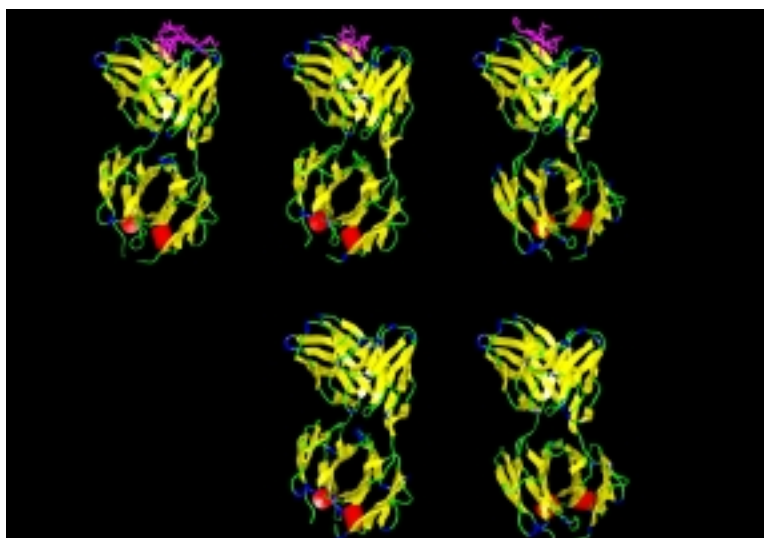


Figure 2

Comparative analysis of these five structures led us to propose that the common epitope recognition by diverse antibodies could lead to conformational convergence in an antibody response. [Nair et al, 2002]. These antibodies display dissimilar binding-site structures in the absence of the antigen. The dissimilarity is primarily expressed in the conformations of CDR H3 which is responsible for defining the epitope specificity. Interestingly, however, the three antibodies exhibit similar CDR conformations in the antigen-binding site while recognizing the common epitope indicating that different pathways of binding are employed for antigen recognition. The epitope also exhibits conformational similarity when bound to each of these antibodies although the peptide antigen was otherwise flexible. The observed conformational convergence in the epitope and the antigen-binding site was facilitated by the plasticity in the nature of interactions. Also, a comparison between crystal structures of one of these antibodies and a homology model of the corresponding germ line ancestor led to the insights with regard to paratope optimization during antibody maturation [Nair et al., 2000]. These structures suggested conformational convergence in an antibody response. The restricted conformational repertoire on antigen binding, observed in these structures, may be relevant for minimizing possibility of self-reactive antibodies.

Among the three antibodies, crystal structure of the monoclonal antibody, PC283, bound to PS1 also led to deciphering novel features in peptide-antibody recognition [Nair et al., 2000]. The PC283-PS1 complex is a unique example wherein the light chain CDRs show more interactions than the heavy chain CDRs and a distal framework residue is involved in antigen binding. The molecular surface area buried upon PS1 binding is 756

Å for the peptide and 625 Å for the Fab, which is higher than what has been seen to date for antibody-peptide complexes.

Thus, to summarize, we have addressed fundamental issues pertaining to the specificity of molecular recognition and molecular mimicry particularly in the context immunological processes. Several chemically dissimilar but functionally equivalent molecular structures were analysed and the structural basis and physiological implications of molecular mimicry were established. This work was further extended to gain structural insights into the maturation of immune recognition using elegantly designed crystallographic studies. Structural and physiological aspects of molecular mimicry and immune recognition were correlated providing important conceptual leads towards design and development of new generation of vaccines based on antigen mimicry.

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