Longin-like folds identified in CHiPS and DUF254 proteins: Vesicle trafficking complexes conserved in eukaryotic evolution

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Abstract

Eukaryotic protein trafficking pathways require specific transfer of cargo vesicles to different target organelles. A number of vesicle trafficking and membrane fusion components participate in this process, including various tethering factor complexes that interact with small GTPases prior to SNARE-mediated vesicle fusion. In *Saccharomyces cerevisiae* a protein complex of Mon1 and Ccz1 functions with the small GTPase Ypt7 to mediate vesicle trafficking to the vacuole. Mon1 belongs to DUF254 found in a diverse range of eukaryotic genomes, while Ccz1 includes a CHiPS domain that is also present in a known human protein trafficking disorder gene (*HPS-4*). The present work identifies the CHiPS domain and a sequence region from another trafficking disorder gene (*HPS-1*) as homologs of an N-terminal domain from DUF254. This link establishes the evolutionary conservation of a protein complex (HPS-1/HPS-4) that functions similarly to Mon1/Ccz1 in vesicle trafficking to lysosome-related organelles of diverse eukaryotic species. Furthermore, the newly identified DUF254 domain is a distant homolog of the μ-adaptin longin domain found in clathrin adapter protein (AP) complexes of known structure that function to localize cargo protein to specific organelles. In support of this fold assignment, known longin domains such as the AP complex σ-adaptin, the synaptobrevin N-terminal domains sec22 and Ykt6, and the srx domain of the signal recognition particle receptor also regulate vesicle trafficking pathways by mediating SNARE fusion, recognizing specialized compartments, and interacting with small GTPases that resemble Ypt7.

Keywords: fold recognition; SNARE-like superfamily; longin domain; DUF254; CHiPS domain; vesicle transport; lysosome-related organelles; Hermansky-Pudlak Syndrome; HPS-1; HPS-4; Mon1; Ccz1

Protein trafficking pathways in eukaryotes require efficient and specific transfer of membrane-bound cargo vesicles between various donor and acceptor compartments (Behnia and Munro 2005). To achieve this specificity, transport occurs in several tightly regulated stages. A cargo-loaded vesicle first forms in the donor compartment. The vesicle then travels to a specific target site, where tethering factors mediate attachment. Subsequent fusion of the two membranes exchanges cargo (Bonifacino and Glick 2004). In the model organism *Saccharomyces cerevisiae*, biochemical and genetic analysis has identified a number of membrane fusion components that mediate vesicle transport to the vacuole. At the tethering stage of this vesicle fusion, a small rab GTPase (Ypt7) specifically interacts with a protein effector complex (C-vps/HOPS) prior to fusion (Wickner and Haas 2000).

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Deletion mutants of the yeast DUF254 protein Mon1 or of the protein Ccz1 display a similar phenotype to deletion of Ypt7, and are thought to act as a complex at the tethering stage of vesicle fusion to the yeast vacuole (Wang et al. 2002, 2003). DUF254 proteins have been identified in all major eukaryotic lineages (Cottage et al. 2004), and the *Caenorhabditis elegans* homolog (SAND-1) also functions in vesicle transport (Poteryaev and Spang 2005). Despite this defined functional preservation, the evolutionary conservation of the complex with Ccz1 remains unresolved. A conserved Ccz1 N-terminal sequence, termed the CHiPS domain, was recently identified in species from all major eukaryotic lineages, suggesting the potential for a preserved functional complex. The CHiPS domain is also present in a human gene (*HPS-4*) implicated in a known protein trafficking disorder to lysosome-related organelles called Hermansky-Pudlak Syndrome (Hoffman-Sommer et al. 2005).

We identify a conserved domain in DUF254 proteins homologous to domains of known structure that assemble into classic cargo vesicle adapter protein (AP) complexes (Collins et al. 2002; Heldwein et al. 2004) (σ-adaptin and μ-adaptin N-terminal domain). In the Structural Classification of Proteins (SCOP) (Murzin et al. 1995), the identified adaptin structures belong to the SNARE-like superfamily also known as longin (Rossi et al. 2004). Longins possess a five-stranded, antiparallel β-sheet (order 21543), surrounded by α-helices on either side. Consistent with a role for DUF254 proteins in vesicle tethering, other known longin domains function in trafficking pathways by mediating SNARE fusion, by recognizing specialized compartments, and by interacting with GTP bound states of small GTPases (Rossi et al. 2004). Our analysis also assigns a longin-like fold to the conserved Ccz1/HPS-4 CHiPS domain, although the CHiPS sequences display little sequence similarity to the DUF254 longin domains. Finally, we identify the HPS-4 binding partner (HPS-1) as a homolog of DUF254 members, supporting an evolutionary conserved role for these complexes in vesicular traffic to specialized lysosome-related compartments.

Results and Discussion

DUF254 and Hermansky-Pudlak Syndrome (HPS-1) proteins contain homologous longin-like domains

The combined results of sequence and structure-based prediction tools collectively assign a longin-like fold to a domain conserved in DUF254 and HPS-1 sequences. Exhaustive sequence searches with PSI-BLAST (Altschul et al. 1997) identified a region in DUF254 homologous to the HPS-1 N terminus (gi|6774626, range 23–436, found gi|2198743, range 59–260, iteration 2, E-value $6e^{-4}$) and to the μ-adaptin longin domain (gi|25396050, range 632–744, found 1w63, iteration 4, E-value $1e^{-10}$). Adaptin-related queries also identified DUF254 sequences (gi|82540681, range 4–143, found gi|66508937, range 120–226, iteration 6, E-value $6e^{-5}$).

The DUF254 longin domain assignment was further justified with results from fold recognition servers assembled by the 3D-JURY meta-server (Ginalski et al. 2003). Reliable scores were assigned to σ-adaptin longin domains (1gw5S, 62.00 and 1w63q, 61.43); and all of the top-scoring hits were to longin folds: μ-adaptin N-terminal domain (1w63M, 40), sedlin (1h3qA, 31.71), gliding protein Mglb (1j3wA, 29.00), and signal recognition particle receptor (srx) α subunit (1nrjA, 27.57 and 2fh5A, 27.29). These results agree with a previous report identifying adaptin (1gw5), among other α/β folds, as a potential DUF254 domain (Cottage et al. 2004). Finally, the top ROSETTA (Rohl et al. 2004) fragment assembly model displays a longin-like topology (Fig. 1B). With an exception of the C-terminal helix (shown in white), this model includes all of the μ-adaptin core secondary structural elements (Fig. 1A, yellow strands and blue helices).

Identified DUF254 longin domains encompass all of the conserved secondary structural elements that define the core structure (Fig. 1A, colored elements); and an alignment of these sequences displays a hydrophobicity pattern characteristic of the longin fold (Fig. 1D, yellow highlights). Pronounced features of this pattern include the enhanced hydrophobic nature of strands β1, β4, and β5, that are surrounded on either side by helices α1 and α2 (Fig. 1A,D), and the predicted secondary structure topology (ββαβββαα) of the sequences.

HPS-1/DUF254 longin-like domains function in an evolutionary conserved complex

Identification of HPS-1 as a DUF254 homolog supports an evolutionary conserved function of these proteins. The best characterized DUF254 representative (Mon1) functions as a complex with the CHiPS domain protein (Ccz1) in vesicle trafficking pathways leading to the yeast vacuole (Wang et al. 2002, 2003), an organelle that functions analogously to the mammalian lysosome. The CHiPS domain is also found in HPS-4 (Hoffman-Sommer et al. 2005), a protein that interacts with HPS-1 to regulate various lysosome-related organelles (Wei 2006). Interestingly, the genes encoding the yeast DUF254 complex have expanded in human genomes, which contain two closely related DUF254 sequences (Cottage et al. 2004) and the more distantly related HPS-1. This expansion perhaps coincides with specialized cell types that have evolved different lysosome-related organelles. Whether DUF254 proteins in other species interact with CHiPS domains remains to be determined.

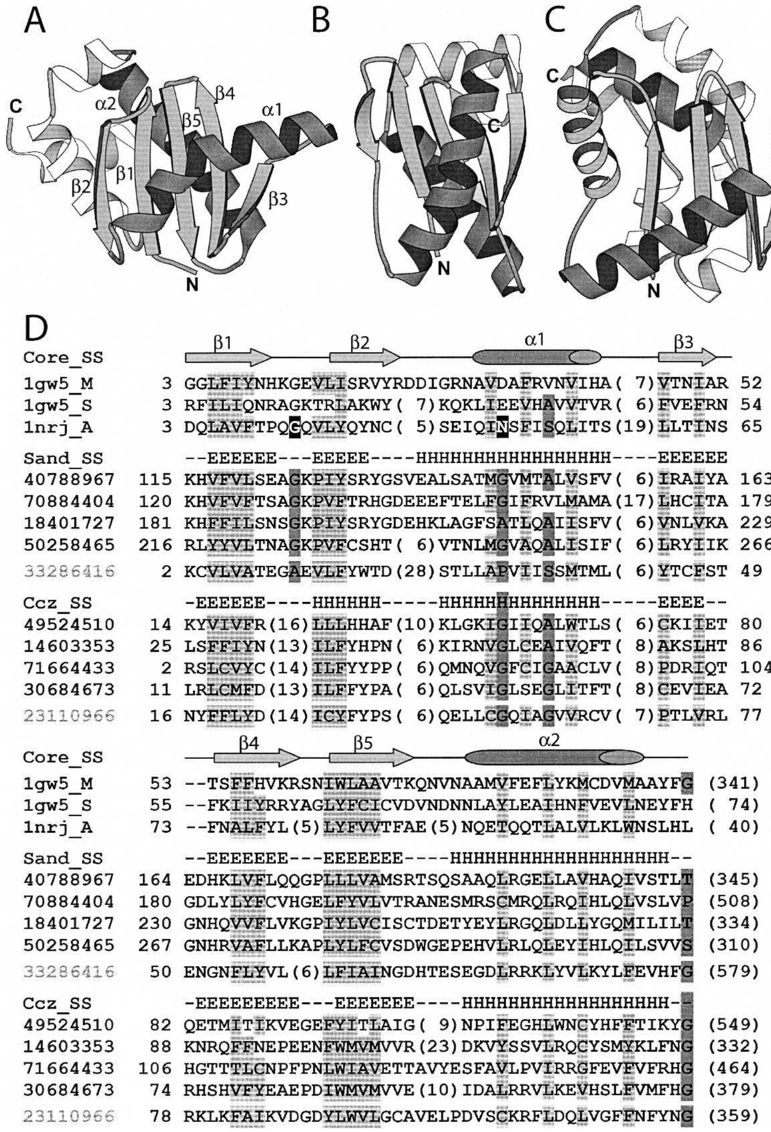

Figure 1. Structure and sequence of CHiPS and DUF254 longin-like domains. Structures of AP1 complex μ-adaptin N-terminal domain (1w63, chain M) (*A*), DUF254 ROSETTA model (*B*), and CHiPS domain ROSETTA model (*C*) were generated using MolScript (Esnouf 1999). N termini and C termini are labeled, and secondary structural elements are colored according to type: (dark gray) conserved core helix, (light gray) conserved core strand, and (white) additional elements. The conserved core is defined as secondary structural elements that are common to all SCOP (Murzin et al. 1995) SNARE-like superfamily structures; core elements are labeled in *A* according to ordered secondary structure topology (β1β2α1β3β4β5α2). (*D*) Conserved core elements from representative longin-like domain structures are aligned with DUF254 and CHiPS domain sequences. Sequences and structures are labeled respectively to the *left* with Gene Bank identification numbers and with Protein Data Bank identification codes with representative chains. Labels for Hermansky-Pudlak associated sequences (HPS1 and HPS4) are colored gray. Secondary structural elements depicted above the alignments are labeled and are colored as in *A*. Positions corresponding to ROSETTA model helix (H) and strand (E) are indicated *above* the respective alignments and labeled according to families. Alignment columns are colored according to conserved residue type: mainly hydrophobic residue positions (light gray) and mainly small residue positions (dark gray) that are conserved in multiple sequence alignment of all DUF254 and CHiPS sequences as well as in some representative structures. Functional residues in srx (1nrj_A) that mediate GTPase binding are highlighted in black with white letters. Residue numbers are indicated to the *right* and to the *left* of each sequence, and deletions are represented with the number of omitted residues in parentheses.

DUF254 longin-like domains are homologs of CHiPS domains

The CHiPS domain identified in HPS-4/Ccz1 contains a homologous stretch of ~200 residues (Hoffman-Sommer et al. 2005), with a hydrophobicity pattern and predicted secondary structure topology resembling the longin fold. Extensive PSI-BLAST searches with CHiPS queries identified both DUF254 and μ-adaptin longin domains with modest scores (E-values <1). For example, the CHiPS sequence (gi|76154640, range 3–165) finds the DUF254 sequence (gi|66508937, range 131–246, sixth iteration, E-value 0.013). More sensitive profile-based searches using CHiPS alignments also revealed links to the DUF254: an HPS-4 alignment confidently identified as the top ranked hit a domain of unknown function (DUF1712, E-value 1.8 e^{-06}) that includes CHiPS sequences, followed by DUF254 (E-value 6.86e^{-05}).

The fold recognition meta-server identified longin structures as top hits to the Ccz1 CHiPS domain: sedlin (1h3qA, 52.17), synaptobrevin (1h8m, 48.83), σ-adaptin (1gw5S, 45.17 and 1w63Q, 45.17), μ-adaptin (1w63M, 42.00), vesicle trafficking protein sec22β (1ifq, 36.83), and srx (1nrjA, 36.83); and a meta-server component (BASIC) (Ginalski et al. 2004) identified DUF254 as a confident hit (score 14.17). The top-ranked CHiPS domain ROSETTA model (Fig. 1C) resembles the DUF254 model (Fig. 1B), except for a helix replacing the edge β strand (β2) of the core sheet, although other CHiPS domain secondary structure predictions (Hoffman-Sommer et al. 2005) assign a strand to this region. These collective results support a homologous relationship between the DUF254 longin domain and the CHiPS domain. Such a relationship mimics the AP complex σ-adaptin and μ-adaptin longins (Collins et al. 2002; Heldwein et al. 2004), which are thought to have arisen from a genetic duplication in spite of retaining little sequence similarity (Boehm and Bonifacino 2001).

Diverse longin-domain complexes interact with small GTPases

The identified DUF254 homolog μ-adaptin functions as a component of AP complexes that link clathrin to specific membrane cargo and lipids during vesicle budding. AP complex structures AP-1 (Heldwein et al. 2004) and AP-2 (Collins et al. 2002) contain related sets of subunits: two trunk domains (γ and β1 in AP-1; α and β2 in AP-2) and two longin-domain subunits (σ1 and μ1 in AP-1; σ2 and μ2 in AP-2). The longin domains stabilize the core of the tetramer, with each making specific interactions to the other three subunits. AP complexes distinguish membrane compartments by ''coincidently'' recognizing phosphoinositide (PI-4-P for AP-1) and an organelle specific GTPase (Arf1 for AP-1) (Heldwein et al. 2004). Interestingly, at the Mon1/Ccz1-mediated tethering stage of vacuole fusion (Wang et al. 2003), the Ypt7 GTPase effector complex c-VPS/HOPS also appears to bind phosphoinositide (Stroupe et al. 2006). Perhaps the DUF254/CHiPS longins help organize the effector complex to coincidently recognize phosphoinositide and Ypt7 GTPase to specifically recognize the vacuolar membrane.

Other identified longins function as small GTPase effectors. Their interaction is defined structurally in signal recognition particle receptors (Schwartz and Blobel 2003; Schlenker et al. 2006), which govern cotranslational targeting of secratory and membrane proteins to the endoplasmic reticulum. In these structures, conserved srx longin domain residues shape the GTPase interface (Fig. 2A). An invariant β1–β2 loop glycine and a somewhat less conserved α1 helix polar residue dictate interactions with GTPase switch loops (Fig. 2A, black), whose conformations are defined by nucleotide (Fig. 2A, red bonds). Thus, conserved srx residues help identify the longin domain as a GTPase effector (Schwartz and Blobel 2003; Schlenker et al. 2006). To help identify potential functional sites of DUF254/CHiPS longin domains, family

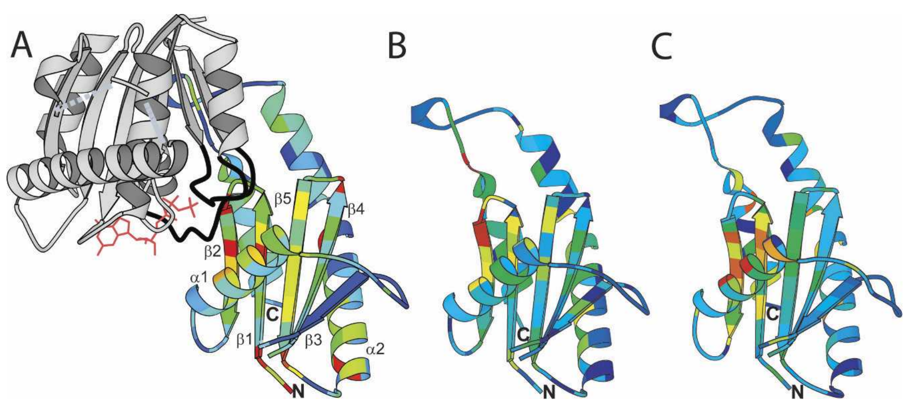

Figure 2. Longin domain interaction with small GTPase and spatial DUF254/CHiPS domain conservations. DUF254 and CHiPS family conservations were mapped to a representative longin domain structure (1nrj) based on the alignments illustrated in Figure 1. Conservations are represented with a rainbow color ramp from blue for less conserved positions to red for mainly conserved positions, and the N termini and C termini are labeled accordingly. (*A*) Interaction of the Srx longin domain (rainbow) with the GTP (red bonds) bound state of the signal recognition particle receptor β subunit small GTPase (gray) is mediated by conserved longin domain residues positioned near the GTPase switch loops (colored black). Core longin domain secondary structural elements are labeled according to topology. DUF254 longin domain conservations (*B*), and CHiPS family longin domain conservations (*C*) mapped to the srx structure (1nrjA) show a similar spatial arrangement of conserved positions.

sequence conservations were mapped to the srx structure (Fig. 2, B and C, respectively). DUF254/CHiPS conservations map to the same β1–β2 loop and α1 helix vicinity (Fig. 2B,C) identified by srx conservations, perhaps suggesting a similar effector interaction for these longin domains. The invariant srx glycine is also an invariant glycine in DUF254 sequences, but is not conserved in β1–β2 loop insertions of CHiPS sequences. The srx α1 polar residue is a conserved small residue (mostly glycine) in DUF254 and CHiPS sequences (Fig. 1C). Substitution of a small residue at this polar position might allow a backbone hydrogen bond to replace an ionic bond. Alternatively, another conserved polar position (like the invariant DUF254 β1–β2 loop lysine) could substitute for this role.

Materials and methods

Identifying DUF254/CHiPS sequence homologs

PSI-BLAST searches (Altschul et al. 1997) were performed against the filtered NCBI nonredundant protein database (posted date, Feb 19, 2006; 3,292,813 sequences, default parameters) using query sequences (gi|13874543 for Mon1 and gi|6319607 for ccz1). Identified sequence ranges were used as queries in new PSI-BLAST rounds (May 30, 2006 nr database; 3,658,078 sequences). Results are reported as the first PSI-BLAST iteration that found a significant (E-value <0.005) target. Similar searches were initiated from known longin-domain sequences to support defined links.

To further justify homology, identified sequences were grouped using linkage clustering (0.6 bit per site threshold) (SEALS Package; Walker and Koonin 1997), and the resulting groups were aligned using MAFFT (Katoh et al. 2005) with iterative refinement (ver 5.743; FFT-NS-I option, default values). MAFFT alignments were used to search profile databases KOG (Tatusov et al. 2003) or PFAM (Bateman et al. 2004) using COMPASS (Sadreyev and Grishin 2003).

Identifying longin structures

Mon1 DUF254 (gi|6321314) and HPS-1 N terminus (gi|33286416, range 1–135) were submitted to 3D-Jury (Ginalski et al. 2003). Scores >50 were considered significant (>90% correct; Ginalski and Rychlewski 2003). Individual scores and alignments from a component of 3D-Jury, meta-BASIC, also substantiated homologs. Meta-BASIC scores >12 were considered confident (<5% probability of being incorrect; Ginalski et al. 2004).

Protein structure prediction from a ROSETTA fragment assembly (Rohl et al. 2004) was applied to a DUF254 longin domain (gi|66508937, range 117–235) and a CHiPS longin domain (gi|49524510, range 11–179). For each target sequence, 1000 independent fold decoys were clustered based on RMSD. The coordinates for the center decoy of the cluster containing the most decoys was used to generate DUF254 and CHiPS models using MolScript (Esnouf 1999).

Multiple sequence-structure alignment

Superposition and alignment of identified structures were carried out using VAST (Madej et al. 1995), with some manual adjustments. Multiple sequence alignments generated by MAFFT (Katoh et al. 2005), corresponding to conserved core elements of identified families, were mapped to the resulting structure alignments, using as guides secondary structure predictions from JPRED (Cuff et al. 1998) and Rosetta models (Rohl et al. 2004) and alignments from PSI-BLAST (Altschul et al. 1997), Meta-BASIC (Ginalski et al. 2004), and COMPASS (Sadreyev and Grishin 2003).

Family conservation mappings

To visualize and compare longin conservations, sequences from each longin-like family (srx, DUF254, and CHiPS) were collected with PSI-BLAST (described above). Srx sequences (excluding fragments) belonging to groups with known structures (1nrj and 2fh5) and all DUF254 or CHiPS sequences (excluding fragments and distant HPS1/HPS4 sequences) identified in the initial round of PSI-BLAST were aligned as described above (Katoh et al. 2005). Positional conservations of alignment columns were calculated using an al2co entropy-based conservation measure (Pei and Grishin 2001), and were mapped to srx (1nrjA) based on the multiple sequence-structure alignment, with a rainbow color ramp from blue (least conserved, al2co score −1.2 as minimum value) to red (most conserved, al2co score 2.35 as a maximum value) using MolScript (Esnouf 1999).

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