Didier Picard - 03/2025

Cyclophilin 40 FACTS & LITERATURE

(necessarily incomplete!)

General:

- Reviews:
    - general: Smith, 2004; Allan and Ratajczak, 2011
    - in neurodegeneration: Bohush et al., 2019
    - Hsp90 complex in malaria (Shonhai et al., 2021).
    - Small molecules to disrupt interaction with Hsp90 (Wang et al., 2021).
- Note that the official gene name is *PPID* in mammals; not to be confused with cyclophilin D, which is a mitochondrial protein.
- first discovered as an estrogen receptor associated protein (Ratajczak et al., 1990; Ratajczak et al., 1993) and found to be identical with a CsA-binding protein (Kieffer et al., 1993).
- for more genetic and biochemical interactions of yeast cyclophilins Cpr6 and Cpr7, see http://www.yeastgenome.org.
- By global analysis in yeast, the Hsp90 complex can be classified as a stress-inducible chaperone complex as opposed to a chaperone linked to protein synthesis (CLIPs) which also associates with nascent polypeptides; however, Cpr6 and Cpr7 fall into separate classes, Hsp and CLIPs, respectively (Albanèse et al., 2006).
- Evolutionary plasticity of Hsp90 and cochaperones (Johnson and Brown, 2009).

Genetics:

- Budding yeast:
    - Δ*cpr7* has slow growth phenotype (Duina et al., 1996b).
    - synthetic enhancement of Δ*cpr7* by Δ*hsc82, hsp82*^{G170D} or Δ*sti1* (Duina et al., 1996a; see also Flom et al., 2006), or in presence geldanamycin (Dolinski et al., 1998).
    - Δ*cpr7*: reduced max. activation of GR and v-src in short term expts (Duina et al., 1996a), and levels of Thi4p (Faou and Tropschug, 2003)
    - both Cpr6 and Cpr7 dispensable in yeast (Duina et al., 1996b; Dolinski et al., 1997; Warth et al., 1997).
    - only TPR domain of Cpr7 required to suppress slow growth phenotype and defective GR (Duina et al., 1998b) and pheromone (Lee et al., 2004) signaling of Δ*cpr7* .
    - slow growth phenotype (Dolinski et al., 1998; Marsh et al., 1998; see also Schopf et al., 2019) and GR (Marsh et al., 1998) signaling can be suppressed by overexpression of Cns1, but not by overexpression of any other TPR protein (Dolinski et al., 1998). Conversely, Cpr7 overexpression suppresses lethality of temperature-sensititive *cns1* alleles (Tesic et al., 2003). Slow growth phenotype of Δ*cpr7* is partially suppressed by thiamine (Faou and Tropschug, 2003).
    - Cpr6 overexpression suppresses synthetic lethality between Δ*cpr1* and mutations in *ZPR1* (Ansari et al., 2002).

- Synthetic effects between Δ*cpr7* and Δ*hsc82* on HSF activity, both required for full negative regulation (Duina et al., 1998a). Double mutant defective for growth on maltose (Bali et al., 2003).
- Δ*cpr7* extends chronological life span (Harris et al., 2001).
- Δ*cpr7* is defective in pheromone signaling (suppressed by *CNS1* overexpression) and Ste11 kinase activity while Δ*cpr6* is only very slightly affected (Lee et al., 2004).
- Δ*cpr7* defective in vertebrate AhR signaling (Yao et al., 2004).
- Δ*cpr7* improves [*PSI*$^+$] propagation in a *SSA1* mutant strain in a probably Hsp90-independent way (Jones et al., 2004), but reduces Hsp104-mediated elimination of prions (Moosavi et al., 2010). No effect of Δ*cpr6* and Δ*cpr7* by themselves on propagation (Kumar et al., 2015).
- Δ*cpr7* but not Δ*cpr6* is hypersensitive to drugs that induce protein misfolding (Albanèse et al., 2006). Only the latter is hypersensitive to a Hsp90 inhibitor (Franzosa et al., 2011).
- *CPR7* (and notably the TPR) becomes essential when the charged linker of Hsp90 is deleted; this synthetic lethality can be suppressed by Cns1 overexpression as well (Zuehlke and Johnson, 2012).
- Δ*cpr6* is synthetic sick with *hsp90-A587T* (Zuehlke et al., 2013).
- Cpr7 (its TPR domain) but not Cpr6 is a restriction factor for replication of Tomato bushy stunt tombusvirus (TBSV) (Lin et al., 2012) and Carnation Italian ringspot tombusvirus (Xu et al., 2014).
- *cns1* point mutants are hypersensitive to overexpression of Cpr6, but not Cpr7, which must be able to bind Hsp90 (Johnson et al., 2014).
- Δ*cpr7* are hypersensitive to hygromycin (Tenge et al., 2015).
- *CPR7* required for propagation of *{URE3}* prions; defect can be suppressed by TPR domain alone or by Cns1 overexpression (Kumar et al., 2015).
- Cpr6 and Cpr7 are differentially required for the activity of exogenous clients (Sahasrabudhe et al., 2017).
- Cpr7 mitigates protein burden, Δ*cpr7* promotes it as well as protein aggregation (Farkas et al., 2018).
- Translation elongation or termination, and accumulation of eEF2 impaired in Δ*cpr7*; overexpression of eEF2 is toxic for Δ*cpr7* cells, rescued by *CNS1* overexpression (Schopf et al., 2019); synthetic sickness between Δ*cpr7* and Δ*hgh1* (Schopf et al., 2019, and high-throughput refs. in there).
- Poor complementation by human Hsp90α compared to Hsp90β mapped to Hsp90 N-terminus, and contributions of Sba1, Cpr6/7 to promote the closed state of α relative to β and yeast Hsp90 (Reidy and Masison, 2020).
- Comprehensive analysis of co-chaperone double mutants in budding yeast for growth and specific clients (Biebl et al., 2020). Forms an epistatic module with Cns1 and Sti1; Δ*sti1* further increases aggregation of Hsp90 client eEF2 in Δ*cpr7* strain (Biebl et al., 2020).
- Impact of *CPR6* deletion on loading/closing/reopening mutants of Hsp90; results notably indicate that Cpr6 antagonizes the destabilizing effect of Hch1 on the formation of the closed complex (Mercier et al., 2023).

- *S. pombe* Cyp40 homolog Wis2 suppresses a cdc25 wee1 win1 triple mutant (Weisman et al., 1996).
- In *C. elegans* it is not clear whether any of the cyclophilins corresponds to cyclophilin 40.
- Mutations in Cyp40 gene (*SQUINT*) of Arabidopsis have effects on vegetative maturation of shoot (Berardini et al., 2001). Can be traced to a reduced Ago1 activity leading to aberrant miRNA activities; no interaction between Cyp40 or Hsp90 and Ago1 could be demonstrated; Hsp90/Squint double mutants have even stronger phenotype (Smith et al., 2009). Hsp90 binding is required (Earley and Poethig, 2011).
- Cyp40 KO in *Leishmania donovani* has no effect on viability but results in ultrastructural defects of promastigotes and prevents parasites from establishing an infection (Yau et al., 2014). Null mutants have increased expression of stress proteins and exosome production (Yau et al., 2016).
- Mouse KO has no obvious phenotype under standard conditions (our unpublished results). Adipocyte-specific KO mice with high fat diet display obesity, dysglycaemia, altered body temperature, and mitochondrial defects (Latorre-Muro et al., 2025).
- AAV-mediated overexpression reduces tau amyloid deposits, preserves neurons, and improves cognitive functions in a mouse model, correlating with *in vitro* disaggregase activity (Baker et al., 2017).
- *Drosophila*: required for spermatid differentiation through the promotion of a specific Ago2-associated miRNA profile (Iki et al., 2020).

Other *in vivo* analyses:

- Overexpression and antibody injections in Xenopus oocytes: overexpression delays attenuation of Hsf1; anti-Cyp40 has no effect (Bharadwaj et al., 1999).
- Intranuclear localization of Cyp40 changes following heat shock (Mark et al., 2001). In yeast, more nuclear localization of Cpr6 upon nitrogen starvation (Breker et al., 2013).
- Cyp40 knock-down reduces AhR (Luu et al., 2008), AR signaling (also inhibited by cyclosporin A) (Periyasamy et al., 2010), replication of Hepatitis C Virus (Goto et al., 2009), and RACK1-mediated reduction of HIF1-α protein (Park et al., 2011).
- Overexpression in mammalian cells does not have much of an effect on steroid receptor function, and cannot compete with inhibition by FKBP51, possibly because of weaker binding (Schülke et al., 2010).
- Knock-down slightly impairs viability of anaplastic large cell lymphoma cells (Pearson et al., 2012). Reduces proliferation of a keratinocyte cell line but also improves resistance to UV-induced apoptosis, ROS production and MTP opening (Jandova et al., 2013).
- Cyp40 levels are upregulated by high fat diet, but this requires PERK; Cyp40 promotes insertion of TOM70 into the outer mitochondrial membrane, and as a result of that, mitochondrial protein import and respiration (Latorre-Muro et al., 2025).

Biochemistry:

- Use of cyclosporin A and FK506 shows that PPIase activity is not required for GR heterocomplex assembly *in vitro* (Owens-Grillo et al., 1995). In contrast, cyclosporin A blocks assembly with Hsp90-Ago1 complex (Iki et al., 2012).
- yeast Cpr6 (Warth et al., 1997) has PPIase activity. Cpr6 has 100-fold higher activity than Cpr7 (Mayr et al., 2000). Cyp40 PPIase (Pirkl and Buchner, 2001) and *N. crassa* NcCyP41 (Faou and Tropschug, 2003) characteristics.
- Hsp90 - yeast cyclophilin binding constants 14-57 nM (similar to Sti1-Hsp90) (Mayr et al., 2000). Affinity of human Cyp40 for Hsp90 is 226 nM and stoichiometry is 1:1 (Pirkl and Buchner, 2001).
- turnover but not steady-state levels of Cyp40 increases during stress (Mark et al., 2001).
- Cpr7 is monomeric (see e.g. Tesic et al., 2003) as is Cpr6 (Li et al., 2011).
- Cyp40 required to promote AhR-Arnt DNA complexes in vitro (Shetty et al., 2004).
- Cyp40 promotes the formation of theAhR/Arnt heterodimer and its DNA binding (Luu et al., 2008).
- Cyp40, in contrast to other TPR co-chaperones, facilitates RISC assembly in an Hsp90-dependent way by promoting or stabilizing the binding of small RNA duplexes to AGO1, but is not present in mature RISC in plants (Iki et al., 2012).
- Associates with Ago2 in *Drosophila* in a Hsp90-dependent fashion, shifting the sorting of some miRNA duplexes from Ago1 to Ago2 (Iki et al., 2020).
- Binding of MEEVD peptide slightly inhibits PPIase activity in a temperature-dependent way; heat-shock may therefore increase free pool of Cyp40 (Blackburn et al., 2015).
- Yeast Cpr6 is differentially required for assembly of GR vs. MR HBD complexes *in vitro* (Sahasrabudhe et al., 2017).
- Cyp40 inhibits phase separation of prion-like domain of TDP-43, irrespective of presence of Hsp90 (which does the opposite) (Carrasco et al., 2023).

Structure:

- two alternate structures of full-length bovine cyclophilin-40 (Taylor et al., 2001).
- extensive structure-function comparison of the human cyclophilin family (Davis et al., 2010).
- Structure of Cpr7 shows U-shape (Qiu et al., 2017).

Complexes:

- Cpr6 and Cpr7 bind Rpd3 in a 2-hybrid screen (Duina et al., 1996b); they bind Hsp90 biochemically (Duina et al., 1996a).
- direct binding to Hsp90 (Hoffmann and Handschumacher, 1995; Owens-Grillo et al., 1995). Mutual competition for Hsp90 binding between Cyp40 and FKBP52 (Owens-Grillo et al., 1995; Owens-Grillo et al., 1996; Ratajczak and Carrello, 1996) or Hop (Owens-Grillo et al., 1996) and by a fragment of PP5 containing 4 TPR repeats (Silverstein et al., 1998). Extreme N-terminus of yeast Hsp90 required for high affinity binding of Sti1 but not Cpr6 (Richter et al., 2003). However, mixed Sti/Hop-PPIase-Hsp90 complexes are a favored intermediate and Cpr6-Aha1-Hsp90 ternary complexes exist as well (Li et al., 2011). Cns1 and Cpr7 can form mixed complexes with Hsp90 dimers (Schopf et al., 2019).

- Cpr6, but not Cpr7, promotes association of Aha1, which in turn drives Hsp90 to a partially closed state; together, Cpr6 and Aha1 displace Sti1, and p23 finally the release of Aha1 (Li et al., 2013).
- Hsc70 through TPR domain, no effect on Hsc70 ATPase (Carrello et al., 2004). Also interacts with Hsp70 (Ssa1) *in vivo* in yeast (Zuehlke et al., 2013).
- also in mutant p53 complexes (Whitesell et al., 1998).
- Cpr7 but not Cpr6 is in CsA-sensitive complexes with Cns1 suggesting direct interaction (Dolinski et al., 1998; Marsh et al., 1998). Interaction must be indirect and also does not depend on the MEEVD of Hsp90 (Tesic et al., 2003). MEEVD sufficient for interaction with cyclophilin-40 (Onuoha et al., 2008).
- Cyclophilin-40 is in a cytosolic complex with caveolin, Hsp56, and CypA, and cholesterol (Uittenbogaard et al., 1998). Formation of functional transport complex but not association with cyclophilin-40 is dependent on caveolin palmitoylation (Uittenbogaard and Smart, 2000).
- Cyp40 in complexes with Harc (Scholz et al., 2001).
- Cpr7 binds to Hsp104 in respiring yeast and directly *in vitro*; competed by Hsp90 (Abbas-Terki et al., 2001).
- Binds cytoplasmic dynein through intermediate chain and PPIase domain (Galigniana et al., 2002).
- *N. crassa* NcCyP41 binds Hsp80 (Hsp90) and also directly the Thi4 homolog CyPBP37 (Faou and Tropschug, 2003).
- calcium-binding and chaperone protein S100A1 of the S100 family (Okada et al., 2004). The S100 family proteins S100A1 and S100A2 bind TPR domains in Ca^{2+}-dependent fashion competing with Hsp90 (Shimamoto et al., 2010).
- no Hsp90α/Hsp90β-isoform specific interactions with a number of cochaperones (p23, immunophilins, Hip, Hop, Hsp70) and substrates detected (Taherian et al., 2008).
- TAP purification of Cyp40 interactors from HeLa cells yielded RACK1, Ku70, NF45, and RPS3, which were validated with recombinant proteins (Park et al., 2011).
- Although interaction of Cpr6 and Cpr7 with Hsp90 is normally ATP-dependent, they interact independently of nucleotide with Hsp90 lacking the charged linker domain, and Cpr6 binds even wt Hsp90 in the absence of Cpr7 suggesting that Cpr7 mediates a conformational signal to relay the nucleotide status to the C-terminal TRP-binding domain (Zuehlke and Johnson, 2012).
- Ternary complexes Hsp90-Cpr6-Cpr7 (Zuehlke and Johnson, 2012).
- Interacts with Ura2 independently of Hsp90 (Zuehlke et al., 2013).
- Cpr7 but not Cpr6 binds and inhibits TBSV replication protein p33 via its TPR (Lin et al., 2012.
- Cpr6/7 (and Cns1) interact with the ribosome and there is genetic evidence that this is required for the *in vivo* functions of Cpr6 (Tenge et al., 2015).
- Cyp40 binds the Clostridium toxin components C2I, Ia and CDTa, and cyclosporin A inhibits translocation into the cytoplasm (Ernst et al., 2015).
- Cpr7 directly interacts with Ure2 and promotes fibrillation (Kumar et al., 2015).
- Diphtheria toxin A, required for Hsp90/Hsp70-mediated translocation into cells in PPIase-dependent way (Schuster et al., 2017).
- Binds proline-rich regions of tau and α-synuclein (Baker et al., 2017).
- Complex of Hsp90-Cns1-Hgh1, possibly with Cpr7, chaperones eEF2 (Schopf et al., 2019).

- TAP purification of Cpr6 and Cpr7 interactors from *C. albicans* (O'Meara et al., 2019).
- Associates with Ago2 in *Drosophila* in a Hsp90-dependent fashion (Iki et al., 2020).
- Cyp40 and TOM70 directly interact through their TPR domains, and this is Hsp90-independent (Latorre-Muro et al., 2025).

Cyp40 chaperone:

- holds denatured proteins in folding competent state (Freeman et al., 1996).
- Mammalian cyclophilin-40 negatively regulates DNA binding of c-myb but not v-myb (Leverson and Ness, 1998).
- Cpr7 and Cpr6 have PPIase-independent chaperone activity in the citrate synthase aggregation assay and that of Cpr7 is higher than that of Cpr6 (Mayr et al., 2000). Characteristics of Cyp40 (Pirkl and Buchner, 2001).
- Can disaggregate tau and α-synuclein amyloid *in vitro*, both of which are enriched in proline residues (Baker et al., 2017; reviewed in Shelton et al., 2017).

Mapping of Cyp40 domains:

- N-terminal domain of 18 kD contains PPIase homology and activity
- C-terminal half contains 3 TPR repeats and a potential calmodulin binding site at extreme C-terminus (see S100A1 above).
- TPR repeats plus some flanking regions required for Hsp90 binding (Hoffmann and Handschumacher, 1995; Duina et al., 1996b; Owens-Grillo et al., 1996; Ratajczak and Carrello, 1996). Detailed mutational analysis reveals importance of MEEVD binding groove (two-carboxylate clamp) and additional residues in TPR domain (Ward et al., 2002).
- Charge-Y motif (-+-+XΦYXXMF) immediately past TPR core, discovered in FKBPs, may fold back and by analogy also be essential for Hsp90 binding (Cheung-Flynn et al., 2003).
- only TPR domain of Cpr7 required to suppress slow growth phenotype and defective GR signaling of Δ*cpr7* (Duina et al., 1998b). Sufficient to maintain viability of Hsp90 mutants lacking charged linker (Zuehlke and Johnson, 2012). A Cpr6 chimera with the last 100 AA of Cpr7 can complement (Zuehlke et al., 2013).
- Suppression of *cns1* lethality by Cpr7 in yeast depends on PPIase and TPR domains, but not catalytic activity (Tesic et al., 2003).
- determinants for binding Hsc70 are similar to those for binding Hsp90 (Carrello et al., 2004).
- Chaperone activity maps to cleft between PPIase and TPR domains (Mok et al., 2006).
- C-terminal basic residues are required for interaction with ribosomes (Tenge et al., 2015).
- PPIase activity required for *in vitro* disaggregase activity (Baker et al., 2017).
- Both PPIase activity and TPR are required for TOM70 insertion (Latorre-Muro et al., 2025).

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