

## ICA News letter, 2003-2004

### **MACROMOLECULAR CRYSTALLOGRAPHY AT THE INDIAN INSTITUTE OF SCIENCE**

X-ray crystallography of biological macromolecules, started in the early eighties at the Institute, has grown into a major activity involving a number of crystallographers. A majority of the current research projects in this field encompassing many proteins from a variety of organisms have been undertaken in collaboration with established biologists. The structural studies aim at understanding fundamental biological processes at the atomic level as well as aid in the design of effective drugs by elucidating the three-dimensional structures of potential target molecules and their complexes. This article highlights the crystallographic work that has been carried out at the Institute that has resulted in significant contributions to structural biology and related fields.

#### **Structure and interactions of plant lectins**

A protein crystallography programme pursued at Bangalore is concerned with lectins, which specifically bind to cell surface carbohydrates and have applications that flow from this specificity. The *de novo* structure determination of the tetrameric peanut lectin, which is specific to the tumour-associated T-antigenic disaccharide, has an unusual 'open' quaternary arrangement in the molecule, which violates the accepted principles of quaternary association (Banerjee *et al.*, 1994). This structure and those of basic (Prabu *et al.*, 1998) and acidic (Manoj *et al.*, 2000) winged bean lectins, demonstrate that legume lectins constitute a family of proteins in which small alterations in essentially the same tertiary structure leads to large variations in quaternary association, an observation relevant to protein folding. Through the X-ray analysis of several carbohydrate complexes of peanut lectin, the importance of water in carbohydrate binding, including the generation of specificity, has been demonstrated (Ravishankar *et al.*, 1997; 1999). Using X-ray studies and computer modelling, the different blood group specificities of the winged bean lectins could be explained in terms of the structure. The *de novo* structure determination of jacalin (Sankaranarayanan *et al.*,

1996), one of the two lectins found in jackfruit seeds and again specific to T-antigen, has resulted in the identification of a novel three-fold symmetric lectin fold made up of three four-stranded  $\beta$ -sheets. This structure exhibits a novel carbohydrate binding site in which specificity is generated by a post translational modification, the first known instance of this kind. Through the X-ray analysis of a number sugar complexes and modelling, the binding site of jacalin has been completely characterized, and the significance of the characteristics for association with cell surface glycoconjugates elucidated (Jeyaprakash *et al.*, 2002). It has been demonstrated that artocarpin, the second lectin from jackfruit seeds, is homologous to jacalin, despite the two having different physico-chemical properties and carbohydrate specificities. The structural basis of the difference in the sugar specificities of the two lectins has been delineated (Pratap *et al.*, 2002). That from garlic is yet another lectin that has been studied at Bangalore. A comparison of the structure of this dimeric lectin with that of the tetrameric snow drop lectin demonstrates how carbohydrate specificity could be generated through oligomerisation (Chandra *et al.*, 1999). Through elaborate modelling of considerable general interest in relation to the multivalency of lectins, the high affinity of garlic lectin for higher oligomers of mannose could be explained in terms of crosslinking among lectin molecules. The studies at Bangalore have led to valuable insights into, and detailed information on, the structural basis for the carbohydrate specificity of lectins, which in turn have formed the basis for knowledge-based re-design of lectins through protein engineering.

### **DNA binding proteins**

The work at Bangalore has now been extended to proteins acting on DNA as well. The X-ray analysis of a complex of the DNA repair enzyme *E.coli* uracil DNA glycosylase (*EcUDG*) with a proteinaceous inhibitor, carried out as part of this effort constitutes the first structure elucidation of a prokaryotic UDG (Ravishankar *et al.*, 1998; Saikrishnan *et al.*, 2002). Subsequently, the structures of RecA from *Mycobacterium tuberculosis* (Datta *et al.*, 2000; 2003) and *Mycobacterium smegmatis* (Datta *et al.*, 2003a) and several of their complexes were determined. The structures provided explanation for differences in the behaviour of mycobacterial RecA and the

enzyme from *E. coli*, in addition to suggesting new lines of investigation pertaining to DNA recombination and repair. More recently, the structure *M. tuberculosis* single stranded DNA binding protein has been determined (Saikrishnan *et al.*, 2003).

It has a quaternary structure different from that of the protein from other sources (Figure 1). The difference in the quaternary structure is such that the length of DNA required to wrap around the single stranded DNA binding protein from *M. tuberculosis* is less than that required in the case of the protein from other sources. The programme on proteins involved in DNA repair and recombination has led to the initiation of a multi-institutional national programme of structural genomics on microbial pathogens.

### Single stranded DNA binding proteins from

*M. tuberculosis*

*E. coli*

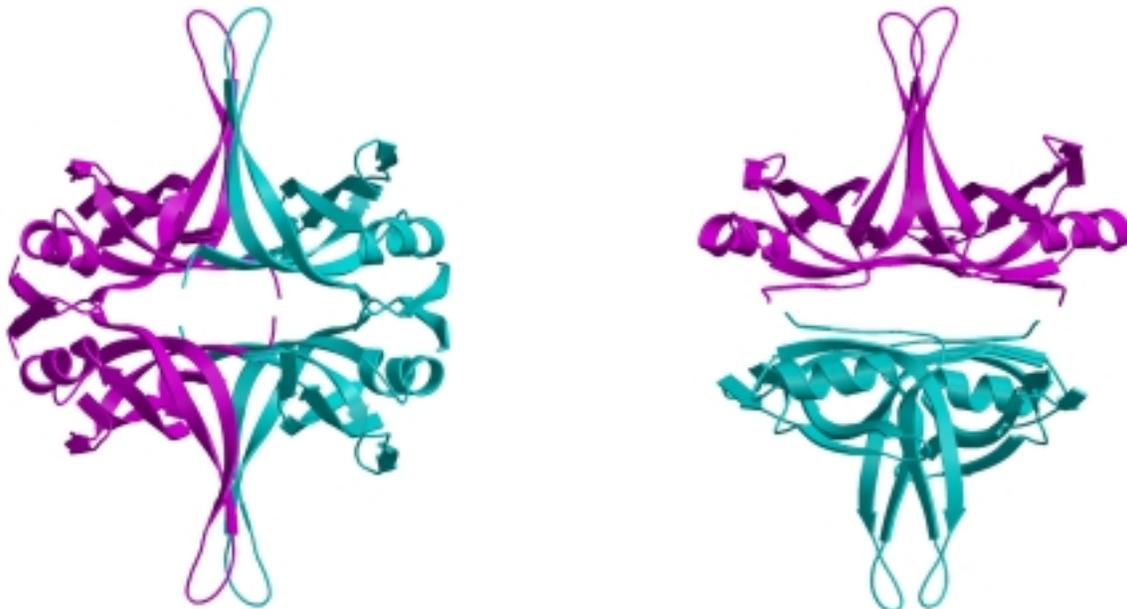


Figure 1

### Virus crystallography

The three dimensional structure of Sesbania Mosaic Virus (SeMV) has been determined at 3.0 Å resolution (Bhuvaneswari et al., 1995).

### Sesbania mosaic virus T=1 particle

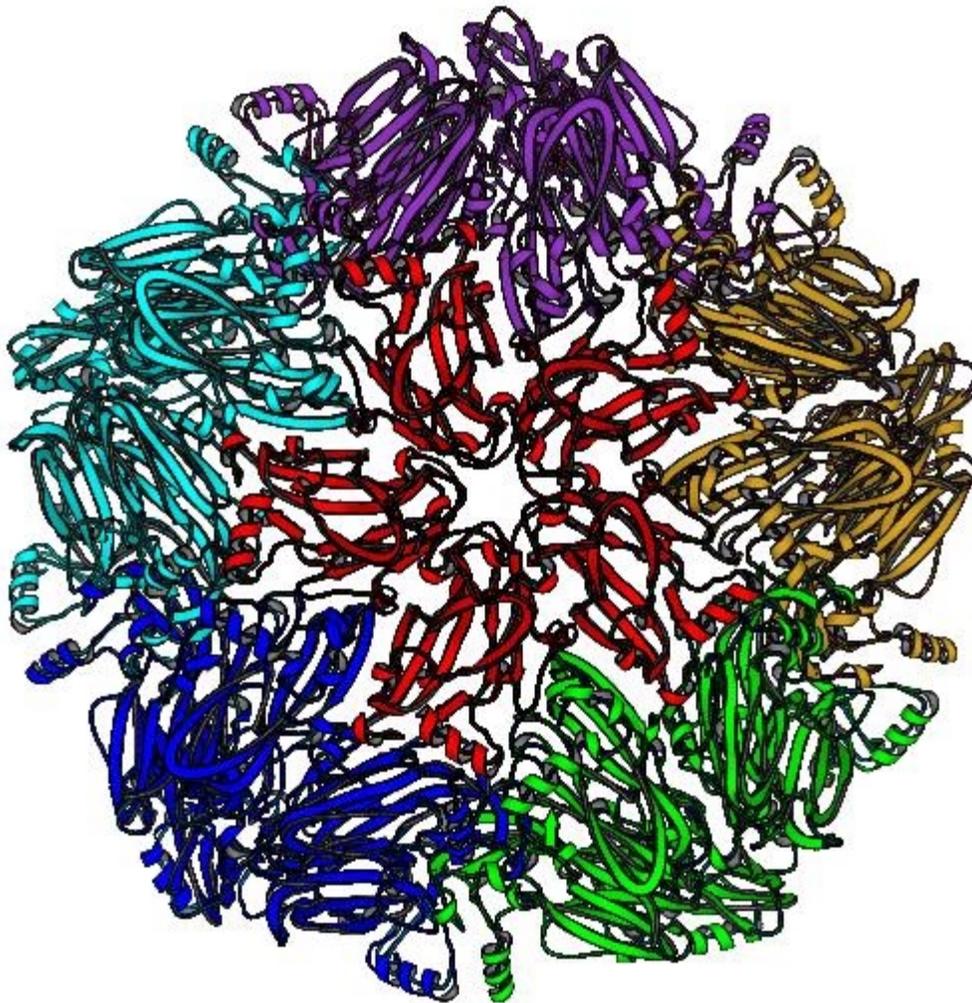


Figure 2

The icosahedral asymmetric unit was found to contain four ions (three calcium and an anion) and three protein subunits, designated A, B and C. The conformation of the C subunit appears to be different from those of A and B in several segments of the polypeptide. The coat protein (CP) of SeMV, when over-expressed in *E.coli* self-

assembles *in vivo* into isometric particles.  $\delta$ N65 mutant forms only T=1 particles. It was possible to crystallize this component and determine its structure at 3 Å resolution (Sangita *et al.*, 2002). The structure (Figure 2) reveals the major differences responsible for T=1 versus T=3 particle assembly. In contrast, the intact recombinant protein assembles into T=3 particles and crystallizes in the rhombohedral space group R3 with cell parameters nearly identical to those of the wild type virus particles and diffract X-rays to 3.5 Å resolution. The structure of these particles also has been determined.

Physalis mottle virus (PhMV) coat protein consisting of 180 subunits (T=3 diameter ~ 300Å), each of MW 21kDa, surrounds a single stranded positive sense RNA genome of size 4MDa. X-ray diffraction data to 3.8 Å resolution was recorded on crystals of wild type virus on films by screen less oscillation photography. The structure of the native virus particles was determined to reveal details of tertiary structure and quaternary interactions (Krishna *et al.*, 1999). In contrast to SeMV, the capsid stability of PhMV is not metal ion dependent and is governed by strong hydrophobic interactions between protein subunits. The recombinant coat protein expressed *E.coli* self-assembles to virus like particles either in the bacterial cell or during purification. The structure of these recombinant capsids have been determined (Krishna *et al.*, 2001).

### **Structural studies on enzymes of *Plasmodium falciparum***

Triosephosphate isomerase (TIM) catalysis the isomerization between dihydroxyacetone phosphate and glyceraldehyde-3-phosphate. The structure of *Plasmodium falciparum* (Pf) TIM was determined at 2.2 Å (Velankar *et al.*, 1997). Comparison of the Pf-TIM structure to that of the human enzyme provided information on potential sites that can be exploited for the design of inhibitor molecules specific to the parasite enzyme. With a view of obtaining more information on the interactions responsible for inhibitor binding, structures of complexes of Pf-TIM with a variety of inhibitors (3PG, G3P, 2PG, PG) were determined (Parthasarathy *et al.*, 2002, 2002a).

Adenylosuccinate synthetase, catalysing the first committed step in the synthesis of AMP from IMP, is a potential target for antiprotozoal chemotherapy. The crystal structure of adenylosuccinate synthetase from the malaria parasite, *Plasmodium falciparum*, complexed to 6-phosphoryl IMP, GDP, hadacidin and Mg<sup>2+</sup>, was determined

at 2 Å resolution (Eaazhisai *et al.*, 2003). The overall architecture of *P. falciparum* AdSS (PfAdSS) is similar to the known structures from *E. coli*, mouse and plants. Differences in substrate interactions seen in this structure provide a plausible explanation for the kinetic differences between PfAdSS and the enzyme from other species. The dimer interface of PfAdSS is also different with a pronounced excess of positively charged residues.

### **Crystal structure of Barstar**

The crystal structure of the C82A mutant of barstar, the intracellular inhibitor of the *Bacillus amyloliquefanciens* ribonuclease, barnase, has been solved using intensity data collected to a resolution of 2.8 Å resolution (Ratnaparkhi *et al.*, 1998). The molecule crystallizes in the space group I4<sub>1</sub> with a dimer in the asymmetric unit. An identical dimer is also found in the crystal structure of barnase-barstar complex. The structure of uncomplexed barstar is compared to the structure of barnase bound to barnase and also to the structure solved using NMR. The free and bound structures are similar with no significant main chain differences in the 27-44 region involved in barstar binding. The C82A structure shows significant differences from the average NMR structure, both overall as well as in the binding region. In contrast to the crystal structure, the NMR structure shows an unusually high packing value based on the occluded surface algorithm, indicating errors in the packing of the structure.

### **Thermostable Xylanase from *Thermoascus aurantiacus* at ultrahigh resolution (0.89Å) at 100 K and atomic resolution (1.11 Å) at 293 K**

*Thermoascus aurantiacus* xylanase is a thermostable enzyme which hydrolyses xylan, a major hemicellulose component of the biosphere. The crystal structure of this F/10 family xylanase, which has a triosephosphate isomerase (TIM) barrel ( $\beta/\alpha$ )<sub>8</sub> fold, has been solved (Natesh *et al.*, 2003) to small-molecule accuracy at atomic resolution (1.11 Å) at 293 K (RTUX) and at ultrahigh resolution (0.89 Å) at 100 K (CTUX) using X-ray diffraction data sets collected on a synchrotron light source, resulting in  $R/R_{free}$  values of 9.94/12.36 and 9.00/10.61% (for all data), respectively. Both structures were refined with anisotropic atomic displacement parameters. The 0.89 Å structure, with 177

476 observed unique reflections, was refined without any stereochemical restraints during the final stages. The salt bridge between Arg124 and Glu232, which is bidentate in RTUX, is water-mediated in CTUX, suggesting the possibility of plasticity of ion pairs in proteins, with water molecules mediating some of the alternate arrangements. Two buried waters present inside the barrel form hydrogen-bond interactions with residues in strands  $\beta 2$ ,  $\beta 3$ ,  $\beta 4$ , and  $\beta 7$  and presumably contribute to structural stability. The availability of accurate structural information at two different temperatures enabled the study of the temperature-dependent deformations of the TIM-barrel fold of the xylanase. Analysis of the derivation of corresponding  $C^\alpha$  atoms between RTUX and CTUX suggests that the interior  $\beta$ -strands are less susceptible to changes as a function of temperature than are the  $\alpha$ -helices, which are on the outside of the barrel.  $\beta\alpha$ -loops, which are longer and contribute residues to the active-site region, are more flexible than  $\alpha\beta$ -loops.

### **Crystal structure of a light harvesting protein C-phycoyanin from *Spirulina platensis***

C-phycoyanin (CPC) is the major light harvesting pigment protein present in the antenna rods of the cyanobacterium *Spirulina Platensis*. The medicinal and pharmacological properties of CPC, which include hepatoprotective, anti-inflammatory, and antioxidant features, have been reported earlier. The crystal structure of CPC has been determined by the method of molecular replacement at a resolution of 2.2 Å using synchrotron X-ray diffraction data (Padayana *et al.*, 2001). The asymmetric unit of the crystal cell consists of two  $(\alpha\beta)_6$  hexamers, each hexamer being the functional unit in the native antenna rod of cyanobacteria. As an outcome of the 'double hexameric' aggregation in the crystal structure,  $\beta 155$  phycocyanobilin chromophores are brought to close proximity of each other within the region between the adjacent hexamers in the crystal asymmetric unit. The present crystal structure of CPC, the major light-harvesting pigment protein in *Spirulina Platensis*, provides a possible model for additional pathways of energy transfer in lateral direction between the adjacent hexamers involving  $\beta 155$  phycocyanobilin chromophores

## **Structure, function and stability of proteins**

### **Lysozyme, Ribonuclease A and Hemoglobin**

Another protein crystallographic project involves the investigation of the variability in protein hydration and its structural consequences using an approach involving water-mediated transformations. Using this approach, the nature of the flexibility in lysozyme (Biswal *et al.*, 2000) and ribonuclease A (Sadasivan *et al.*, 1998) molecules has been elucidated and the invariant features in their hydration shell have been identified. More interestingly, the studies have also provided valuable insights into the relationship among hydration, molecular flexibility and enzyme action. More recently, the existence of ensembles of relaxed and tense states in hemoglobin (Biswal & Vijayan, 2002), has been demonstrated.

### **Rhizopuspepsin**

Aspartic proteinases exhibit pH-dependent activity usually associated with interesting structural changes. The crystal structure of rhizopuspepsin, a fungal aspartic proteinase, has been determined at 3 different pH values of 4.6, 7.0 and 8.0 to investigate whether the structure undergoes any changes by a variation in pH, which in turn may influence its activity. A detailed comparison of different pH forms including the previously reported crystal form at pH 6.0 resulted in the identification of a region in the protein where certain structural changes take place at pH 8.0 (Prasad & Suguna, 2003). An increase in the mobility of the loops, weakening of hydrogen bonding and ionic interactions and a change in the water structure have been observed in this region. The loop between the first and the second  $\beta$ -strands of the N-terminus shows increased mobility at high pH. This loop is known to be highly flexible in aspartic proteinases aiding in relocating the N-terminal  $\beta$ -strand segment in pH-related structural transformations. The observed changes in rhizopuspepsin indicate that the enzyme begins to denature at pH 8. Conformation of the active aspartates and the geometry of the catalytic site exhibit remarkable rigidity in this pH range.

### **Mutants of Phospholipase A<sub>2</sub>**

Phospholipase A<sub>2</sub> catalyses hydrolysis of the ester bond at the C2 position of 3 – *sn* - phosphoglycerides. Crystal structure of the triple mutant K56,120,121M of bovine pancreatic phospholipase A<sub>2</sub> has been determined. The residues 62 to 66, which are in a loop, are always disordered in all the mutant structures of bovine pancreatic Phospholipase A<sub>2</sub>. It is interesting to note that this loop, in the present structure, is ordered and the conformation varies substantially compared to that of the trigonal and the orthorhombic forms of this recombinant enzyme. An unexpected and interesting observation in the present study is, in addition to the functionally important calcium ion in the active site, one more calcium ion is found near the N-terminus. This is the first time such a second calcium ion is found in the bovine phospholipase A<sub>2</sub> structure. Crystal structures of the free and anisic acid bound forms of another triple mutant (K53,56,120M) of the enzyme have also been determined. In the bound structure, the small organic molecule, *p*-anisic acid, is found in the active site and one of the carboxylate oxygen atoms is coordinated to the functionally important primary calcium ion. The other carboxylate oxygen atom is hydrogen bonded to the phenolic hydroxyl of Tyr69. In addition, the bound anisic acid molecule replaces one of the functionally important water molecules in the active site. The residues 60 to 70, which are in a loop (surface loop), are ordered in the bound triple mutant structure but are disordered in the free triple mutant structure (Yu *et al.*, 2000; Rajakannan *et al.*, 2002; Sekar *et al.*, 2003)..

### **Ribonuclease S**

In an attempt to find the effect of denaturation on the structure of ribonuclease A, X-ray intensity data were collected on RNase S crystals soaked in 0, 1.5, 2, 3 & 5 M urea. At urea concentrations above 2 M it became necessary to crosslink the crystals with gluteraldehyde. Data were also collected on the RNase S crystals at low pH to study the onset of pH denaturation. The structures of RNase S show an increase in disorder with the increase of urea concentration based on rmsd and B-factor analysis. In the 5 M urea structure this increase in disorder is apparent all over the structure but is more so in loop/flexible regions. The increase in disorder appears to be larger for the  $\alpha$  helices than for the  $\beta$ -strands. In the low pH structure there is an increase in disorder and in addition a

major change in the main chain (1 Å) in the loop 65-71 (Ratnaparkhi & Varadarajan, 1999).

### **Thioredoxin**

While it is well known that introduction of Pro residues into the interior of protein  $\alpha$ -helices is destabilizing, there have been few studies that have examined the structural and thermodynamic effects of the replacement of a Pro residue in the interior of a protein  $\alpha$ -helix. We have previously reported an increase in stability in the P40S mutant of *Escherichia coli* thioredoxin of 1-1.5 kcal/mol in the temperature range 280-330 K. We have now determined the structure of the P40S mutant at a resolution of 1.8 Å (Rudresh *et al.*, 2002). In wild-type thioredoxin, P40 is located in the interior of helix two, a long  $\alpha$ -helix that extends from residues 32 to 49 with a kink at residue 40. Structural differences between the wild-type and P40S are largely localized to the above helix. In the P40S mutant, there is an expected additional hydrogen bond formed between the amide of S40 and the carbonyl of residue K36 and also additional hydrogen bonds between the side chain of S40 and the carbonyl of K36. The helix remains kinked. In the wild-type, main chain hydrogen bonds exist between the amide of 44 and carbonyl of 40 and between the amide of 43 and carbonyl of 39. However, these are absent in P40S. Instead, these main chain atoms are hydrogen bonded to water molecules. The increased stability of P40S is likely to be due to the net increase in the number of hydrogen bonds in helix two of *E.coli* thioredoxin.

## References

1. Banerjee, R., Mande, S.C., Ganesh, V., Das, K., Dhanaraj, V., Mahanta, S. K., Suguna, K., Surolia, A. & Vijayan, M. (1994). Crystal structure of peanut lectin, a protein with an unusual quaternary structure. *Proc. Natl. Acad. Sci., U.S.A.*, **91**, 227-231.
2. Bhuvaneshwari, M., Subramanya, H.S., Gopinath, K., Savithri, H.S., Nayudu, M.V. & Murthy, M.R.N. (1995). Structure of sesbania mosaic virus at 3 Å resolution. *Structure*, **3**, 1021-30.
3. Biswal, B.K., Sukumar, N. & Vijayan, M. (2000). Hydration, mobility and accessibility of lysozyme: structures of a pH 6.5 orthorhombic form and its low-humidity variant and a comparative study involving 20 crystallographically independent molecules. *Acta Crystallogr.*, **D56**, 1110-1119.
4. Biswal, B.K. & Vijayan, M. (2002). Crystal structures of human oxy and deoxyhemoglobin at different levels of humidity. Variability in the T state. *Acta Crystallogr.*, **D58**, 1155-1161.
5. Chandra, N.R., Ramachandraiah, G., Bachhawat, K., Dam T.K., Surolia, A. & Vijayan, M. (1999). Crystal structure of a dimeric mannose specific agglutinin from garlic: Quaternary association and carbohydrate specificity. *J. Mol. Biol.*, **285**, 157-1168.
6. Datta, S., Ganesh, N., Chandra, N. R., Muniyappa, K. & Vijayan, M. (2003). Structural studies on MtRecA-Nucleotide complexes: Insights into DNA and nucleotide binding and the structural signature of NTP recognition. *PROTEINS: Structure, Function and Genetics*, **50**, 474-485.
7. Datta, S., Krishna, R., Ganesh, N., Chandra, N. R., Muniyappa, K. & Vijayan, M. (2003a). Crystal structures of *Mycobacterium smegmatis* RecA and its nucleotide complexes. *J. Bacteriology*, **185**, 4280-4284.
8. Datta, S., Prabu, M.M., Vaze, M.B., Ganesh, N., Nagasuma Chandra, R., Muniyappa, K. & Vijayan, M. (2000). Crystal structure of *Mycobacterium tuberculosis* RecA and its complex with ADP-AIF<sub>4</sub>: implications for decreased ATPase activity and molecular aggregation. *Nucleic Acids Res.*, **28**, 4964-4973.

9. Eaazhisai, K., Jayalakshmi, R., Gayathri, P., Anand, R. P., Sumathy, K., Balaram, H. & Murthy, M.R.N. (2003). Crystal Structure of fully ligated Adenylosuccinate synthetase from *Plasmodium falciparum* (communicated).
10. Jeyaprakash, A.A., Geetha Rani, P., Banuprakash Reddy, G., Banumathi, S., Betzel, C., Sekar, K., Surolia, A. & Vijayan, M. (2002). Crystal structure of the jacalin-T-antigen complex and a comparative study of lectin-T-antigen complexes. *J. Mol. Biol.*, **321**, 637-645.
11. Krishna S.S., Hiremath, C.N., Munshi, S.K., Prahadeeswaran, D., Sastri, M., Savithri, H.S. & Murthy, M.R.N. (1999). Three-dimensional structure of physalis mottle virus: implications for the viral assembly. *J Mol Biol.*, **289**, 919-34.
12. Krishna, S.S., Sastri, M., Savithri, H.S. & Murthy, M.R.N. (2001). Structural studies on the empty capsids of Physalis mottle virus. *J Mol Biol.*, **307**, 1035-47.
13. Manoj, N., Srinivas, V.R., Surolia, A., Vijayan, M. & Suguna, K. (2000). Carbohydrate specificity and salt bridge mediated conformational change in acidic winged bean agglutinin. *J. Mol. Biol.*, **302**, 1129-1137.
14. Natesh, R., Manikandan, K., Bhanumoorthy, P., Viswamitra, M.A. & Ramakumar, S. (2003). Thermostable xylanase from *Thermoascus aurantiacus* at ultrahigh resolution (0.89 Å at 100 K and atomic resolution (1.11 Å) at 293K refined anisotropically to small-molecule accuracy. *Acta Crystallogr.*, **D59**, 105-17.
15. Padayana, A.K., Bhat, V.B., Madyastha, K.M. Rajashankar, K.R. & Ramakumar, S. (2001). Crystal structure of a light harvesting protein c-phycoyanin from *Spirulina platensis*. *Biochem Biophys Res Comm*, **282**, 893-898.
16. Parthasarathy S., Balaram H., Balaram P. & Murthy, M.R.N. (2002). Structures of *Plasmodium falciparum* triosephosphate isomerase complexed to substrate analogues: observation of the catalytic loop in the open conformation in the ligand-bound state. *Acta Crystallogr.* **D58**, 1992-2000.
17. Parthasarathy S., Ravindra, G., Balaram H., Balaram, P. & Murthy, M.R.N. (2002a). Structure of the *Plasmodium falciparum* triosephosphate isomerase-phosphoglycolate complex in two crystal forms: characterization of catalytic loop open and closed conformations in the ligand-bound state. *Biochemistry*, **41**, 13178- 13188.

18. Prabu, M.M., Sankaranarayanan, R., Puri, K.D., Sharma, V., Surolia, A., Vijayan, M. & Suguna, K. (1998). Carbohydrate specificity and quaternary association in basic winged bean lectin. *J. Mol. Biol.*, **276**, 787-796.
19. Prasad, B.V.L.S. & Suguna, K. (2003). Effect of pH on the crystal structure of rhizopuspepsin. *Acta Crystallogr. Section D* (in press).
20. Pratap, J.V., Jeyaprakash, A.A., Geetha Rani, P., Sekar, K., Surolia, A. & Vijayan, M. (2002). Crystal structure of artocarpin, a *Moraceae* lectin with mannose specificity, and its complex with methyl- $\alpha$ -D-mannose. Implications to the generation of carbohydrate specificity. *J. Mol. Biol.*, **317**, 237-247.
21. Rajakannan, V., Yogavel, M., Ming-Jye Poi, Jeya Prakash, A., Jeyakanthan, J. , Velmurugan, D., Ming-Daw Tsai & Sekar, K. (2002). Observation of additional calcium ion in the crystal structure of the triple mutant of bovine pancreatic phospholipase A<sub>2</sub>. *J. Mol. Biol.*, **324**, 755-762.
22. Ratnaparkhi, G.S., Ramachandran, S., Udgaonkar, J.B. & Varadarajan, R. (1998). Discrepancies between the NMR and X-ray structures of uncomplexed barstar: An analysis suggests that packing densities of protein structures determined by NMR are unreliable. *Biochemistry*, **37**, 6958-6966.
23. Ratnaparkhi, G.S. & Varadarajan, R. (1999). X-ray crystallographic studies of the denaturation of ribonuclease S. *Proteins*, **36**, 282-294.
24. Ravishankar, R., Bidyasagar, M., Roy, S., Purnapatre, K., Handa, P., Varshney, U. & Vijayan, M. (1998). X-ray analysis of *Escherichia coli* uracil DNA glycosylase (EcUDG) with a proteinaceous inhibitor. The structure elucidation of a prokaryotic UDG. *Nucleic Acids Res.*, **26**, 4880-4887.
25. Ravishankar, R., Ravindran, M., Suguna, K., Surolia, A. & Vijayan, M. (1997). Crystal structure of the peanut lectin-T-antigen complex. Carbohydrate specificity generated by water bridges. *Current Science*, **72**, 855-861.
26. Ravishankar, R., Suguna, K., Surolia, A. & Vijayan, M. (1999). The crystal structures of the complexes of peanut lectin with methyl- $\beta$ -Galactose and N-acetyllactosamine and a comparative study of carbohydrate binding in Gal/GalNAc specific legume lectins. *Acta Crystallogr.*, **D55**, 1375-1382.

27. Rudresh, Rinku Jain, Vardhan Dani, Ashima Mitra, Sarika Srivastava, Siddhartha P. Sarma, Varadarajan, R. & Ramakumar, S. (2002). Structural consequences of replacement of an  $\alpha$ -helical Pro residue in *E. coli* thioredoxin. *Protein Engg.*, **15**, 627- 633.
28. Sadasivan, C., Nagendra, H.G. & Vijayan, M. (1998). Plasticity, hydration and accessibility in Ribonuclease A. The structure of a new crystal form and its low humidity variant. *Acta Crystallogr.* **D54**, 1343-1352.
29. Saikrishnan, K., Bidya Sagar, M., Ravishankar, R., Roy, S., Purnapatre, K., Handa, P., Varshney, U. & Vijayan, M. (2002). Domain closure and action of uracil DNA glycosylase (UDG). Structures of new crystal forms containing the *Escherichia coli* enzyme and a comparative study of the known structures involving UDG. *Acta Crystallogr.*, **D58**, 1269-1276.
30. Saikrishnan, K., Jeyakanthan, J., Venkatesh, J., Acharya, N., Sekar, K. Varshney, U. & Vijayan, M. (2003). Structure of *Mycobacterium tuberculosis* single-stranded DNA-binding Protein. variability in quaternary structure and its implications. *J. Mol. Biol.*, **331**, 385–393.
31. Sangita, V., Parthasarathy, S., Toma, S., Lokesh, G.L., Gowri, T.D.S., Satheshkumar, P.S., Savithri. H.S. & Murthy, M.R.N. (2002). Determination of the structure of the recombinant T=1 capsid of Sesbania mosaic virus. *Curr Sci.*, **82**,1123-31.
32. Sankaranarayanan, R., Sekar, K., Banerjee, R., Sharma, V., Surolia, A. & Vijayan, M. (1996). A novel mode of carbohydrate recognition in jacalin, a *Moraceae* plant lectin with a  $\beta$ -prism fold. *Nature Structural Biology*, **3**, 596-603.
33. Sekar, K., Vijayanthi Mala, S., Yogavel, M., Velmurugan, D., Ming-Jye Poi, Vishwanath, B.S., Gowda, T.V., Arokia Jeyaprakash, A. & Tsai, M.D. (2003) Crystal Structures of the Free and Anisic Acid Bound Triple Mutant of Phospholipase A<sub>2</sub>. *J. Mol. Biol.*, (In the Press).
34. Velanker, S.S., Ray, S.S., Gokhale, R.S., Suma, S., Balaram, H., Balaram, P. & Murthy, M.R.N. (1997). Triosephosphate isomerase from *Plasmodium falciparum*: the crystal structure provides insights into antimalarial drug design. *Structure*, **5**,751-61.

35. Yu, B-Z., Poi, M.J., Ramagopal, U.A., Jain, R., Ramakumar, S., Berg, O.G., Tsai, M-D., Sekar, K. & Jain, M.K. (2000). Structural Basis of the Anionic Interface Preference and Kcat Activation of Pancreatic Phospholipase A2. *Biochemistry*, **39**, 12312-12323.