# STRUCTURAL PROPERTIES OF PHYCOERYTHRIN FROM DULSE PALMARIA PALMATA

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**Short title:** Structural properties of dulse phycoerythrin

**ABSTRACT**

We found that the red alga dulse (*Palmaria palmata*) contains a lot of proteins, which is mainly composed of phycoerythrin (PE), and the protein hydrolysates showed high angiotensin I converting enzyme (ACE) inhibitory activities. Therefore, we investigated the structure of dulse PE to discuss its structure-function relationship. We prepared the chloroplast DNA and analyzed the nucleotide sequences encoding PE by cDNA cloning method. It was clarified that dulse PE has α- and β-subunits and they are composed by 164 amino acids (MW: 17,638) and 177 amino acids (MW: 18,407), respectively. The dulse PE contained conserved cysteine residues for chromophore attachment site. On the alignment of amino acid sequences of dulse PE with those of other red algal PE, the sequence identities were very high (81-92%). In addition, we purified and crystallized the dulse PE, and its crystal structure was determined at 2.09 Å resolution by molecular replacement method. The revealed 3-D structure of dulse PE which forms an (αβ□□hexamer was similar to other red algal PEs. On the other hand, it was clarified that the dulse PE proteins are rich in hydrophobic amino acid residues (51.0%), especially aromatic amino acid and proline residues. The data imply that the high ACE inhibitory activity of dulse protein hydrolysates would be caused by the specific amino acid composition and sequence of dulse PE.

**PRACTICAL APPLICATIONS**

Dulse is an abundant and underused resource, which contains a lot of phycobiliproteins. Then, the dulse protein hydrolysates strongly inhibited the activity of angiotensin I converting enzyme. Therefore, it has the potential to be an ingredient of functional food.

**KEYWORDS:** Red alga; Dulse; *Palmaria palmata*; ACE inhibitory activity; phycoerythrin; Primary structure; 3-D structure

## INTRODUCTION

In red algae, phycobiliproteins locate as phycobilisomes on the stromal side of thylakoid membranes in a chloroplast and play a role of light capturing on photosynthesis (Apt *et al*. 1995; Sekar and Chandramohan 2008). The prominent classes of red algal phycobiliproteins are phycoerythrin (PE) followed by phycocyanin (PC) and allophycocyanin (APC), and they are divided on their spectral properties (λ-max of PE = 490-570 nm, λ-max of PC = 610-625 nm, λ-max of APC = 650-660 nm) (Sun *et al*. 2009). Phycobiliproteins of red algae commonly contain α- and β-subunits, and each subunit bears covalently binding one or several phycobilin chromophores at the specific cysteine residues (PE: phycoerythrobilin and phycourobilin, PC: phycocyanobilin and phycoerythrobilin, APC: phycocyanobilin) (Apt *et al.* 1995). The above spectroscopic property of each phycobiliprotein is derived from the specific chromophore composition. The α- and β-subunits of phycobiliprotein combine with each other to form an (αβ) heterodimer, and then three (αβ)s form (αβ□□ trimer arranging a symmetry disc (Apt *et al.* 1995). The discs are organized in supramolecular complexes called phycobilisomes. The core of phycobilisomes is composed of APC discs and the rod is composed of PC and PE discs. On the previous proteomic and genomic studies, some marine red algal phycobiliproteins were studied (Roell and Morse 1993; Ducret *et al*. 1994; Hagopian *et al*. 2004; Niu *et al*. 2006; Tajima *et al*. 2012; Wang *et al*. 2013; DePriest *et al*. 2013). However, there is no information about structural properties of dulse phycobiliproteins.

Dulse (*Palmaria palmata*) is a red alga mainly distributed in high-latitude coastal areas, and it is popular in Ireland and Atlantic Canada as a food and a source of minerals. Fitzgerald *et al.* (2012) and Harnedy *et al*. (2015) also reported the dulse protein hydrolysates show the inhibitory effects for renin and dipeptidyl peptidase IV, respectively. In Japan,

dulse is also distributed around the coast of Hokkaido Prefecture and at Pacific coast of Aomori Prefecture. However, dulse is rarely eaten in Japan. In addition, dulse is even removed from Kombu (*Laminaria* sp.) farming areas in Hokkaido, because it inhibits the growth of young Kombu in winter season. Therefore, we have begun exploring the health benefits of dulse to advance its use as a functional food material. In the previous study, we found that dulse contains a lot of proteins, which are mainly composed of PE followed by PC and APC **(**Furuta *et al*., 2016). Then, the dulse protein hydrolysates strongly inhibited the activity of angiotensin I converting enzyme (ACE). Moreover, it was suggested that the ACE inhibitory peptides are mainly derived from the dulse PE by thermolysin hydrolysis. Therefore, in this study, we investigated the primary and 3-D structures of dulse PE to discuss its structure-function relationship.

## MATERIALS AND METHODS

### Materials

Dulse (*P. palmata*) was collected in the coast of Usujiri, Hokkaido, Japan in February. A portion of the thalli was steeped into RNAlater solution (Applied Biosystems, CA, USA) and stored at -80 $^{o}$C until use.

Restriction enzymes, *Hin*d III and *Ssp* I, were purchased from TaKaRa Bio (Shiga, Japan). RNase A was purchased from Nacalai Tesque (Kyoto, Japan). ACE from rabbit lung was purchased from Sigma Chemical Co. (Mo, USA). Hyppuryl-L-histidyl-L-leucine (Hip-His-Leu), thermolysin (EC 3.4.24.27) from *Bucillus thermoproteolyticus*, pepsin (EC 3.4.23.1) from porcine stomach, and trypsin (EC 3.4.21.4) from bovine pancreas were purchased from Wako Pure Chemical (Osaka, Japan). All other regents were purchased from Wako Pure Chemical (Osaka, Japan).

### Preparation of dulse protein hydrolysates

The frozen samples were lyophilized and ground into a fine powder by Wonder Blender WB-1 (OSAKA CHEMICAL Co., Osaka, Japan). Proteins were extracted from the powder by adding 20 v/w of distilled water at 4 $^{o}$C for 7 h. The extracts were centrifuged (H-200, Kokusan, Tokyo, Japan) at 4 $^{o}$C, 15,000 x *g* for 10 min, and then the supernatants were used as “dulse proteins”. Some of the dulse proteins were hydrolyzed by 1.0 wt% of thermolysin at 70 $^{o}$C for 3 h, and the reaction was terminated by heat treatment at 100 $^{o}$C for 5 min. Subsequently, the solution was centrifuged at 4 $^{o}$C, 15,000 x *g* for 10 min. The supernatants were dried by lyophilization into the “thermolysin hydrolysates”. Other dulse proteins were

adjusted to pH 2.0, and the proteins were digested by 1.0 wt% of pepsin at 37 $^{o}$C for 3 h. After the reaction, the pepsin digests were adjusted to pH 8.0. Subsequently, the solutions were centrifuged at 4 $^{o}$C, 15,000 x *g* for 10 min. The supernatants were dried by lyophilization into the "pepsin hydrolysates". Some of the pepsin hydrolysates were digested by 1.0 wt% of trypsin at 37 $^{o}$C for 3 h. After that, the digested solutions were boiled for 5 min to inactivate the enzymes, and then centrifuged at 4 $^{o}$C, 15,000 x *g* for 10 min. The supernatants were dried by lyophilization into the "pepsin-trypsin hydrolysates".

ACE Inhibitory Assay

ACE inhibitory assay was carried out according to the method of Cheung and Cushman (1973) with some modifications. Fifteen microliters of sample solution (5.0 mg/mL) was added to 30 μL of ACE (0.2 U/mL), and incubated at 37 $^{o}$C for 5 min. Thirty microliters of Hip-His-Leu solution (12.5 mM in 0.1 M sodium borate buffer containing 400 mM NaCl at pH 8.3) was added to the mixture. After incubation at 37 $^{o}$C for 1 h, the reaction was stopped by adding 75 μL of 1.0 M HCl, and the mixture was extracted with 450 μL of ethyl acetate. Four hundred microliters of the upper layer was evaporated, and then the hippuric acid was dissolved in 1.5 mL of distilled water. The absorbance at 228 nm of the solution was measured by a spectrophotometer. The inhibition was calculated from the equation [1- (As-Asb) / (Ac-Acb)] x 100, where Ac is the absorbance of the buffer, Acb is the absorbance when the stop solution was added to the buffer before the reaction, As is the absorbance of the sample, and Asb is the absorbance when the stop solution was added to the sample before the reaction.

Isolation of Dulse Chloroplast DNA

Thawed dulse sample was dissected with scissors and 150 mg of it was put into a microcentrifuge tube. The sample was homogenized in 1.5 mL of TRIzol reagent (Invitrogen, CA, USA) using disperser. Then, 300 μL of chloroform was added to the homogenate, and the solution was mixed. The mixture was centrifuged at 4 $^{o}$C, 15,000 x *g* for 20 min, and the supernatant was pooled in a micro tube. Next, equal volume of 2-propanol was added in the tube to precipitate chloroplast DNA, and the solution was centrifuged at 4 $^{o}$C, 15,000 x *g* for 20 min. The precipitate was dissolved in 100 μL of TE buffer, and the remaining RNA in it was removed by RNase A treatment (10 μg, 37 $^{o}$C, 30 min). After the reaction, 200 μL of sterilized ultrapure water and 300 μL of phenol-chloroform-isoamyl alcohol (25:24:1, v/v/v) were added, and the mixed solution was centrifuged at 4 $^{o}$C, 15,000 x *g* for 15 min. Following similar treatment with chloroform-isoamyl alcohol (24:1, v/v), chloroplast DNA was collected by ethanol precipitation. The dried precipitate was dissolved in 100 μL of TE buffer.

Degenerate PCR

Forward primer (PE-F1: ATGCT (A/C/G/T) AA (C/T) GC (A/C/G/T) TTTTC (A/C/G/T) (A/C) G) and reverse primer (PE-R1: CC (A/C/G/T) GC (A/G/T) AT (A/C/G/T) CCCCA (C/T) TC (A/G) TC) for degenerate PCR were designed on the basis of well-conserved regions of red algal PE genes (*rpeB* and *rpeA*) (Fig. 1a). TaKaRa EX *Taq* Hot Start Version (TaKaRa Bio, Shiga, Japan) was used on the amplification. The PCR program for TaKaRa EX *Taq* HS was 40 cycles of 98 $^{o}$C for 10 sec, 47 $^{o}$C for 30 sec, 72 $^{o}$C for 2 min, and 10 min at 72 $^{o}$C. The PCR products were separated by low melting agarose gel electrophoresis and

were purified from the gel using Wizard SV Gel and PCR Clean-Up System (Promega, WI, USA).

Inverse PCR

The remaining 5'- and 3'-regions of dulse PE genes were determined by inverse PCR method. Dulse chloroplast DNA was digested with restriction enzymes, *Ssp* I and *Hin*d III. The digested DNA fragments were cleaned by Mini Elute Spin Columns (QIAGEN, Dusseldorf, Germany), and ligated with T4 DNA ligase (TaKaRa Bio, Shiga, Japan) at 16 $^{o}$C for 18 h. For amplifications, specific forward (PE-IF1: CATTACTGATGGTAACAAACGC, PE-IF2: GAGACGTTGATCATTATATGCG) and reverse (PE-IR1: TCACTGCCACCAACGTAAGC, PE-IR2: CTCCACCTTCTTTTACAACAGC) primers were designed using the sequence data determined by degenerate PCR (Fig. 1b). TaKaRa EX *Taq* Hot Start Version (TaKaRa Bio, Shiga, Japan) was used on the amplification, and the PCR program was 40 cycles of 98 $^{o}$C for 10 sec, 50 $^{o}$C for 30 sec, 72 $^{o}$C for 2 min, and 10 min at 72 $^{o}$C.

Cloning and Sequencing

PCR products were subcloned to pDrive Cloning Vector using QIAGEN PCR Cloning Kit (QIAGEN, Dusseldorf, Germany) for sequencing. The nucleotide sequences of cDNAs were determined with BigDye Terminator v3.1 Cycle Sequencing Kit (Applied Biosystems, CA, USA) using ABI PRISM 310 Genetic Analyzer (Applied Biosystems, CA, USA). Nucleotide and deduced amino acid sequences of dulse PE gene were aligned using CLUSTAL W program (Thompson, *et al*. 1994). Molecular weight and isoelectric point of dulse PE were calculated from deduced amino acid sequences by using Compute pI/Mw tool

(Bjellqvist *et al*. 1993; Bjellqvist *et al*. 1994; Hoogland *et al*. 2000).

Crystallization, X-ray diffraction data collection, and structure determination

Frozen dulse samples (-30 $^{o}$C) were taken into a flask, and 4 volumes (v/w) of distilled water was added in it. The dulse phycobiliproteins were extracted at 4 $^{o}$C for 12 h, and the extracts were filtered. Then, the filtrates were centrifuged at 4 $^{o}$C, 15,000 x *g* for 15 min. The extracted dulse proteins were dialyzed against distilled water at 4 $^{o}$C for 24 h. The dulse PE was purified from the protein extracts by a preparative electrofocusing using Rotofor system (Bio-Rad, CA, USA) (Fig. 4a and 4b). Crystallization was carried out by hanging-drop vapor diffusion method. Crystals of dulse PE were grown from a buffer containing 0.1 M sodium acetate (pH 4.8) and 12% PEG4000 (Fig. 4b). X-ray diffraction dataset of dulse PE was collected on the beamline BL17A at Photon Factory (Tsukuba, Japan) under cryogenic condition (100 K). Crystals were mounted on the X-ray diffractometer after soaked into a crystallization buffer containing 20% PEG400 as a cryoprotectant. The diffraction data were indexed, integrated, scaled, and merged using the XDS program (Kabsch 2010). The data statistics are shown in Table 1. Crystal structures were determined by the molecular replacement method with the program MOLREP (Vagin and Teplyakov 1997) using the structure of PE from *Polysiphonia urceolata* (PDB ID 1LIA) as a search model. To monitor the refinement, a random 5% subset was set aside for the calculation of the $R_{free}$ factor. Structure refinement was carried out with phenix.refine (Adams *et al*. 2010). The stereochemical quality of the structure was analyzed with the program MOLPROBITY (Chen *et al*. 2010). The refinement statistics are summarized in Table 1. The atomic coordinates of dulse PE has been deposited in the Protein Data Bank, www.pdb.org (PDB ID code 5B13).

## RESULTS AND DISCUSSION

Inhibition of ACE activity of dulse protein hydrolysates

In the previous study, we found that dulse contains a lot of proteins, which are mainly composed of PE (Furuta *et al*. 2016). The extracted dulse proteins showed slight ACE inhibitory activity, but the activity was extremely enhanced by thermolysin hydrolysis. In addition, nine ACE inhibitory peptides (YRD, AGGEY, VYRT, VDHY, IKGHY, LKNPG, LDY, LRY, FEQDWAS) were isolated from the hydrolysates by reversed-phase high-performance liquid chromatography (HPLC), and the sequences of YRD, AGGEY, VYRT, VDHY, LKNPG, LDY and LRY were detected in the primary structures of PE α- and β-subunits (Furuta *et al*. 2016). From these results, it was suggested that the ACE inhibitory peptides are mainly derived from the dulse PE by thermolysin hydrolysis. Therefore, in this study, we prepared the dulse protein hydrolysates by thermolysin, pepsin, and pepsin-trypsin digestion, and we compared with their ACE inhibitory activity. As shown in Fig. 2, the thermolysin hydrolysates inhibited 88% of ACE activity, and pepsin and pepsin-trypsin hydrolysates also suppressed 72% and 75% of them, respectively. We calculated the peptide sequences derived from the deduced amino acid sequences of dulse PE α- and β- subunits by using PEPTIDEMASS (Wilkins *et al.* 1997). As a result, it was predicted that 76 peptides (α-subunit: 38 peptides, av. length=3, av. mass=346; β- subunit: 38 peptides, av. length=4, av. mass=396) are derived from dulse PE α- and β- subunits by pepsin-trypsin hydrolysis. From the result, ACE inhibitory peptides are also produced from dulse proteins, especially PE, by proteolytic hydrolysis in our digestive tract. In future, we would like to analyze the structural properties of ACE inhibitory peptides in the pepsin-trypsin hydrolysates to compare with those of thermolysin hydrolysates.

Then, in the next stage, we investigated the primary and 3-D structures of dulse PE to discuss its structure-function relationship.

Nucleotide sequences of dulse phycoerythrin genes

In this study, we obtained 1,560 bp of nucleotide sequences on the analysis of the dulse PE gene, and the gene structure encoding dulse PE (*rpeA* and *rpeB*, GenBank accession number AB625450) (Fig. 3) was clarified. This is the first report for the PE gene of Palmariales.

As shown in Fig. 3, the dulse PE gene was constituted of α- and β-subunit genes and A/T-rich spacer. AT contents of the spacer in dulse PE gene were 79% (60 bp/76 bp). Bernard *et al*. (1992) reported that *rpeB* gene of *Rhodella violacea* is split by intervening sequence and the sequence has a feature of group II intron that is typical in eukaryotic organisms, however the dulse PE gene has no introns. The dulse *rpeB* was present in prior to the *rpeA* (Fig. 3). The positions of *rpeA* and *rpeB* were the same as those of other red algae, for example *Gracilaria tenuistipitata* (Hagopian *et al*. 2004), *Chondrus crispus* (GenBank accession number HF562234), *Pyropia yezoensis* (Wang *et al*. 2013), *P. haitanensis* (Wang *et al*. 2013) and *P. purpurea* (GenBank accession number U38804). The nucleotide sequences of dulse PE gene also showed considerably high identities (about 80%) with those of other red algae (Table 2). The GC contents in dulse PE gene were about 40% (*rpeA*: 40.2%, *rpeB*: 40.5%), and these numerical values showed very high similarity to those of *P. yezoensis* (*rpeA*: 42.6%, *rpeB*: 40.6%), *P. haitanensis* (*rpeA*: 41.2%, *rpeB*: 41.4%) and *P. purpurea* (*rpeA*: 41.8%, *rpeB*: 42.0%), whereas it was a little higher than those of *G. tenuistipitata* (*rpeA*: 37.0%, *rpeB*: 38.8%) and *C. crispus* (*rpeA*: 37.2%, *rpeB*: 39.1%) (Table 2).

The consensus sequences at -10 (5’-TATAAT-3’) and -35 (5’-TTGACA-3’)

promoter elements for RNA polymerase were searched in the dulse PE genes. As a result, putative motifs were found at upstream regions of *rpeB* (-10: TATATT or TGTAAT, -35: TAAACA or GAAACA) (single and double underlines in Fig. 3). We also sought out the Shine-Dalgarno sequence (5'-AGGAGGT-3') acting as a binding site with 16S rRNA, and then the homologous structures were detected in the upstream of each gene (*rpeB*: AGGAGA, *rpeA*: AGGAGA,) (dotted underlines in Fig. 2).

Primary structure of dulse phycoerythrin

The deduced amino acid sequences of dulse PE α- and β-subunits are shown in Fig. 3. The PE α-subunit consists of 164 amino acids (495 bp), and its molecular weight and isoelectric point were calculated at 17,638 and 5.40, respectively. Red algal PE commonly has two kinds of chromophores, phycoerythrobilin and phycourobilin. Generally, red algal PE α-subunit binds to two phycoerythrobilin with two Cys residues (Lundell *et al*. 1984; Ficner *et al*. 1992), and the dulse PE α-subunit also retained Cys residues at the corresponding positions (αCys82 and αCys139 in Fig. 3 and Fig. 4a). The dulse PE β-subunit consists of 177 amino acids (534 bp), and its molecular weight and isoelectric point were calculated at 18,407 and 5.42, respectively. It is already known that one phycourobilin and two phycoerythrobilins bind to four Cys residues in β-subunit apo-protein through thioether linkage (Lundell, *et al*. 1984; Ficner *et al*. 1992). In the dulse PE β-subunit, corresponding Cys residues binding with phycourobilin (βCys50 and βCys61 in Fig. 3 and Fig. 4b) and with phycoerythrobilins (βCys82 and βCys158) were all conserved.

3-D structures of dulse phycoerythrin

We purified and crystallized the dulse PE (Fig.5a), and its crystal structure was determined by molecular replacement method (Fig.5b and Table 1). The revealed 3-D structure of purified dulse PE in this study formed an (αβ□□hexamer, which was similar to other red algal PEs (Chang *et al*. 1996; Contreras-Martel *et al*. 2001; Ritter *et al*. 1999). The root mean square deviations (r.m.s.d) with other PEs are as follows, *Polysiphonia urceolata* PE: 0.70 Å, *Griffithsia monilis* PE: 0.55 Å, *Gracilaria chilensis* PE: 0.60 Å. As observed for other homologous phycobiliproteins such as PE, PC and APC, the backbone conformations of α- and β-subunits of dulse PE have nine α-helices (X, Y, A, B, E, F', F, G, and H) as a dominant secondary structure element (Fig. 5b) (Lundell *et al*. 1984; Ficner *et al*. 1992; Liu *et al*. 1999; Jiang *et al*. 2001). Each subunit had a structure quite similar to those of other PEs. The r.m.s.d. was 0.39 Å, 0.33 Å, and 0.37 Å for α-subunit, and 0.56 Å, 0.48Å, and 0.55Å for β-subunit of *P. urceolata* PE, *G. monilis* PE and *G. chilensis* PE, respectively. The electron density clearly showed the presence of chromophores covalently linked to Cys residue through thioether bond. Phycoerythrobilins were linked covalently with each of αCys82, αCys139, βCys82, and βCys158, whereas a phycourobilin was linked doubly to βCys50 and βCys61. The presence of chromophores at these sites is highly conserved among PEs of which structures have been reported (Camara-Artigas *et al*. 2012; Chang *et al*. 1996; Contreras-Martel *et al*. 2001; Lundell *et al*. 1984; Ritter *et al*. 1999). Taken these observations together, we concluded that dulse PE has structural characteristics common to other PEs.

Structure-function relationship of dulse phycoerythrin

ACE is a key enzyme in the regulation of peripheral blood pressure catalyzing the production of angiotensin II and the destruction of bradykinin (Cheung *et al*. 1980). The specific

inhibitors of the enzyme therefore have been considered with effective antihypertensive drugs. In addition to the drugs, ACE inhibitory peptides from daily food are also useful for maintaining blood pressure at a healthy level. Although the potency of peptide is lower than drug, it does not have side effect (Balti *et al*. 2015). Up to now, many researchers have identified various ACE inhibitory peptides from the enzymatic hydrolysates of food (Amado *et al*. 2014; Ghassem *et al*. 2014; Balti *et al*. 2015; García-Moreno *et al*. 2015). Besides, Cheung *et al*. (1980) obtained the interesting results by using several synthetic peptides for a substrate of ACE, that is to say, the ACE inhibitory activity of peptide is closely related to the C-terminal dipeptide residues in it. Specifically, in case of tryptophan, tyrosine, or proline residue is located at the N-terminal side of dipeptide and aromatic amino acid or proline residue is at the C-terminus, its inhibitory potency is the most. Indeed, it has been well known that the peptides are usually composed of hydrophobic and aromatic amino acids (Amado *et al*. 2014; Ghassem *et al*. 2014; Balti *et al*. 2015; García-Moreno *et al*. 2015). Therefore, we calculated the contents of hydrophobic and aromatic amino acid residues in dulse PE by using the primary structures in this study (Fig. 3). As a result, it was clarified that the dulse PE are rich in hydrophobic amino acids (51.0%), especially the contents of aromatic amino acids and proline (10.0-10.9%) are relatively high. On the other hand, crystal structure analysis clearly showed that dulse PE shares significant similarity in their tertiary structure with other PEs. Therefore, we concluded that the cause of high ACE inhibitory activity of dulse PE hydrolysates would be the specific amino acid compositions and sequences, independent of the tertiary structure.

## ACKNOWLEDGMENTS

We thank Dr. Koji Mikami, Faculty of Fisheries Sciences, Hokkaido University, for the technical assistance of inverse PCR. We thank Dr. Hiroki Saeki, Faculty of Fisheries Sciences, Hokkaido University, for the technical assistance of preparative electrofocusing using Rotofor system. We also thank Mr. Yuki Kato, Hokkaido Industrial Technology Center, for the operative support of DNA sequencer.

This work was supported in part by the Regional Innovation Cluster Program (Global Type), Ministry of Education, Culture, Sports, Science and Technology, Japan and the Grant-in-Aid for High Technology Research Program from the Ministry of Education, Culture, Sports, Science, and Technology of Japan. This work was supported in part by Grants-in-Aid for Scientific Research (24000011, 20374225, and 16H00748 to YT) and Platform for Drug Discovery, Informatics, and Structural Life Science from the Ministry of Education, Culture, Sports, Science and Technology, Japan, and JST, PRESTO (YT).

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**(Captions to figures)**

**FIG. 1.** GENERAL STRUCTURES OF RED ALGAL PHYCOERYTHRIN GENES AND POSITIONS OF PRIMERS USED IN DEGENERATE AND INVERSE PCRS.

a: Positions of primers used in degenerate PCR.

b: Positions of primers used in inverse PCR.

PE represent phycoerythrin. Sequences of each primer are shown in the text. Restriction sites are expressed as *Ssp* I, *Hin*d III.

**FIG. 2.** ACE INHIBITORY ACTIVITIES BY DULSE PROTEIN HYDROLYSATES.

1: ACE inhibitory activity with thermolysin hydrolysates.

2: ACE inhibitory activity with pepsin hydrolysates.

3: ACE inhibitory activity with pepsin-trypsin hydrolysates.

**FIG. 3.** NUCLEOTIDE AND DEDUCED AMINO ACID SEQUENCES OF DULSE PHYCOERYTHRIN GENE.

Asterisks show stop codon. Single and double underlines express putative -10 and -35 consensus sequences, respectively. Dotted underline is putative RNA polymerase-binding motif.

**FIG. 4.** ALIGNMENT OF AMINO ACID SEQUENCES OF RED ALGAL PHYCOERYTHRINS.

a: PEα; Phycoerythrin α-subunit.

b: PEβ; Phycoerythrin β-subunit.

Asterisks show characteristic amino acid residues in the molecule. *P. palmata* (GenBank accession number: AB625450, in this study); *G. tenuistipitata* (AY673996), *C.*

*crispus* (HF562234), *P. yezoensis* (D89878), *P. haitanensis* (DQ449070), *P. purpurea* (U38804).

**FIG. 5.** DULSE PHYCOERYTHRIN CRYSTAL AND 3-D STRUCTURE OF DULSE PHYCOERYTHRIN.

a: Crystallization of purified dulse phycoerythrin.

Purified PE: purified dulse phycoerythrin. PE crystal: dulse phycoerythrin crystal.

b: 3-D structure of dulse phycoerythrin.

PE (αβ□□ □□□□ mer: Ribbon representation of dulse phycoerythrin (αβ□□□□□□ mer. The α- and β-subunits are colored red and blue, respectively. For clarity, one subunit of α- and β-subunit is colored orange and green, respectively. The bound CYC and PUB are also shown as yellow and green sticks, respectively. PEα: Ribbon representation of dulse phycoerythrin α-subunit. The model is colored according to the sequence from blue at the N-terminus to red at the C-terminus. Bound CYC chromophores are shown as yellow sticks. The cysteine resides linked with the chromophres are also shown. PEβ: Ribbon representation of dulse phycoerythrin β-subunit colored according to the sequence from blue at the N-terminus to red at the C-terminus. Bound CYC and PUB chromophores are shown as yellow and green sticks.

**TABLE 1** DATA COLLECTION AND REFINEMENT STATISTICS

| | |
|---|---|
| Data collection | |
| Beamline | Photon Factory BL17A |
| Space group | *C*2 |
| Cell dimensions | |
| a, b, c (Å) | 187.5, 111.9, 112.7 |
| α, β, γ (°) | 90.0, 91.9, 90.0 |
| Wavelength (Å) | 0.98 |
| Resolution (Å) [a] | 50–2.09 (2.22–2.09) |
| No. of total/unique reflections | 519,606/135,827 (81,130/21,390) |
| $R_{sym}$ (%)[a, b] | 11.6 (69.9) |
| Completeness (%)[a] | 99.5 (97.6) |
| Multiplicity[a] | 3.8 (3.8) |
| Average $I/\sigma(I)$ [a] | 11.21 (2.13) |
| | |
| Refinement | |
| Resolution (Å) | 50–2.09 |
| $R_{work}/R_{free}$ | 0.198/0.237 |
| No. of atoms | |
| Protein | 15,114 |
| Ligand | 1,290 |
| Solvent | 1,812 |
| r.m.s.d. | |
| Bond lengths (Å) | 0.003 |
| Bond angles (°) | 1.318 |
| Ramachandran plot | |
| Favored (%) | 97.6 |
| Allowed (%) | 2.4 |
| Outlier (%) | 0 |

*a* Values in parentheses correspond to the highest resolution shell.

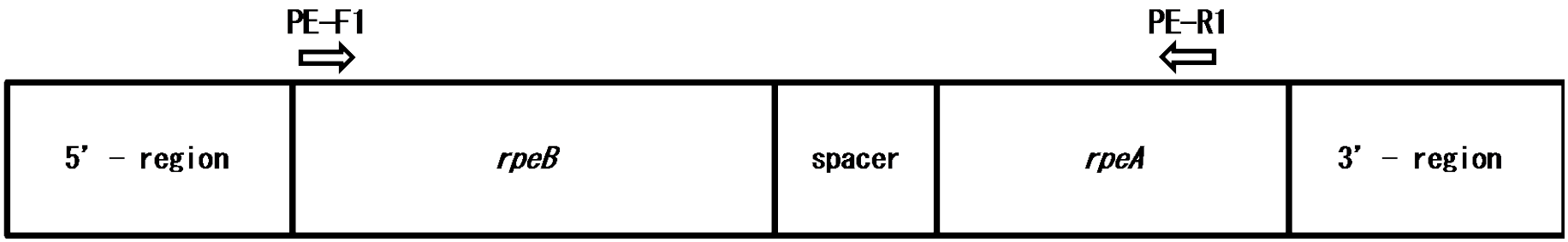
*b* $R_{merge} = \Sigma_h \ \Sigma_i \ |I_{h,i} - \langle I_h \rangle| / \Sigma_h \Sigma_i \ |I_{h,i}|$, where $\langle I_h \rangle$ is the mean intensity of a set of equivalent reflections.

**TABLE 2.** GC CONTENT, NUCLEOTIDE IDENTITY, AND AMINO ACID IDENTITY ON RED ALGAL PHYCOERYTHRINS

| Organism | Gene name | | GC content (%) | Nucleotide identity to *P.palmata* (%) | Amino acid identity to *P.palmata* (%) | Accession No. |
|---|---|---|---|---|---|---|
| *Palmaria palmata* | PE | α-subunit | 40.2 | — | — | AB625450 |
| | | β-subnuit | 40.5 | — | — | |
| *Gracilaria tenuistipitata* | PE | α-subunit | 37.0 | 79 | 87 | AY673996 |
| | | β-subnuit | 38.8 | 78 | 81 | |
| *Chondrus crispus* | PE | α-subunit | 37.2 | 82 | 85 | HF562234 |
| | | β-subnuit | 39.1 | 80 | 85 | |
| *Porphyra yezoensis* | PE | α-subunit | 42.6 | 82 | 89 | D89878 |
| | | β-subnuit | 40.6 | 82 | 92 | |
| *Porphyra haitanensis* | PE | α-subunit | 41.2 | 83 | 90 | HM008261 |
| | | β-subnuit | 41.4 | 83 | 92 | |
| *Porphyra purpurea* | PE | α-subunit | 41.8 | 82 | 90 | NC_000925.1 |
| | | β-subnuit | 42.0 | 83 | 92 | |

FIG.1

a: degenerate PCR




b: invers PCR

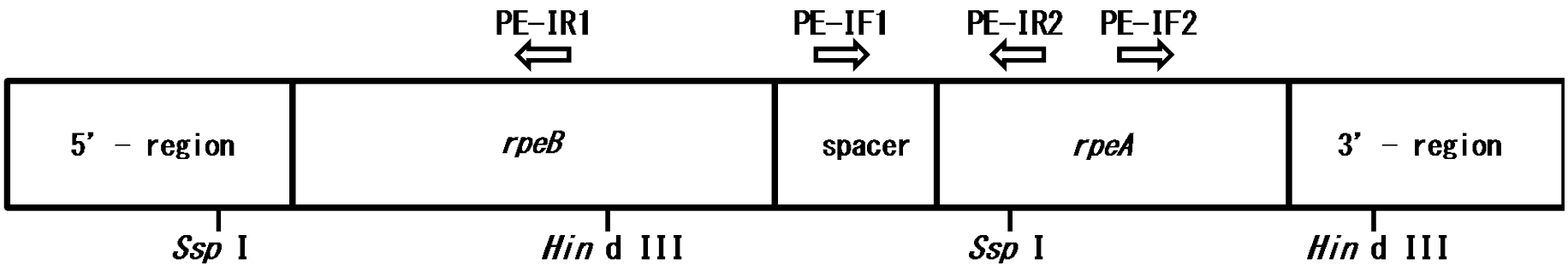


FIG. 2

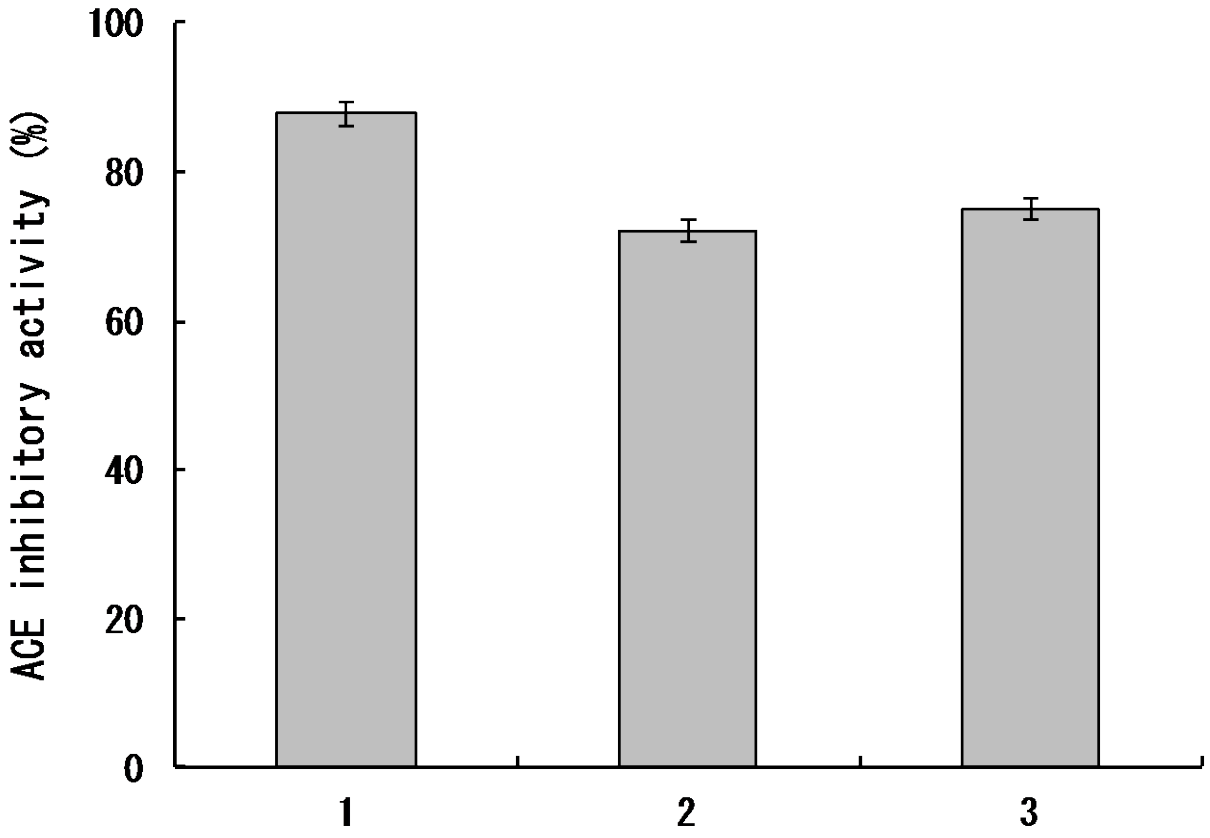


FIG. 3

5' -ATAATTAAATTTATGATTAAAAACAGTAAGTTTTAAATCCTCTATTTTTAACTAAATTTTATTGTTACAATATATTACTTTGTTCTTAATAGGTTATTAGAACTGTCATATATTATGTAT 120

TCGATACTAATACATCAGCAAGTTCAATTTTTTAACAGCTGAAACAGCTAAGTCCTTTATATTTGTAATAAGGAGAGTTCCATGCTTGACGCATTTTCCAGAGTTGTAGTAAATTCAGAC 240

M L D A F S R V V V N S D

GCTAAAGCTGCTTACGTTGGTGGCAGTGACCTACAGGCTCTAAAAAAATTCATTACTGATGGTAACAAACGCTTAGATTCTGTTAGCTTTGTTGTTTCAAACGCTAGCTGTATCGTTTCT 360

A K A A Y V G G S D L Q A L K K F I T D G N K R L D S V S F V V S N A S C I V S

GATGCAGTATCAGGTATGATTTGTGAAAATCCTGGCTTAATTGCTCCTGGTGGTAATTGTTACACTAATCGTCGTATGGCTGCTTGTCTACGTGATGGTGAAATCATTCTACGTTATGCT 480

D A V S G M I C E N P G L I A P G G N C Y T N R R M A A C L R D G E I I L R Y A

TCTTATGCTTTACTAGCTGGCGATCCTTCTGTACTAGAAGATCGTTGTCTTAATGGATTAAAAGAAACTTACATTGCGTTAGGAGTTCCTACTAATTCATCAGTAAGAGCTGTAAGCATT 600

S Y A L L A G D P S V L E D R C L N G L K E T Y I A L G V P T N S S V R A V S I

ATGAAAGCTTCAGCTACAGCGTTTGTATCAGGCACAGCTTCTGACCGTAAAATGGCTTGTCCTGATGGAGACTGTTCAGCTCTAGCATCAGAACTAGGTAGCTATTGTGATAGAGTTGCT 720

M K A S A T A F V S G T A S D R K M A C P D G D C S A L A S E L G S Y C D R V A

GCTGCAATTAGCTAATAAAAGCTGTTATAGACTAGAGTATATAAATTTTTATACTCTTAGGCTAAATACTTAATAAAAAAAGGAGATTAATATGAAATCAGTTATGACTACAACGATTAG 840

A A I S *

M K S V M T T T I S

TGCTGCAGACGCAGCTGGTCGTTTCCCTTCATCTTCAGATCTTGAATCAGTTCAAGGTAATATTCAACGTGCTGCTGCTAGATTAGAAGCTGCTGAAAAGTTAGCTAGTAATCATGAAGC 960

A A D A A G R F P S S S D L E S V Q G N I Q R A A A R L E A A E K L A S N H E A

TGTTGTAAAAGAAGGTGGAGACGCTTGTTTTGCTAAGTATTCTTACTTAAAAAATCCAGGTGAAGCTGGCGATAGCCAAGAAAAAGTAAACAAGTGCTACAGAGACGTTGATCATTATAT 1,080

V V K E G G D A C F A K Y S Y L K N P G E A G D S Q E K V N K C Y R D V D H Y M

GCGTCTTGTAAACTATTCTTTAGTAGTTGGCGGAACTGGTCCTCTTGATGAGTGGGCTATTGCTGGTGCTCGTGAAGTTTATAGAACTTTAAATCTTCCATCAGCTTCTTATGTTGCTGC 1,200

R L V N Y S L V V G G T G P L D E W A I A G A R E V Y R T L N L P S A S Y V A A

TTTCGCTTTCACTCGTGATAGACTATGTGTGCCACGTGACATGTCTGCTCAAGCAGGTGGAGAATATGTTGCAGCTCTAGATTATATTGTTAATGCTTTAACCTAATTTATAGCTTGATA 1,320

F A F T R D R L C V P R D M S A Q A G G E Y V A A L D Y I V N A L T *

ATATAATAAACAAATAAAATAGCTAAGCAAGCTTATTGCTTAGCTATTTTATTTGTTTATTGAACAACTAAGCTCAGTTATGATATTGATGTATAGTAGTACTATATAATATACGTAATT 1,440

ATAAATACTACATACGTTGGAGCTTATTATGGATTCAAGTACAATGCAAAATACATGCATTAATATATCTTTTGGTCTTCTACTAGTGACTTTATTGGCTTATTGGACAAGTATTGCCTT- 3' 1,560

FIG.4a

a: PEα

```
                    1         10        20        30        40        50
P.palmata           MKSVMTTTISAADAAGRFPSSSDLESVQGNIQRAAARLEAAEKLASNHEA
G.tenuistipitata    MKSVITTVISAADAAGRFPSSSDLESIQGNIQRASARLEAAEKLADNHDA
C.crispus           MKSVITTIISAADAAGRFLTSSDLESVQGNIQRAGARLEAAEKLANNHEA
P.yezoensis         MKSVITTTIGAADAAGRFPSSSDLESVQGNIQRAAARLEAAEKLASNHEA
P.haitanensis       MKSVITTTISAADAAGRFPSSSDLESVQGNIQRAAARLEAAEKLASNHEA
P.purpurea          MKSVITTTISAADAAGRFPSSSDLESVQGNIQRAAARLEAAEKLASNHEA
                     **         *   *     *

                              60        70        80        90       100
P.palmata           VVKEGGDACFAKYSYLKNPGEAGDSQEKVNKCYRDVDHYMRLVNYSLVVG
G.tenuistipitata    VVKEAGDACFGKYSYLKNAGEAGENQEKVNKCYRDIDHYMRLVNYSLVVG
C.crispus           VVKEAGDACFAKYSFLKNSGEAGDSQEKVNKCYRDIDHYMRLINYALIVG
P.yezoensis         VVKEAGDACFAKYSYLKNPGEAGDSQEKVNKCYRDVDHYMRLVNYCLVVG
P.haitanensis       VVKEAGDACFAKYSYLKNPGEAGDSQEKVNKCYRDVDHYMRLVNYCLVVG
P.purpurea          VVKEAGDACFAKYSYLKNPGEAGDSQEKVNKCYRDVDHYMRLVNYCLVVG
                                                     *       *

                              110       120       130       140       150
P.palmata           GTGPLDEWAIAGAREVYRTLNLPSASYVAAFAFTRDRLCVPRDMSAQAGG
G.tenuistipitata    GTGPLDEWAIAGAREVYRTLNLPTSAYVAAFAFTRDRLCVPRDMSAQAGV
C.crispus           GTGPFDEWGIAGAREVYRALNLPSASYLAAFVFTRDRLCVPRDMSAQAGL
P.yezoensis         GTGPVDEWGIAGAREVYRTLNLPTSAYVASFAFARDRLCVPRDMSAQAGV
P.haitanensis       GTGPVDEWGIAGAREVYRTLNLPTSAYVASFAFARDRLCVPRDMSAQAGV
P.purpurea          GTGPVDEWGIAGAREVYRTLNLPTSAYVASFAFARDRLCVPRDMSAQAGV
                         *                                 *

                              160
P.palmata           EYVAALDYIVNALT
G.tenuistipitata    EYTTALDYIINSLS
C.crispus           EYGAALDYVINSLS
P.yezoensis         EYAGNLDYLINALS
P.haitanensis       EYAGNLDYIINSLC
P.purpurea          EYAGNLDYIINSLC
```

FIG. 4b

b: PEβ

```
                    1         10        20        30        40        50
P. palmata          MLDAFSRVVVNSDAKAAYVGGSDLQALKKFITDGNKRLDSVSFVVSNASC
G. tenuistipitata   MLDAFSRVVIDSDTKAAYVGGSNLQALKTFISEGNQRLDAVNSIVSNASC
C. crispus          MLDAFSRVVVNSDAKAAYVGGSDLQALKTFIADGNKRLDAVNSIVSNASC
P. yezoensis        MLDAFSRVVVNSDAKAAYVGGSDLQALKKFIADGNKRLDSVNAIVSNASC
P. haitanensis      MLDAFSRVVVNSDAKAAYVGGSDLQALKKFIADGNKRLDSVNAIVSNASC
P. purpurea         MLDAFSRVVVNSDAKAAYVGGSDLQALKKFIADGNKRLDSVNAIVSNASC
                      *                                             *

                              60        70        80        90       100
P. palmata          IVSDAVSGMICENPGLIAPGGNCYTNRRMAACLRDGEIILRYASYALLAG
G. tenuistipitata   IVSDAVSGMICENPGLTSPGGNCYTNRRMAACLRDGEIILRYISYALLAG
C. crispus          IVSDAVSGMICENPGLIAPGGNCYTNRRMAACLRDGEIILRYISYALLAG
P. yezoensis        IVSDAVSGMICENPGLIAPGGNCYTNRRMAACLRDGEIILRYVSYALLAG
P. haitanensis      IVSDAVSGMICENPGLIAPGGNCYTNRRMAACLRDGEIILRYVSYALLAG
P. purpurea         IVSDAVSGMICENPGLIAPGGNCYTNRRMAACLRDGEIILRYVSYALLAG
                               *           * *     *        **  *

                              110       120       130       140       150
P. palmata          DPSVLEDRCLNGLKETYIALGVPTNSSVRAVSIMKASATAFVSGTASDRK
G. tenuistipitata   DPSVLEDRCLNGLKETYIALGVPITSSARAVNIMKASVAAFILNTAPGRK
C. crispus          DASVLEDRCLNGLKETYIALGVPNNSSIRSVVIMKAAAVAFVNNTASQRK
P. yezoensis        DPSVLEDRCLNGLKETYIALGVPTNSSVRAVSIMKAAAVAFITNTASQRK
P. haitanensis      DPSVLEDRCLNGLKETYIALGVPTNSSVRAVSIMKAAAVAFITNTASQRK
P. purpurea         DPSVLEDRCLNGLKETYIALGVPTNSSVRAVSIMKASAVAFITNTASQRK
                           *

                              160       170
P. palmata          MACPDGDCSALASELGSYCDRVAAAIS
G. tenuistipitata   MDTASGDCTALASEVGSYFDRVCAAIS
C. crispus          MATTSGDCSALSAEVASYCDRVGAALS
P. yezoensis        MATADGDCSALASEVASYCDRVAAAIS
P. haitanensis      MATADGDCSALASEVASYCDRVAAAIS
P. purpurea         MATADGDCSALASEVASYCDRVAAAIS
                           *
```

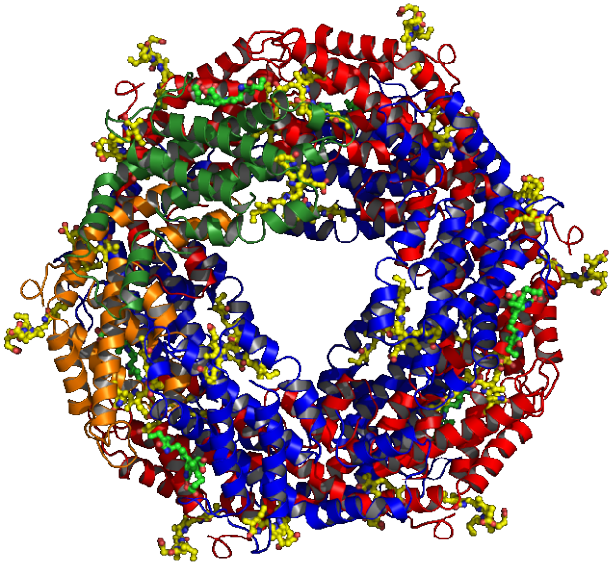
FIG. 5

a

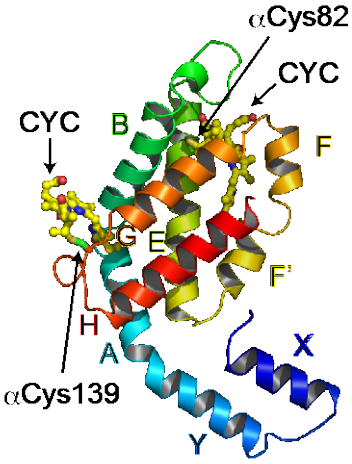
Purified PE

PE crystal

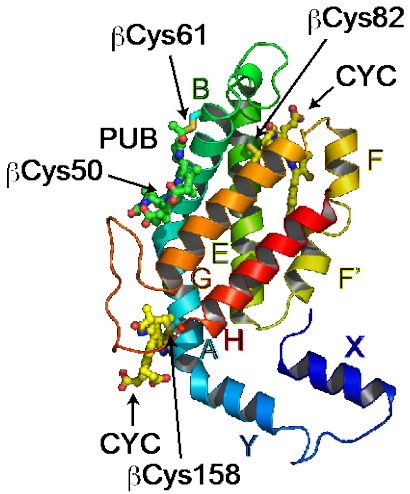
b



PE$(\alpha\beta)_6$ hexamer




PEα




PEβ