The *Hansenula polymorpha* PER1 Gene Is Essential for Peroxisome Biogenesis and Encodes a Peroxisomal Matrix Protein with Both Carboxy- and Amino-terminal Targeting Signals

Hans R. Waterham,*§ Vladimir I. Titorenko,† Peter Haima, James M. Cregg,§ Wim Harder,* and Marten Veenhuis*†

*Department of Microbiology and †Laboratory for Electron Microscopy, Biological Centre, University of Groningen, Kerklaan 30, 9751 NN Haren, The Netherlands; and §Department of Chemistry, Biochemistry, and Molecular Biology, Oregon Graduate Institute of Science and Technology, Portland, Oregon 97291-1000

Abstract. We describe the cloning of the *Hansenula polymorpha* PER1 gene and the characterization of the gene and its product, PERlp. The gene was cloned by functional complementation of a per1 mutant of *H. polymorpha*, which was impaired in the import of peroxisomal matrix proteins (Pim− phenotype). The DNA sequence of PER1 predicts that PERlp is a polypeptide of 650 amino acids with no significant sequence similarity to other known proteins. PER1 expression was low but significant in wild-type *H. polymorpha* growing on glucose and increased during growth on any one of a number of substrates which induce peroxisome proliferation. PERlp contains both a carboxy- (PTS1) and an amino-terminal (PTS2) peroxisomal targeting signal which both were demonstrated to be capable of directing bacterial β-lactamase to the organelle. In wild-type *H. polymorpha* PERlp is a protein of low abundance which was demonstrated to be localized in the peroxisomal matrix. Our results suggest that the import of PERlp into peroxisomes is a prerequisite for the import of additional matrix proteins and we suggest a regulatory function of PERlp on peroxisomal protein import.

Eukaryotic cells are characterized by the compartmentalization of various metabolic functions into separate subcellular organelles. Each organelle contains a characteristic set of proteins to accomplish specific metabolic functions essential for the cell. Microbodies (peroxisomes, glyoxysomes) represent the most recently discovered class of organelles, which are ubiquitous in higher and lower eukaryotic organisms (Borst, 1989; van den Bosch et al., 1992). They are involved in a variety of metabolic functions (Lazarow and Kindl, 1982; Veenhuis and Harder, 1991; van den Bosch et al., 1992) and in many cases their presence appears to be essential for the cell's viability. Consequently, the organelles have been intensively studied and in recent years the knowledge on the molecular mechanisms of microbody biogenesis and function is rapidly expanding.

It is now generally accepted that upon their induction microbodies develop by multiplication of preexisting organelles. Microbody proteins are encoded by nuclear genes, synthesized on free cytosolic polysomes to their mature size, and posttranslationally translocated into their target organelles (Lazarow and Fujiki, 1985; Borst, 1989). At present two different peroxisomal-targeting signals (PTS) have been identified which are capable of directing matrix proteins to the organelles. The first one (designated PTS1) resides at the extreme carboxy terminus of the protein and includes the tripeptide motif SKL or degenerate forms of it. The PTS1 motif has been shown to serve as a general microbody targeting sequence in animals, plants, and yeasts (Gould et al., 1989, 1990; Swinkels et al., 1992). However, in particular in yeast, additional variations of the PTS1 motif were found indicating that more extensive degenerations of the original PTS1 are functional in these organisms (de Hoop and AB, 1992). Examples of these include the carboxy-terminal tripeptides AKI (Aitchison et al., 1991), SKI (Didion and Roggenkamp, 1992), SKF (Kragler et al., 1993), ARE and NKL (Hansen et al., 1992) which act as a PTS1 in different yeast species. Subsequently, a second peroxiso-
nal-targeting signal was identified, located at the amino terminus of rat peroxisomal thiolase (Osumi et al., 1991; Swinkels et al., 1991). Sequence comparison with other peroxisomal matrix proteins, lacking a distinct PTS1, revealed a consensus sequence RLxQ/HL which is observed in the amino terminus of various thiolases, watermelon malate dehydrogenase, *Hansena aurora* amine oxidase, and *Trypanosoma brucei* aldolase (de Hoop and AB, 1992). Recently, evidence was obtained that this conserved sequence (designated PTS2) indeed serves as a peroxisomal-targeting signal in watermelon malate dehydrogenase (Gietl et al., 1994) and *H. polymorpha* amine oxidase (Faber, K. N., I. Keizer-Gunnih, C. Pluim, W. Harder, G. AB, and M. Veenhuis, manuscript submitted for publication).

A further increase in our knowledge of microbody biogenesis is to be expected from the analysis of the various peroxisome-deficient yeast mutants as they have been isolated from *Saccharomyces cerevisiae* (Erdmann et al., 1989; van der Leij et al., 1992; Elgersma et al., 1993; Zhang et al., 1993), *H. polymorpha* (Cregg et al., 1991; Veenhuis, 1992; Waterham et al., 1992b), *P. pastoris* (Goud et al., 1992; Liu et al., 1992), and *Yarrowia lipolytica* (Nuttley et al., 1993). A major advantage of these mutants is that, in contrast to other cell organelles, the complete absence of peroxisomal biogenesis. At present several genes, essential for peroxisome biogenesis, have been cloned and characterized by functional complementation of the corresponding mutants (Erdmann et al., 1991; Höhfeld et al., 1991, Wiebel and Kunau, 1992; McCollum et al., 1993; Spong et al., 1993).

Recently, we have cloned several *H. polymorpha* PER genes by functional complementation of various peroxisome-deficient mutants of this organism. Here, we report the molecular cloning and sequencing of the *peri* gene and the characterization of its product.

**Materials and Methods**

**Strains and Plasmids**

*H. polymorpha* and *Escherichia coli* strains and plasmids used in this study are listed in Table I.

**Cultivation Media and Growth Conditions**

*E. coli* strains used for molecular manipulations were grown as described (Sambrook et al., 1989).

*H. polymorpha* strains were grown at 37°C in selective minimal YND or YNM media (0.7% [wt/vol] DIFCO [Detroit, MI] Yeast Nitrogen Base without amino acids supplemented with 1% [wt/vol] destarch glucose), or 0.5% [vol/vol] methanol, respectively), in YPD medium (1% [wt/vol] yeast extract, 2% [wt/vol] peptone, 1% [wt/vol] dextrose), or in mineral medium (Veenhuis et al., 1989) supplemented with 0.5 or 1% (wt/vol) carbon and 0.25% (wt/vol) nitrogen source. In addition, cells were grown in continuous culture at 37°C in mineral medium (van Dijken et al., 1976) using a mixture of 0.25% (wt/vol) glucose and 0.2% (vol/vol) methanol as carbon energy source. Amino acids and uracil were added to a final concentration of 40 μg/ml.

For growth on agar plates all media were supplemented with 1.5% (wt/vol) granulated agar.

**Isolation and Characterization of Peri Mutants**

The isolation, back-crossing, complementation analysis, gene mapping, and phenotype characterization of various *H. polymorpha* per mutants, including *peri* mutants, are detailed in previous papers (Veenhuis, 1992; Waterham et al., 1992b; Titorenko et al., 1993).

**Construction of a H. polymorpha Genomic DNA Library**

Chromosomal DNA from YPD-grown wild-type (WT) *H. polymorpha* harvested at OD600=1.5, was isolated essentially as described by Sherman et al. (1986). A six-fold fraction of genomic DNA fragments ranging from 5 to 10 kb was obtained by partial digestion of chromosomal DNA with Sac3A, followed by fractionation on a sucrose gradient (seven layers of 1.7 ml sucrose in 10 Mm Tris/1 Mm EDTA [pH 7.5], increasing in steps of 5% from 10 to 40% [wt/vol], using a Beckman Instars [Carlisbad, CA] SW41 rotor (20 h, 25,000 rpm at 20°C). The sized DNA fragments were ligated in the phosphatase-treated unique BamHI site of the autonomous replicating *E. coli-H. polymorpha* shuttle vectors pHRP1 and pHRP2. Ligation mixtures were transformed to *E. coli* MC1061 by electroporation (Faber et al., 1992). After transformation ~2 × 10^6 colonies with an average insert size of 6 kb were obtained. Using the formula of Clarke and Carbon (1976), the chance for a random DNA sequence to be present in the obtained DNA library amounts to 99% (the total *H. polymorpha* genomic DNA size was estimated to be 2 × 10^9 bp).

**Cloning of the PERI Gene**

To isolate the *peri* gene, a three-times backcrossed strain of mutant *peri-L24/2D* (Waterham et al., 1992b) was transformed with the constructed genomic DNA library (Faber et al., 1992). After 4–5 d growth on YND-agar plates, leucine prototrophic transformants were replica-plated onto YNM-agar plates and screened for the ability to utilize methanol (growth generally within 3–5 d). Plasmids were recovered by electrophoresis of *E. coli* MC1061 with plasmid DNA isolated from complemented *H. polymorpha* strains (Faber et al., 1992). As a control the original *peri-L24/2D* strain was retransformed with the isolated plasmid, again followed by plasmid recovery in *E. coli*. To facilitate restriction analysis and construction of subclones, the complementing genomic DNA fragment was subcloned as a T4 polymerase-treated NheI-SphI fragment (both sites exclusively present in pHRP2-vector) in the unique Smal-site of the phosphaglucisene II KS' (pBSII KS') and isolated in two different orientations.

**DNA Sequencing and Analysis**

Sequencing was performed in two directions by double-stranded sequencing according to the dideoxy method (Sanger et al., 1977) using the DeazaT sequencing kit of Pharmacia LKB Biotechnology and the TAQ Track Sequencing System of Promega. For sequencing, segments of the 3-kb complementing DNA fragment were subcloned in PBSII KS' using restriction sites present on the fragment. The reverse primer and T7 primer (Stratagene Inc., La Jolla, CA) were used as sequence primers. In addition different *peri* gene-specific 17 basepair oligonucleotides were generated to obtain overlapping sequences.

For analysis of the DNA and amino acid sequence the PCGENE-program release 6.5 (IntelliGenetics, Mountain View, CA) was used.

**Northern Hybridization, 3' End Mapping and cDNA Isolation**

Poly(A)^*^ RNA was isolated from WT *H. polymorpha* grown in methanol-limited continuous culture as described by Bruinenberg et al. (1989).

Poly(A)^*^ RNA was fractionated on formaldehyde-1% agarose gels and transferred onto nitrocellulose according to Sambrook et al. (1989). As probes for Northern analysis the 3-kb BamHI-BglII and the 630-bp Asp178-HindIII fragments were labeled using the random primed labeling kit of Boehringer Mannheim (Indianapolis, IN). Hybridization was performed in 0.5 M NaHPO4-buffer (pH 7.2) supplemented with 1 mM EDTA and 7% (vol/vol) SDS at 65°C for 16–18 h. After hybridization, filters were washed once in 2× SSC (Sambrook et al., 1989), 0.5% SDS for 10 min at 65°C, and three times in 1× SSC, 0.5% SDS for 10 min at room temperature. Finally the SDS was removed by two short washes with 2× SSC at room temperature. For determination of the 3' end of the *peri* gene the Rapid Amplification of cDNA Ends (RACE) protocol (Frohman et al., 1988) was used as described by Frohman (1991) with slight modifications. Poly(A)^*^ RNA of *H. polymorpha* was reverse transcribed into CDNA using AMV Reverse Transcripase (Boehringer Mannheim Corp.) and a hybrid dT17-adapter primer: 5' AACACCTATGACCATGCACCAGCTT G TTTTTTTTTTTTTTTTTTTTTTTTT.
Table 1. Strains and Plasmids Used in This Study

| Strain/plasmid       | Relevant properties | Source or reference                      |
|----------------------|---------------------|-----------------------------------------|
| H. polymorpha        |                     |                                         |
| per1-124/2D          | leu1.1 per1         | Waterham et al., 1992b                  |
| per1::LEU2           | per1 ura3           | This study                              |
| CBS4732              | WT                  | Central Bureau Schimmelcultures        |
| NCYC495              | auxotrophic collection | The Netherlands                        |
| E. coli              |                     |                                         |
| MC1061               | hsdR mcrB araD139 (araABC-leu)7679 lacX74 galU galK rpsL (Str') | Sambrook et al., 1989                  |
| DH5α                 | supE44 hsdR17 thi-1 recA1 endA1 gyrA relA | Sambrook et al., 1989                  |
| C600                 | supE44 hsdR thi-1 relA leuB6 lacY1 tonA21 | Sambrook et al., 1989                  |
| Plasmids             |                     |                                         |
| pHRP1/2              | Ap', LEU2, HARS1     | Faber et al., 1992                      |
| pHARS1               | Ap', URA3, HARS1     | Roggenkamp et al., 1986                 |
| pBluescriptIISK'     | Ap'                  | Stratagene Inc.                         |
| pMAL-C2              | Ap', P₅malE          | New England Biolabs                     |
| pHIPX4               | Km', LEU2           | Giel et al., 1994                       |

3', containing a Nod restriction site. PCR amplification of the 3' end of PER1 gene using CETUS Taq-polymerase (The Perkin-Elmer Corp., Norwalk, CT) was performed with the adapter primer: AACAGCTATGACATTG and the PER1 gene specific primers B: 5'CAGTCGAGCTATACCCCAACGAC 3' (position 137-153; see Fig. 2) or D: 5'TGAGATTCCCTCACTACATCC 3' (position 902-918; see Fig. 2). After amplification, the specific eDNA fragment obtained with primer D was subcloned in pBSH KS+ by digestion with Asp718 and PstI. After isolation of a genomic DNA fragment comprising the 3' end of the PER1 gene, chromosomal DNA was digested with HindIII, fractionated on a 1% agarose gel and transferred onto nitrocellulose according to Sambrook et al. (1989). As probe for Southern analysis the 670-bp HindIII-BglII fragment was used. Labeling and hybridization was performed as described for Northern blotting. Fragments ranging from 2.5 to 5 kb were subsequently isolated from agarose gel and ligated in phosphatase-treated HindIII-digested pBSII KS+.

For isolation of a genomic DNA fragment comprising the 3' end of the PER1 gene, chromosomal DNA was digested with HindIII, fractionated on a 1% agarose gel and transferred onto nitrocellulose according to Sambrook et al. (1989). As probe for Southern analysis the 670-bp HindIII-BglII fragment was used. Labeling and hybridization was performed as described for Northern blotting. Fragments ranging from 2.5 to 5 kb were subsequently isolated from agarose gel and ligated in phosphatase-treated HindIII-digested pBSII KS+. The plasmid with the genomic DNA fragment comprising the 3' end was identified by E. coli colony hybridization using the 670-bp HindIII-BglII fragment as probe (Sambrook et al., 1989).

PER1 Disruption

For disruption of the WT PER1 gene, the LEU2 gene of Candida albicans (Gift of Dr. E. Berardi, Ancona, Italy) was blunt-ligated between the Klenow-treated Asp718 and HindIII sites of the complementing 3-kb fragment in pHBS KS+. Selection for LEU2 insertion was performed with E. coli C600 grown on minimal M9 medium supplied with 40 μg/ml thiamine and threonine (Sambrook et al., 1989). The LEU2-containing insert was subsequently released from pHBS KS+ by digestion with BamHI and BglII and linearly transformed to a leu1.1 ura3 H. polymorpha strain by electroporation (Faber et al., 1994). Leucine prototrophic strains were screened for their ability to grow on methanol by replica-plating on YNM agar plates. Methanol utilization-deficient (Mut-) strains were selected, mated with per1-124/2D and the resulting diploids checked for complementation. In addition, Mut+ strains were mated with different auxotrophic H. polymorpha NCYC 495 strains to determine the location of the genomic LEU2 integration by random spore analysis. Integration was confirmed by Southern blot analysis of chromosomal DNA using the ECL direct nucleic acid labeling and detection system of Amersham Corp. (Arlington Heights, IL).

Generation of Antisera

For expression and purification of PER1p the Protein Fusion and Purification System supplied by New England Biolabs (Beverly, MA) was used. A Asp718-Por1 (pBSII KS+) fragment was subcloned in frame behind the malE gene into the pMAL-C2 vector digested with EcoRI and PstI, after Klenow-treatment of the Asp718 and EcoRI sites and transformed to E. coli strain DH5α. Expression of the maltose-binding protein (MBP)-PER1 hybrid protein under control of Pm was induced by addition of 0.03 mM isopropyl-β-D-thiogalactopyranoside to exponentially growing cultures. Purification of the hybrid protein, cleavage of the protein with factor Xa and the final purification of the PER1p was according to the manual of New England Biolabs, except that in all steps 0.25% Tween 20 was added to the buffer solutions.

Polyclonal antibodies against the purified protein were raised in rabbit.

Cell Fractionation

For cell fractionation, protoplasts were prepared and subsequently homogenized as described by Douma et al. (1985). The homogenate was subjected to differential centrifugation (6,500 g for 10 min, followed by 12,000 g for 10 min and 30,000 g for 30 min). The 30,000-g pellet (P3) and corresponding supernatant (S3) were used for biochemical analysis. In addition, P3 pellets were fractionated on a discontinuous sucrose gradient as described (Douma et al., 1985).

Purified peroxisomal fractions were separated in soluble matrix and membrane-associated proteins after lysis in 20 mM triethanolamine buffer, pH 7.8, followed by centrifugation as described by Sulter et al. (1993a).

Biochemical Methods

Crude extracts were prepared as described before (Waterham et al., 1992a). Enzyme activities of alcohol oxidase (Verduyn et al., 1984), catalase (Lück, 1963), formaldehyde dehydrogenase (van Dijken et al., 1976) and cytochrome c oxidase (Douma et al., 1985) were assayed by established procedures. β-Lactamase activity was measured spectrophotometrically at 486 nm in 100 mM potassium phosphate buffer, pH 7.0, using nitrocefin (final concentration of 0.025 mg/ml, Becton Dickinson, Eten, Leur, The Netherlands) as substrate. Protein concentrations were determined with the Biorad protein assay kit using bovine serum albumin as standard. SDS-PAGE electrophoresis was performed as described by Laemmli (1970). Gels were stained with Coomassie Brilliant Blue R-250. Western blotting experiments were performed with the ECL Western blot analysis system (Amerham Corp.). Transfer of proteins onto nitrocellulose after SDS-PAGE electrophoresis using a semi-dry electroblotter was according to Kyhse-Andersen (1984).

Expression of the PER1 Gene

Expression of the PER1 gene in WT H. polymorpha cells under various growth conditions was studied by Northern blot analysis of total RNA isolated from the cells and by measuring β-lactamase activity as reporter for the PER1 promoter (P₅PER1) induction. For the latter approach WT β-lactamase (see below) was cloned in frame behind P₅PER1 using the unique Asp718 site. The expression unit was subcloned in pHIPX4 and trans-
formed to a leu1.1 H. polymorpha strain. The transformant was grown in batch cultures on selective mineral media supplemented with various carbon and nitrogen sources; cells were harvested at OD$_{663}$ = 2 for biochemical analysis.

**Targeting Experiments**

For targeting studies the $\beta$-lactamase gene of *E. coli* was used as reporter protein (Sutcliffe, 1978). This gene was cloned behind P$_{PERI}$ and the initial 47 base pairs of the PERI gene, using the HaeIII site at position 47 (Fig. 2), resulting in a hybrid protein containing the amino-terminal 16 amino acids of PERI$_p$ preceding $\beta$-lactamase protein expressed under control of the P$_{PERI}$. In addition, the final 27 base pairs of the PERI gene were cloned behind the modified $\beta$-lactamase gene using the HindIII site at position 1923 (see Fig. 2), and expressed under control of the P$_{Mox}$, resulting in a hybrid protein containing $\beta$-lactamase in front of the carboxy-terminal 9 amino acids of the PERI$_p$. All $\beta$-lactamase constructs were cloned in the E. coli–H. polymorpha shuttle-vector pHIPX4 and transformed to a leu1.1 H. polymorpha strain.

A deletion of the amino acids HKLGRQG (position 6-12) in the amino terminus of the PERI$_p$ gene was introduced by restriction with Asp718 and NarI, followed by Klenow-treatment and self-ligation (Fig. 2). The carboxy-terminal AKL tripeptide of the PERI$_p$ was specifically removed by PCR, introducing a stop codon at position 1942-1944 using as primer 5' CCGTTAACTTATTTTTCCTCACTCTCGTTGAC 3'. The deletion constructs were cloned in the pHARS1 vector and tested for functional complementation of a peri::LEU2 disruption mutant. Constructs were checked by restriction analysis and sequencing. The primary sequences of the resulting constructs are shown in Table II.

**Electron Microscopy**

Whole cells were fixed in 1.5% (wt/vol) KMnO$_4$ for 20 min at room temperature. Spheroplasts were fixed in 6% (vol/vol) glutaraldehyde in 0.1 M sodium cacodylate buffer (pH 7.2) for 90 min at 0°C, dehydrated in a graded ethanol series followed by postfixation in a mixture of 0.5% (wt/vol) OsO$_4$ and 2.5% (wt/vol) K$_2$Cr$_2$O$_7$ in the cacodylate buffer for 90 min at 0°C. After dehydration in a graded ethanol series the samples were embedded in Epon 812; ultrathin sections were cut with a diamond knife and examined in a Philips EM 300.

For immunocytochemistry intact cells were fixed in either 3% (vol/vol) glutaraldehyde or 3% (vol/vol) formaldehyde in 0.1 M sodium cacodylate buffer (pH 7.2) for 90 min at 0°C, dehydrated in a graded ethanol series and embedded in Unicryl. Immunolabeling was performed on ultrathin sections with specific antibodies and gold-coupled goat anti-rabbit antibodies by the method of Slot and Geuze (1984).

**Miscellaneous DNA Techniques**

Standard recombinant DNA techniques were performed essentially as described by Sambrook et al. (1989). Restriction and DNA-modifying enzymes were obtained from and used as recommended by the manufacturers (Boehringer Mannheim Corp., Pharmacia Diagnostics Inc. (Fairfield, NJ), and New England Biolabs).

**Results**

**Cloning of the PERI Gene**

The PERI gene was cloned by functional complementation of one of the representative mutants of the PERI complementation group (strain per1-124/2D) using a *H. polymorpha* genomic DNA library. As reported before, this mutant belongs to a class of peroxisomal protein import mutants which are characterized by the presence of several small peroxisomes, although the bulk of the peroxisomal matrix protein resides in the cytosol (Pim- phenotype, Fig. 1 B; Waterham et al., 1992b). Transformants were screened for leucine prototrophy and the ability to grow on methanol (Mut$^+$-phenotype). Subsequently, one Mut$^+$ transformant was isolated and further characterized. From this complemented strain three different plasmids with different inserts (6.6, 3.2, and 3 kb) were recovered in *E. coli*; upon retransformation only the plasmid with 3-kb insert could functionally complement the original peri-124/2D mutant. The presence of normal peroxisomes in the complemented mutant was confirmed by electron microscopy (Fig. 1 C).

Northern blot analysis using poly(A)$^+$ RNA of methanol-grown *H. polymorpha* and the 3-kb insert as a probe, revealed a transcript of $\sim$2.2 kb (not shown); an identical transcript was also detected using the 3' half of the insert (Asp718-BglII fragment) which indicates that at least part of the gene was present on the latter fragment.

Sequence analysis (see below) and additional Northern blotting, using small segments of the 3' end of the 3-kb complementing fragment as probe, indicated that the fragment did not contain the entire PERI gene. This was confirmed by determination of the 3' end of the PERI transcript using the RACE protocol. Two different cDNA fragments of $\sim$1.8 and 1.1 kb were amplified using the two PERI gene-specific primers B and D (see Materials and Methods), demonstrating that the complementing 3-kb fragment lacked $\sim$300 bp of the 3' end of the PERI gene (not shown). Using part of the amplified cDNA fragments as probe an additional 3.7-kb HindIII genomic DNA fragment comprising the 3' end of the PERI gene was subsequently isolated.

**Sequence Analysis of PERI**

Sequencing of the initially isolated 3-kb complementing DNA fragment revealed a large open reading frame (ORF) starting 11 bp in front of a unique Asp718 site and running out of the fragment without ending in a stop codon (Fig. 2). This indicated that not the entire PERI gene was cloned, thus confirming the data presented above. The ORF on this 3-kb genomic fragment only encodes 535 amino acids while vector PHRP2, used for the construction of the genomic DNA library, encodes an additional 88 amino acids, which results in a protein with a calculated total molecular mass of 70,616 kD.

Sequencing of the cloned PCR amplified 1.1-kb cDNA fragment and of a part of the genomic HindIII fragment re-

**Table II. Primary Sequences of DNA Constructs Used for Targeting Studies**

| Construct       | Promoter | Amino acid sequence                        |
|-----------------|----------|-------------------------------------------|
| N$^{\text{H}}$-BLAC | P$_{PERI}$ | M'QFWYHKLGROGLA$^{16}$PE-262aa-HW$^{205a}$ |
| BLAC-C$^*$      | P$_{Mox}$ | MSGH$^{11}$PE-262aa-HW$^{192}$SN$^{193}$EQEKAKT$^{565a}$ |
| per1-3'-HKLGRQG | P$_{PERI}$ | M'QFWY$^{11}$RQLEQWQ-625aa-E$^{498}$KAKT$^{565a}$ |
| per1-3'-AKL     | P$_{PERI}$ | M'QFWYHKLGROGLA$^{16}$-625aa-V$^{498}$NESQEK$^{567a}$ |

Roman, amino acid sequence of PERI$p$; numbers as indicated in Fig. 2.

Italics, amino acid sequence of $\beta$-lactamase; numbers correspond with WT $\beta$-lactamase (Sutcliffe, 1978).

* carboxy terminus of resulting proteins.
revealed an additional stretch of 345 bp which belongs to the PERI-ORF and encodes 115 amino acids. Therefore, the entire PERI gene contains an ORF of 1,950 kb (Fig. 2). Several observations indicated that the first ATG of the ORF is the translation initiation site. Firstly, in front of this ATG several promoter elements were identified, like two putative TATA-elements, noted between positions -101 and -83, and the sequence CAAG, which often defines transcription initiation in yeast (Dobson et al., 1982), at position -34. Secondly, the large spacing between the observed promoter elements and the second ATG of the ORF (position 316) together with the possibility to amplify a cDNA fragment using the gene-specific primer B (position 137–153) make this second ATG unlikely to serve as translation initiation site. Furthermore, the size of the encoded protein determined by Western blotting (~70 kD; see below) approximates the calculated molecular mass when translation initiates at the first ATG. Initiation at the second ATG would result in a predicted molecular mass of 61.5 kD. The polyadenylation site was identified at position 1978 by sequencing of the cDNA fragments; the TAG codon in addition is part of the sequence TAG(T(N))TTT which might serve as a polyadenylation signal in yeast (Zaret and Sherman, 1982). A yeast consensus sequence TACTAAC (Langford et al., 1984) for intron-splicing was not detected; the absence of introns was confirmed by the sizes of the two PCR amplified cDNA fragments obtained with the two different PERI gene-specific primers.

The entire PERI gene thus encodes a protein of 650 amino acids with a calculated molecular mass of 74 kD. Hydropathy analysis (Kyte and Doolittle, 1982) did not reveal any membrane-spanning segments although the protein is predicted to be rather hydrophobic. The amino acid sequence contains the extreme carboxy-terminal tripeptide AKL, a

Figure 1. Overall morphology of methanol-grown WT cells of H. polymorpha, showing proliferation of peroxisomes (A, KMnO4), compared to methanol-induced cells of the perl-124/2D mutant strain, showing a large cytosolic alcohol oxidase crystalloid (*) and several small peroxisomes (B, KMnO4). Thin section through a methanol-grown cell of the functionally complemented perl-124/2D strain showing the presence of normal, intact peroxisomes (C, KMnO4). Immunocytochemistry, using specific antibodies raised against PERlp revealed that PERlp is localized at the edge of peroxisomes (D). The rather low labeling intensity is significant for organelles of these growth conditions and most probably reflects the low abundance of the Perlp. P, peroxisome; N, nucleus; V, vacuole; M, mitochondrion. Bar, 0.5 μm.

Waterham et al. Characterization of PER1 of Hansenula polymorpha
The Journal of Cell Biology, Volume 127, 1994 742

Figure 2. Nucleotide sequence and deduced primary sequence of the PERI gene. Some relevant restriction sites used for the different constructions are indicated above the nucleotide sequence. The initial complementing 3-kb fragment ended at the Sau3A site at position 1607. These sequence data are available from EMBL/GenBank/DDBJ under accession number Z30206.

Figure 3. Disruption of the PERI gene. (a) The LEU2 gene of C. albicans was inserted between the Asp718 (A) and the HindIII (H) site of the coding region of PERI. Subsequently, the obtained construct was introduced into the genome by homologous integration. (b) The correct integration was confirmed by Southern blotting of genomic DNA cut with Sacl (S) and probed with a BamH1 (B)-BglII (G) DNA fragment as indicated. Lane 1, genomic DNA isolated from the disintegration mutant.
variant of the PTS1 which has been shown to serve as a peroxisomal targeting signal in PMP20 from Candida boidinii (Gould et al., 1989). An intriguing observation is that the amino terminus of the PER1 protein (PERlp) shows strong similarity to the consensus sequence RlxH/QL proposed for PTS2 (de Hoop and AB, 1992). In the PER1 sequence the arginine residue of the PTS2 consensus sequence is substituted by the similar residue lysine. Besides these two putative peroxisomal targeting signals, no functional sites were detected using the PROSITE software of the PC/GENE program. A search in different protein databases did not reveal any significant sequence similarity of PERlp to other proteins. However, recently the Pasteuria pastoris PER3 gene was cloned by functional complementation of one of the P. pastoris per mutants (Liu et al., 1992). The PER3 protein shows \~60\% similarity to PERlp (J. M. Cregg, unpublished results).

Construction and Characterization of PER1 Disruption Mutants

In order to confirm that the cloned complementing fragment indeed represents the PER1 gene, a gene disruption was performed (Fig. 3 A); 35\% of the leucine prototrophic transformants obtained appeared to be unable to utilize methanol (Mut\(^{+}\)-phenotype). Southern blot analysis performed with one randomly chosen Mut\(^{+}\) transformant (perl::LEU2) indicated a correctly targeted chromosomal integration (Fig. 3 B). After mating of the perl::LEU2 strain with auxotrophic WT strains to perform random spore analysis, a complete cosegregation of the Mut\(^{+}\) phenotype and the LEU2 gene was observed in all cases. In addition, diploids obtained after crossing of the perl::LEU2 strain with the original mutant perl-124/2D, displayed the Mut\(^{+}\) phenotype. These results demonstrate a correctly targeted integration of the LEU2 gene in the PER1 locus and therefore prove that the authentic PER1 gene has been cloned. The perl::LEU2 disruption mutant could only be functionally complemented by the entire PER1 gene; after transformation with the initially isolated 3-kb genomic fragment, which encodes PERlp without its carboxy-terminal 115 amino acids (Fig. 2), the cells remained unable to grow on methanol.

Electron microscopy revealed that, after incubation of cells of the perl::LEU2 disruption mutant on methanol, normal peroxisomes were lacking and the peroxisomal matrix proteins were localized in the cytosol (Fig. 4, A and B). However, several small vesicular structures were observed, which were absent in glucose-grown cells and therefore might represent peroxisomal remnants (Fig. 4, A, C, and D). Attempts to demonstrate the presence of alcohol oxidase protein (by immunocytochemistry) or activity (by the very sensitive Ce\(^{3+}\) method) failed (results not shown). Therefore, matrix proteins are most probably lacking from these structures. It should be emphasized, that these structures however basically differ from the small protein–lipid aggregates, composed of mainly peroxisomal membrane proteins, which are observed in other peroxisome-deficient mutants of H. polymorpha (Sulter et al., 1993b; Waterham et
al., 1993). Like all *H. polymorpha* Per" mutants studied so far (Sulter et al., 1990, 1991), the *perl::LEU2* disruption mutant grew well on various compounds, the metabolism of which are mediated by peroxisomal matrix proteins (e.g., ethanol, d-alanine and methylamine). Also on these substrates normal peroxisomes were lacking and the matrix proteins were localized in the cytosol which indicates that PERlp is essential for peroxisome biogenesis in general.

In order to further analyze the nature of the vesicular structures cells of the *perl::LEU2* disruption mutant, grown in continuous culture on a glucose/methanol mixture (Fig. 4, A and C), were fractionated by differential and sucrose density centrifugation. Protein analysis of the different fractions obtained from the sucrose gradient revealed the presence of one major protein peak at 43.5% sucrose (Fig. 5 a, fraction 25) and a small peak at 49% sucrose (Fig. 5 a, fraction 11). As expected from electron microscopy, the majority of the peroxisomal matrix proteins alcohol oxidase and catalase were soluble after differential centrifugation and thus a distinct peroxisomal peak fraction was not observed when these proteins were considered as reporter proteins (Fig. 5 b, intact WT peroxisomes usually fractionate at 53% sucrose). The minor alcohol oxidase protein peak, which fractionated on top of the 60–65% sucrose layer (Fig. 5 b), most probably represents remnants of the alcohol oxidase crystalloids which were present in the cells (Fig. 4 A). The protein peak fraction at 43.5% sucrose mainly consists of mitochondria (Fig. 5 c).

The protein contents of fraction 11 was analyzed by SDS-PAGE electrophoresis and compared to purified peroxisomes isolated from methanol-grown WT cells. As is evident from Fig. 6 a, fraction 11 clearly has several proteins in common with WT peroxisomes; furthermore, Western blotting experiments using specific antibodies against the peroxisomal membrane protein PER8 (Tan, X., H. R. Waterham, M. Veenhuis, and J. M. Cregg, manuscript in preparation) clearly demonstrate the presence of this protein in fraction 11 (Fig. 6 b). These results indicate that this fraction contains components of peroxisomal membranes. The low levels of alcohol oxidase protein in this fraction is probably caused by the mentioned contamination with the alcohol oxidase crystalloids.

**Expression of the PER1 Gene**

To obtain insight in the significance of PERlp in peroxisome biogenesis, the expression of the protein was studied during growth of WT cells in media containing various carbon and nitrogen sources, known to induce peroxisome Proliferation...
in *H. polymorpha*. Northern blot analysis of 25 μg total RNA isolated from cells grown in batch culture on glucose, methanol, ethanol, glycerol, α-alanine, or methylamine, using the *PER1* gene as probe, only revealed a rather weak signal in methanol-grown cells; in all other samples no signal was detected (not shown). For this reason we decided to study the P*PER1*-driven synthesis of bacterial β-lactamase, thus taking advantage of the sensitive β-lactamase activity assay. The results shown in Fig. 7 indicate that P*PER1* is active under all growth conditions tested. Compared to glucose/ammoniumsulphate-grown cells, a small increase in activity was observed when ammoniumsulphate was replaced by α-alanine or methylamine as nitrogen source. P*PER1* activity was further enhanced when cells were grown on carbon sources, the metabolism of which require microbody enzymes. As was expected, maximal activity was observed during growth of cells on methanol. The observed regulation of P*PER1* differs from the induction of the promoters of alcohol oxidase and catalase, as is indicated by the respective enzyme activities, detected in the same cells (Fig. 7). Since we used an autonomous replicating plasmid in these experiments, control experiments were performed using the same vector containing the β-lactamase gene expressed under control of the P*MOX*. In glucose- or ethanol-grown cells no β-lactamase activity was detected, which indicates that carbon catabolite repression of P*MOX* (Veenhuis and Harder, 1991) operates efficiently, even in the case of replicating plasmids. In methanol-grown transformants the P*PER1*-driven β-lactamase activity (1.5 units) is low compared to the activity resulting from expression behind P*MOX* (100.4 units), which indicates that PERlp is a protein of low abundance in *H. polymorpha*.

**The PER1 Gene Product Is a Peroxisomal Matrix Protein**

Polyclonal antibodies raised against PERlp were used in Western blotting experiments to determine its subcellular localization. The size of the protein, which was specifically recognized by these antibodies, is ~70 kD which is in good agreement with the calculated molecular mass and the size of PERlp observed after cleavage with factor Xa of the maltose-binding protein-PERlp fusion protein synthesized in *E. coli* (not shown). In crude extracts prepared of methanol-grown cells of WT *H. polymorpha* PERlp could hardly be detected, again indicating that PERlp is a low abundant protein. However, when these cells were fractionated by differential centrifugation and subsequent sucrose density centrifugation, PERlp was specifically detected in highly purified peroxisomes (Fig. 8 and 9). The occasionally coexisting of alcohol oxidase in the Western blots, decorated with anti-PER19, most probably is not specific but due to the excessive amounts of alcohol oxidase proteins present in peroxisomes of WT *H. polymorpha*. When subsequently purified peroxisomes were separated in a soluble matrix and a membrane protein fraction, PERlp was exclusively detected in the soluble fraction, indicating that PERlp is a component of the peroxisomal matrix (Fig. 8). As expected, PERlp could not be detected in fraction 11 of the sucrose gradient obtained from the *perl::LEU2* disruption mutant (not shown).

The intra-peroxisomal localization of PERlp in WT *H. polymorpha* was also studied by immunocytochemistry, performed on thin sections of transformants in which the *PER1* gene was expressed behind the P*MOX*. In these cells labeling was predominantly present at edge of the peroxisomes (Fig. 1 D). We have interpreted our combined data in that PERlp...
Figure 9. Localization of PERlp. Equal amounts of purified peroxisomes (lane 1) and mitochondria (lane 2) obtained after differential and subsequent sucrose density centrifugation of methanol-grown WT cells of H. polymorpha (compare Fig. 8, fraction 7 and fraction 28, respectively) were fractionated on a 7.5% SDS-polyacrylamide gel and blotted for Western analysis using specific antibodies raised against PERlp (40 μg protein/lane). The intra-peroxisomal localization was evident after Western analysis of pelletable (lane 3) and soluble (lane 4) fractions obtained from 40 μg purified WT peroxisomes (Fig. 8, fraction 8) after lysis in 20 mM triethanolamine buffer, pH 7.8.

is not included in the alcohol oxidase crystalloids but instead present in the small zone between the crystalloid and the surrounding membrane, comparable to for instance catalase protein in identically grown cells (Keizer-Gunnink et al., 1992).

PER1 Protein Contains the Two Conserved Peroxisomal Targeting Signals PTS1 and PTS2

As indicated above, PERlp contains both the carboxy-terminal PTS1 (AKL) and the amino-terminal PTS2 (KLxQL) peroxisomal targeting consensus sequences. In order to test whether these putative PTS sequences are indeed functional in H. polymorpha, we studied whether they were capable of targeting bacterial β-lactamase protein to peroxisomes. Previously, this protein was successfully used to identify the PTS1 targeting signals of H. polymorpha alcohol oxidase and dihydroxyacetone synthase (Hansen et al., 1992). Recent experiments showed that β-lactamase was also suitable for targeting studies with the PTS2 signal (Faber, K. N., P. Haima, C. Gietl, W. Harder, G. AB, and M. Veenhuis, manuscript submitted for publication). The primary sequences of the hybrid proteins used for these experiments are detailed in Table II. Immunocytochemical experiments, using antibodies against β-lactamase, showed that both the amino-terminal 16 amino acids, containing the PTS2 consensus sequence, as well as the 9 carboxy-terminal amino acids, containing the PTS1 sequence, were capable of targeting β-lactamase to peroxisomes (Fig. 10).

The functionality of the carboxy- and amino-terminal targeting signals was furthermore analyzed by transformation of the perl::LEU2 disruption mutant with different mutated versions of the PER1 gene, specifically mutagenized in the PTS consensus sequences (see Table II). The mutant could still be functionally complemented by the PER1 constructs in which either the whole PTS1 sequence (AKL) or a major part of the PTS2 consensus sequence (HKLGRQG) was deleted. In both cases the transformed cells were able to grow on methanol and contained several peroxisomes.

Discussion

We have identified and characterized a peroxisomal protein essential for the biogenesis of peroxisomes in the methylotrophic yeast H. polymorpha. The PER1 gene coding for this protein was cloned by functional complementation of a H. polymorpha peroxisomal protein import mutant (Pim- phenotype; Waterham et al., 1992b), using a H. polymorpha genomic DNA library. The gene comprises an ORF which encodes a polypeptide of 650 amino acids with a calculated molecular mass of 74 kDa.

Interestingly, the original complementing genomic fragment lacked the 3' end of the PER1 gene, which encodes the 114 carboxy-terminal amino acids. One possible explanation for this rather surprising result could be that a recombination event took place between the complementing fragment and the mutant perl allele, thus giving rise to a WT PER1 gene
in the genome. Several observations, however, indicated that this was not the case. First, after introduction of the incomplete gene on the pHRP2 vector in the original perl-124/2D mutant, all leucine prototrophic strains were complemented for growth on methanol. Second, the pHRP2 vector was readily recovered from the complemented mutant yeast strain by electrottransformation of \textit{E. coli} with total yeast DNA. Third, the complemented mutant could be forced to lose its plasmid by growth on nonselective media, resulting again in a Mut\textsuperscript{-} leu strain. These results, together with the fact that this fragment could not functionally complement the perl::LEU2 disruption mutant, indicate that PERlp probably functions as a multimeric protein containing at least two PER1 subunits; in the original perl-124/2D strain one mutated subunit is apparently able to functionally complement the other.

So far, PERlp is the only peroxisomal protein described which contains both a PTS1 and a PTS2 motif although other peroxisomal matrix proteins are reported to contain several putative (internal) targeting sequences, like \textit{Candida tropicalis} acyl CoA oxidase (Small et al., 1988) and \textit{S. cerevisiae} catalase (Kragler et al., 1993). The complementation experiments with the perl::LEU2 disruption mutant using different mutated \textit{PER1} genes, combined with the results obtained in the targeting experiments using \(\beta\)-lactamase as a reporter protein, suggest that both PTS motifs might function in vivo. Additional evidence for the in vivo functionality of the PTS2 sequence was obtained by studying the location of PERlp in a \textit{PER3} disruption mutant of \textit{H. polymorpha}. This mutant is impaired in the import of PTS1 targeted peroxisomal proteins (similar to the \textit{Pichia pastoris} PAS8; McCollum et al., 1993), whereas PTS2 containing proteins are correctly imported into the present small peroxisomes (van de Klei, I. J., G. J. Swaving, R. H. Hilbrands, H. R. Waterham, V. Titorenko, J. M. Cregg, W. Harder, and M. Veenhuis, manuscript in preparation). Western blot analysis of purified peroxisomes from the \textit{PER3} disruption mutant revealed that PERlp was localized in these organelles (H. R. Waterham and G. J. Swaving, unpublished results).

The biochemical studies showed that PERlp is a protein of low abundance located in the peroxisomal matrix. At present, PERlp is the first matrix protein shown to be essential for peroxisome biogenesis. Deletion of other major peroxisomal matrix proteins in \textit{H. polymorpha}, like alcool oxidase, catalase, or amine oxidase, results in a decrease in size of peroxisomes, but never affects the biogenesis of the organelles (M. Veenhuis, unpublished results). However, for \textit{S. cerevisiae} a gene essential for peroxisome biogenesis is reported which contains a PTS1 signal and therefore might encode a peroxisomal matrix protein (PAS6p, Erdrmann and Kunau, 1992).

Although we could not deduce a specific function for PERlp, we speculate that PERlp may play a role in triggering the protein import competence of individual peroxisomes. In earlier reports, we have shown that yeast peroxisomes are only temporarily capable to import newly synthesized matrix proteins. This import competence is related to the developmental stage of the organelles: newly developed peroxisomes are able to incorporate proteins whereas the large, mature organelles have lost this ability (Veenhuis et al., 1989; Waterham et al., 1992a). Our hypothesis for the role of PERlp is based on the presence of peroxisomal vesicular structures which lacked matrix proteins in the perl::LEU2 disruption mutant. The presence of these vesicles has not been observed before in other \textit{H. polymorpha} mutants; in these mutants peroxisomal membrane proteins are primarily located in small protein-phospholipid aggregates (Sulter et al., 1993b; Waterham et al., 1993). Thus the induction of peroxisomal vesicles in the cells of the perl::LEU2 disruption mutant suggests that protein import is blocked but that peroxisome multiplication (proliferation) is not affected. Therefore, the import of PERlp into preperoxisomal structures appears to be a prerequisite to import of other matrix proteins. The presence of two functional PTS sequences on PERlp suggests that a correct peroxisomal localization of the protein is critical for peroxisome development.

The proposed function for PERlp requires that PERlp is constitutively present. This is indeed the case, as was indicated by the expression studies which showed that PERlp is synthesized even in glucose-grown cells, where peroxisome induction is fully repressed. This is consistent with the fact that the small peroxisomes present in repressed WT cells are capable of importing peroxisomal matrix proteins (e.g., alcohol oxidase) synthesized during non-methylotrophic growth conditions (Distel et al., 1988). In view of the above hypothesis of the role of PERlp, this import would not occur if the protein was absent under these conditions. However, PERlp is not predicted to be a core protein of the peroxisomal protein import machinery since its role requires that the protein itself has to be imported into the organelles. The results of the targeting experiments indicate that this import most probably occurs via the same import routes as for other matrix proteins.

The putative role of PERlp may be linked with a physical interaction of the protein with the PER8 protein as was suggested from a classical genetic study, performed with 12 different \textit{H. polymorpha} \textit{PER} genes (Titorenko et al., 1993). The \textit{PER8} gene was recently cloned and encodes an integral peroxisomal membrane protein (Tan, X., H. R. Waterham, M. Veenhuis, and J. M. Cregg, unpublished results). Interestingly, when the \textit{PER8} gene was overexpressed behind the \(P_{\text{max}}\) a strongly enhanced proliferation of peroxisomes occurred in methanol-grown cells, indicating that PER8p plays an important role in the regulation of peroxisome proliferation. Our observations that in the perl::LEU2 disruption mutant PER8p was present in the vesicular structures and that multiplication of these structures occurred but no import of matrix proteins, suggest that PERlp and PER8p may coordinately regulate the development of new protein import competent peroxisomes by fission from preexisting organelles.

We are grateful to K. N. Faber for his support and valuable suggestions on molecular genetics and thank R. Hilbrands, I. Keizer-Gunnink, J. Schanstra, and G. J. Swaving for assistance in different parts of this study; X. Tan for the gift of specific antibodies against Per6p; and E. Berardi for the gift of the \textit{Candida albicans} LEU2 gene.

H. Waterham is supported by the Netherlands Technology Foundation (STW), which is subsidized by the Netherlands Organization for the Advancement of Pure Research (NWO).

Received for publication 31 January 1994 and in revised form 8 July 1994.
References

Aitchison, J. D., W. W. Murray, and R. A. Rachubinski. 1991. The carboxy-
terminal tripeptide Ala-Lys-Ile is essential for targeting Candida tropicalis
trifunctional enzyme to yeast peroxisomes. J. Biol. Chem. 266: 23197–
23202.

Borst, P. 1989. Peroxisome biogenesis revisited. Biochim. Biophys. Acta
1010:1–13.

van den Bosch, H., R. B. H. Schutgens, R. J. A. Wanders, and J. M. Tager.
1992. Localization of peroxisomes. Annu. Rev. Biochem. 61:157–197.

Bruinenberg, P. G., M. Evers, H. R. Waterham, J. Kuipers, A. C. Aarnberg,
and G. A. Ab. 1989. Cloning and sequencing of the peroxisomal amine oxidase
gene from Hansenula polymorpha. Biochim. Biophys. Acta. 1008:157–167.

Clarke, D. F., and W. Harder. 1976. A colony bank containing synthetic Col/E1
hybrids representative of the entire E. coli genome. Cell. 9:1–99.

Cregg, J. M., I. J. van der Klei, G. J. Suitor, M. Veenhuis, and W. Harder.
1990. Peroxisome-deficient mutants of Hansenula polymorpha. Yeast.
6:67–77.

Didion, T., and R. Roggenkamp. 1992. Targeting signal of the peroxisomal
catalase in the methylothrophic yeast Hansenula polymorpha. FEMS (Fed.
Eur. Biochem. Soc.) Lett. 303:113–116.

van Dijken, J. P., R. Otto, and W. Harder. 1976. Growth of Hansenula polymor-
pha in a methanol-limited chemostat. Physiological responses to the
involvement of methanol oxide as a key enzyme in methanol metabolism.
Arch. Microbiol. 111:137–144.

Distel, B., J. van der Leij, M. Veenhuis, and H. F. Tabak. 1988. Alcohol oxide-
dase expressed under non-methylothrophic conditions is imported, assem-
dled, and enzymatically active in peroxisomes of Hansenula polymorpha. J.
Cell Biol. 107:1669–1675.

Douma, A. C., M. Veenhuis, N. A. Roberta, J. A. Kingman, and S. M. Kingman.
1982. Conservation of high efficiency promoter sequences in Saccharomyces
cerevisiae. Nucleic Acids Res. 10:2625–2637.

Douma, A. C., M. Veenhuis, W. de Koning, M. Evers, and W. Harder. 1985.
Dihydroxy-acetone synthase is localized in the peroxisomal matrix of metha-
hol grown Hansenula polymorpha. Arch. Microbiol. 143:237–243.

Eldersma, Y., M. van der Berg, H. F. Tabak, and B. Distel. 1993. An efficient
positive selection procedure for the isolation of peroxisome import and
peroxisomal 3-assembly mutants in Saccharomyces cerevisiae. Genetics.
135:731–740.

Erdmann, R., and W.-H. Kunau. 1992. A genetic approach to the biogenesis
of peroxisomes in the yeast Saccharomyces cerevisiae. Cell. Biochem. Funct.
10:167–174.

Erdmann, R., M. Veenhuis, D. Mertens, and W. H. Kunau. 1989. Isolation of
peroxisome-deficient mutants of Saccharomyces cerevisiae. Proc. Natl.
Acad. Sci. USA 86:5419–5422.

Erdmann, R., F. F. Wiebel, A. Flessau, J. Rytka, A. Beyer, K.-U. Frohlich,
and W.-H. Kunau. 1991. PAS1, a gene required for peroxisome biogenesis in
the methylotrophic yeast Hansenula polymorpha. Biochim. Biophys. Acta.
143:237–243.

Faber, K. N., P. Haima, W. Harder, M. Veenhuis, and G. AB. 1994. Highly-
templated mutants of Hansenula polymorpha. J. Biol. Chem. 269:267–275.

Frohman, M. A. 1990. RACE: rapid amplification of CDNA ends.
Proc. Nat. Acad. Sci. USA 87:9736–9740.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of
a gene from hybrid of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of a
gene from hybrids of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of a
gene from hybrids of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of a
gene from hybrids of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of a
gene from hybrids of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of a
gene from hybrids of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of a
gene from hybrids of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of a
gene from hybrids of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of a
gene from hybrids of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of a
gene from hybrids of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of a
gene from hybrids of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of a
gene from hybrids of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.

Frohman, M. A., M. K. Dush, and G. R. Martin. 1988. Rapid production of a
gene from hybrids of Hansenula polymorpha. J. Biol. Chem. 263:7690–7696.
Swinkels, B. W., S. J. Gould, and S. Subramani. 1992. Targeting efficiencies of various permutations of the consensum C-terminal tripeptide peroxisomal targeting signal. FEBS (Fed. Eur. Biochem. Soc.) Lett. 305:133–136.

Titorenko, V. I., H. R. Waterham, J. M. Cregg, W. Harder, and M. Veenhuis. 1993. Peroxisome biogenesis in the yeast Hansenula polymorpha is controlled by a complex set of interacting gene products. Proc. Natl. Acad. Sci. USA. 90:7470–7474.

Veenhuis, M. 1992. Peroxisome biogenesis and function in Hansenula polymorpha. Cell Biochem. Func. 10:175–184.

Veenhuis, M., and W. Harder. 1991. Microbodies. In The Yeasts. 2nd ed. Vol. 4. A. H. Rose and J. S. Harrison, editors. Academic Press Limited, London. 601–653.

Veenhuis, M., G. J. Sulter, I. J. van der Klei, and W. Harder. 1989. Evidence for functional heterogeneity among microbodies in yeasts. Arch. Microbiol. 151:105–110.

Verduyn, C., J. P. van Dijken, and W. A. Scheffers. 1984. Colorometric alcohol assays with alcohol oxidase. J. Microbiol. Methods. 2:15–25.

Waterham, H. R., I. Keizer-Gunnink, J. M. Goodman, W. Harder, and M. Veenhuis. 1992. Development of multipurpose peroxisomes in Candida boidinii growth in oleic acid-methanol limited continuous cultures. J. Bacteriol. 174:4057–4063.

Waterham, H. R., V. I. Titorenko, I. J. van der Klei, W. Harder, and M. Veenhuis. 1992b. Isolation and characterization of peroxisomal protein import (Pim') mutants of Hansenula polymorpha. Yeast. 8:961–972.

Waterham, H. R., V. I. Titorenko, G. J. Swaying, W. Harder, and M. Veenhuis. 1993. Peroxisomes in the methylotrophic yeast Hansenula polymorpha do not necessary derive from pre-existing organelles. EMBO (Eur. Mol. Biol. Organ.) J. 12:4785–4794.

Wiebel, F. F., and W.-H. Kunau. 1992. The Pau2 protein essential for peroxisome biogenesis is related to ubiquitin-conjugating enzymes. Nature (Lond.). 359:73–76.

Zaret, K. S., and F. Sherman. 1982. DNA sequence required for efficient transcription termination of yeast. Cell. 28:563–573.

Zhang, J. W., Y. Han, and P. B. Lazarow. 1993. Novel peroxisome clustering mutants and peroxisome biogenesis mutants of Saccharomyces cerevisiae. J. Cell Biol. 123:1133–1147.