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Structural and Functional Characterization of a Macrophage Migration Inhibitory Factor Homologue from the Marine Cyanobacterium Prochlorococcus marinus


ABSTRACT: Macrophage migration inhibitory factor (MIF) is a multifunctional mammalian cytokine, which exhibits tautomerase and oxidoreductase activity. MIF homologues with pairwise sequence identities to human MIF ranging from 31% to 41% have been detected in various cyanobacteria. The gene encoding the MIF homologue from the marine cyanobacterium Prochlorococcus marinus strain MIT9313 has been cloned and the corresponding protein (PmMIF) overproduced, purified, and subjected to functional and structural characterization. Kinetic and 1H NMR spectroscopic studies show that PmMIF tautomerizes phenylenolpyruvate and (p-hydroxyphenyl)enolpyruvate at low levels. The N-terminal proline of PmMIF is critical for these reactions because the P1A mutant has strongly reduced tautomerase activities. PmMIF shows high structural homology with mammalian MIFs as revealed by a crystal structure of PmMIF at 1.63 Å resolution. MIF contains a Cys-X-X-Cys motif that mediates oxidoreductase activity, which is lacking from PmMIF. Engineering of the motif into PmMIF did not result in oxidoreductase activity but increased the tautomerase activity 8-fold. The shared tautomerase activities and the conservation of the β-α-β structural fold and key functional groups suggest that eukaryotic MIFs and cyanobacterial PmMIF are related by divergent evolution from a common ancestor. While several MIF homologues have been identified in eukaryotic parasites, where they are thought to play a role in modulating the host immune response, PmMIF is the first nonparasitic, bacterial MIF-like protein characterized in detail. This work sets the stage for future studies which could address the question whether a MIF-like protein from a free-living bacterium possesses immunostimulatory features similar to those of mammalian MIFs and MIF-like proteins found in parasitic nematodes and protozoa.

Macrophage migration inhibitory factor (MIF) was one of the first cytokines to be discovered. It was first identified in mammals as a T-lymphocyte-associated activity released at the site of an infection, where it causes macrophages to concentrate and carry out antigen processing and phagocytosis. Since its initial discovery, MIF has been implicated in a number of infections, inflammatory, and immune responses. MIF is involved in the activation of macrophages, neutrophils, and T-cells and may play a role in conditions such as sepsis, adult respiratory distress syndrome, asthma, bowel disease, rheumatoid arthritis, certain types of cancer and diabetes, and atherosclerosis. MIF contains a Cys-X-X-Cys motif that mediates oxidoreductase activity, which is lacking from PmMIF. Engineering of the motif into PmMIF did not result in oxidoreductase activity but increased the tautomerase activity 8-fold. The shared tautomerase activities and the conservation of the β-α-β structural fold and key functional groups suggest that eukaryotic MIFs and cyanobacterial PmMIF are related by divergent evolution from a common ancestor. While several MIF homologues have been identified in eukaryotic parasites, where they are thought to play a role in modulating the host immune response, PmMIF is the first nonparasitic, bacterial MIF-like protein characterized in detail. This work sets the stage for future studies which could address the question whether a MIF-like protein from a free-living bacterium possesses immunostimulatory features similar to those of mammalian MIFs and MIF-like proteins found in parasitic nematodes and protozoa.
functions as the catalytic base (20). It has also been reported that MIF exhibits low-level oxidoreductase activity, reducing small molecule and protein disulfides, which appears to be associated with a thioredoxin-like Cys-X-X-Cys motif (25, 26). It is not yet clear how and if these catalytic activities are related to any of the immunological or inflammatory activities of MIF.

Intriguingly, several eukaryotic parasites have been reported to produce MIF-like proteins that show remarkable functional and structural similarities to mammalian MIFs (27–34). These include human parasites such as the nematodes Brugia malayi and Ancylostoma ceylonicum and the protozoa Leishmania major and Plasmodium falciparum. The question has been raised whether these MIF homologues function as virulence factors and play a role in the parasite–host interaction (34, 35).

In this study, we screened the prokaryotic genomes available in the NCBI database for MIF-like proteins with the aim to identify new MIF family members and provide further insight into the evolutionary history of MIF. We report the identification of a large group of cyanobacterial proteins that share significant sequence identity with mammalian MIFs. The gene encoding the MIF homologue from the marine cyanobacterium Prochlorococcus marinus strain MIT9313 has been cloned and the corresponding protein (designated PmMIF) overproduced, purified, and subjected to kinetic, mutational, and structural characterization. The results show that PmMIF is an active tautomerase that shares mechanistic and structural similarities with mammalian MIFs. These observations suggest that cyanobacterial PmMIF and mammalian MIFs are related by divergent evolution and invite speculation about the intrinsic physiological function of MIF-like proteins in marine cyanobacteria. With PmMIF being the first nonparasitic, prokaryotic MIF-like protein characterized in detail, this work sets the stage for future studies that could address the intriguing question whether a MIF-like protein from a free-living bacterium may possess immunostimulatory features similar to those of mammalian MIFs and MIF-like proteins found in parasitic nematodes and protozoa.

**EXPERIMENTAL PROCEDURES**

**Materials.** 3-Bromopyruvate, phenylpyruvate, and (p-hydroxyphenyl)pyruvate were purchased from Sigma-Aldrich Chemical Co. (St. Louis, MO). Ingredients for media and buffers were obtained from Qiagen (Valencia, CA) or Duchefa Biochemie (Haarlem, The Netherlands). Molecular biology reagents and protein molecular weight standards were obtained from F. Chiswell (Massachusetts Institute of Technology, Cambridge, MA). The forward primer 5'-CAG CGA CAT ATG CCC TTG ATC AAC-3' contains a Ndel restriction site (in bold) followed by 12 bases corresponding to the coding sequence of the PmMIF gene. Two different reverse primers were used. To clone the PmMIF gene in frame with the sequence that codes for the polyhistidine region of the expression vector pET20b(+), the reverse primer 5'-GCA CTG CTC GAG ACC GAA GTT ACT TCC-3', which contains a Xhol restriction site (in bold), was used. To clone the gene without fusion tag, the reverse primer 5'-CTG ATG CAT CCT CAA CCG AAG GTA CT-3', which contains a BamHI restriction site (in bold), was used. The MIF gene was PCR-amplified from plasmid pET11b(MIF) (20). The forward primer 5'-CAG CGA CAT ATG CCT ATG TTC ATC-3' contains a Ndel restriction site (in bold) followed by 12 bases corresponding to the coding sequence of the MIF gene. To clone the MIF gene in frame with the sequence that codes for the polyhistidine region of the expression vector pET20b(+), the reverse primer 5'-CTG ATG CAT CCT GAG ACC GAA GTT ACT TCC-3', which contains a Xhol restriction site (in bold), was used.

Amplification mixtures contained the two appropriate synthetic primers, deoxyribonucleotide triphosphates, template DNA, Phusion DNA polymerase, and Phusion High-Fidelity Buffer. The resulting PCR products and the pET20b(+) vector (Novagen)
were digested with the appropriate restriction enzymes, purified, and ligated using T4 DNA ligase. An aliquot of each ligation mixture was transformed into competent *Escherichia coli* DH10B or XL-1 Blue cells. Transformants were selected at 37 °C on LB/Ap plates. Plasmid DNA was isolated from several colonies and analyzed by restriction analysis for the presence of the insert. For each expression vector, the cloned gene was sequenced to verify that no mutations had been introduced during the amplification of the gene. The newly constructed expression vectors were named pET20b(PmMIF-His), pET20b(PmMIF), and pET20b-(MIF-His).

**Construction of the PmMIF and MIF Mutants.** Mutants of PmMIF and MIF were generated by the overlap extension PCR method (39) using plasmid pET20b(PmMIF-His) or pET20b-(MIF-His), respectively, as the template. The final PCR products were gel-purified, digested with *NdeI* and *XhoI* restriction enzymes, and ligated in frame with both the initiation ATG start codon and the sequence that codes for the polyhistidine region of the expression vector pET20b(+). All mutant genes were completely sequenced (with overlapping reads) to verify that only the intended mutation had been introduced.

**Expression and Purification of His-Tagged PmMIF and MIF Proteins.** The PmMIF and MIF proteins, either wild type or mutant, were produced in *E. coli* BL21(DE3) using the pET20b(+) expression system. Fresh BL21(DE3) cells containing the appropriate expression plasmid were collected from a LB/Ap plate using a sterile loop and used to inoculate LB/Ap medium (10 mL). After growth for 16 h at 37 °C, this culture was used to inoculate fresh LB/Ap medium (1 L) in a 5 L Erlenmeyer flask. Cultures were grown for 16–18 h at 37 °C with vigorous shaking. Cells were harvested by centrifugation (6000g, 15 min) and stored at −20 °C until further use.

In a typical purification experiment, cells of a 1 L culture were thawed and suspended in lysis buffer (10 mL, 50 mM NaH₂PO₄, 300 mM NaCl, 10 mM imidazole, pH 8.0). Cells were disrupted by sonication for 6 × 1 min (with 4–6 min rest in between each cycle) at a 60 W output, after which unbroken cells and debris were removed by centrifugation (10000g, 45 min). The supernatant was filtered through a 0.45 μM pore diameter filter and incubated with Ni-NTA (1 mL slurry in a small column at 4 °C until further use. A typical yield is ∼50 mg of protein purified to near homogeneity per liter of culture.

**Enzymatic Assays.** The ketonization of phenylenolpyruvate (1) or (p-hydroxyphenyl)enolpyruvate (3) by MIF, PmMIF, and the PmMIF mutants was monitored by following the depletion of the enol isomer at 255 nm (*ε* = 6615 M⁻¹ cm⁻¹; *ε* = 4423 M⁻¹ cm⁻¹) in 20 mM NaH₂PO₄ buffer, pH 6.5, at 22 °C. By monitoring the ketonization of the two substrates at 255 nm, rather than at the reported *λ*<sub>max</sub> values for 1 and 3 (288 and 292 nm, respectively) (20, 40), it was possible to use higher substrate concentrations and achieve saturation due to the lower *ε* values at this wavelength. An appropriate aliquot of each enzyme was diluted into 50 mL of buffer and incubated for at least 30 min at 22 °C. This incubation period results in more reproducible kinetic data. Subsequently, 1 mL aliquots were transferred to a cuvette, and the assay was initiated by the addition of a small quantity (1–10 μL) of either 1 or 3 from a stock solution. Stock solutions (300 mM) of 1 and 3 were initially generated by dissolving the appropriate amount of phenylpyruvic acid or (p-hydroxyphenyl)pyruvic acid in ethanol and diluted (with ethanol) to generate 100 and 25 mM solutions. The crystalline free acid of phenylpyruvic acid or (p-hydroxyphenyl)pyruvic acid is exclusively the enol form. In general, the concentrations of 1 and 3 used in the assays ranged from 0 to 800 μM. At all substrate concentrations, the nonenzymatic rate was subtracted from the enzymatic rate of ketonization.

**1H NMR Spectroscopic Analysis of the Reaction of PmMIF with (p-Hydroxyphenyl)enolpyruvate (3).** A series of 1H NMR spectra monitoring the PmMIF-catalyzed ketonization of 3 were recorded using the following conditions. An amount of 100 and 25 mM solutions. The crystalline free acid of phenylpyruvic acid or (p-hydroxyphenyl)pyruvic acid is exclusively the enol form. In general, the concentrations of 1 and 3 used in the assays ranged from 0 to 800 μM. At all substrate concentrations, the nonenzymatic rate was subtracted from the enzymatic rate of ketonization.
treated with 3-bromopyruvate in separate incubation mixtures as follows. Each sample contained \( \sim 2 \) mg of enzyme and a sufficient quantity of 100 mM NaH\(_2\)PO\(_4\) buffer (pH 7.3) to give a final volume of 1 mL. Each sample was treated with 3-bromopyruvate (10 mM final concentration) and incubated at 22°C for 1 h. In separate control experiments, the same quantity of MIF or PmMIF was incubated without inhibitor under otherwise identical conditions. Subsequently, the four samples were treated with NaBH\(_4\) (25 mM) and loaded onto separate PD-10 Sephadex G-25 gel filtration columns, which had previously been equilibrated with 20 mM NaH\(_2\)PO\(_4\) buffer (pH 7.3). The proteins were eluted by gravity flow using the same buffer. Fractions (0.5 mL) were analyzed for the presence of protein by UV absorbance at 215 nm. The appropriate fractions containing the purified proteins were combined and assayed for residual activity and analyzed by ESI-MS.

**Crystal Growth and Structure Determination.** Purified PmMIF was concentrated to 11 mg/mL in buffer (10 mM Tris-HCl, pH 7.3). The protein was subjected to crystallization trials against 384 commercially available crystallization conditions using the hanging drop vapor diffusion technique. Initial conditions were identified with the Crystal Screen Cryo crystallization kit (Hampton Research) at 293 K. Optimization resulted in the growth of large crystals, obtained from hanging drops with

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**Figure 1:** MIF-like proteins in cyanobacteria. (A) Amino acid sequence alignment of selected cyanobacterial MIF-like proteins along with human and mouse MIF proteins. The NCBI reference sequences for the selected proteins are as follows: *Crocosphaera watsonii* WH8501, ZP_00514858.1; *Acaryochloris marina* MBIC11017, YP_001515361.1; *Microcoleus chthonoplastes* PCC7420, ZP_05029084.1; *Synechococcus* sp. CC9902, ZP_001515361.1; *P. marinus* strain MIT9313, NP_894336.1; *P. marinus* strain NATL1A, YP_001015373.1; *P. marinus* strain NATL2A, YP_291908.1; *P. marinus* strain MIT9211, YP_001551039.1. (B) Amino acid sequence alignment of the MIF-like protein from *P. marinus* strain MIT9313 (PmMIF) and human MIF (hMIF). Identical residues are shaded in black. The position of the Cys-X-X-Cys motif in the alignments is shaded in gray. The six active site residues that interact with the substrate in the structure of the human MIF–substrate complex (48) are indicated by an asterisk.
RESULTS

Identification of Cyanobacterial MIF Homologues. A BLAST search with the amino acid sequence of human MIF as the query was performed in the NCBI microbial databases containing finished and unfinished genome sequences. This search yielded bacterial proteins that shared significant sequence identity with human MIF, including various sequences from Synechococcus, Prochlorococcus, and other cyanobacteria. Interestingly, the top 15 hits were sequences from cyanobacteria only. Pairwise identities between human MIF and these identified cyanobacterial MIF homologues range from 31% to 41% (Figure 1A).

The MIF homologue from the marine cyanobacterium P. marinus strain MIT9313, designated PmMIF, is annotated as an ATLS1-like light-inducible protein. The genomic context of the gene encoding PmMIF does not provide any clues about the biological function of this protein in P. marinus. The mature PmMIF protein is predicted to be 114 amino acids in length, assuming excision of the initiating methionine residue. The relationship between PmMIF and the MIF family is readily detected by sequence similarity searches. The results of a conserved domain search (CD search) predict the presence of a MIF-like domain in PmMIF. The results of a PSI-BLAST search (with the amino acid sequence of PmMIF as the query) further support this prediction. The hit list after the first iteration includes many hypothetical proteins annotated either as ATLS1-like light-inducible proteins or MIF-like proteins. But, starting from the second iteration, there are a growing number of hits to functionally characterized mammalian MIFs, including mouse and human MIF. The sequence of PmMIF is 34% identical with that of human MIF, and in the pairwise alignment there are no insertions or deletions (Figure 1B). We have selected PmMIF for further study in order to gain insight into the structural and functional properties of this cyanobacterial MIF homologue.

Expression and Purification of PmMIF. The gene coding for PmMIF was amplified from genomic DNA of P. marinus strain MIT9313 and cloned in the expression vector pET20b (+), resulting in the construct pET20b(PmMIF-His). The PmMIF gene in pET20b(PmMIF-His) is under transcriptional control of the T7 promoter, and the recombinant enzyme was produced constitutively in E. coli BL21(DE3) as a C-terminal hexahistidine fusion protein. The recombinant enzyme was purified by a one-step Ni-based immobilized metal affinity chromatography protocol, which typically provides ~20 mg of homogeneous enzyme per liter of culture. Analysis of the purified enzyme by electrospray ionization mass spectrometry revealed one major peak that corresponds to a mass of 13305 ± 1 Da. A comparison of this value to the calculated subunit mass (13437 Da) indicates that the initiating methionine is removed during posttranslational processing, resulting in a protein with an N-terminal proline.

Tautomerase Activity of PmMIF. It has previously been determined that MIF functions as a tautomerase and processes substrates such as phenylpyruvate (1) and (p-hydroxyphenyl)pyruvate. The enzyme catalyzes a decrease in $k_{cat}$, a 2.1-fold decrease in $K_m$, resulting in a $k_{cat}/K_m$ of $2.3 \times 10^2$ M$^{-1}$ s$^{-1}$. In comparison to MIF, PmMIF shows a 377-fold decrease in $k_{cat}$, a 2.1-fold decrease in $K_m$, and a 177-fold decrease in $k_{cat}/K_m$. A comparison of the parameters measured for the conversion of 3 to 4 shows that the $k_{cat}$, $K_m$, and $k_{cat}/K_m$ values for PmMIF are 2940-, 2.6-, and 1148-fold lower, respectively, than those for MIF.

The PmMIF-catalyzed tautomeration of 3 (i.e., the enol form) was also monitored by $^1$H NMR spectroscopy to verify that the product of the reaction is 4 (i.e., the keto form). The spectrum recorded immediately after dissolving (p-hydroxyphenyl)pyruvate in acetate buffer revealed two doublets in the aromatic region (at 7.55–7.57 and 6.81–6.82 ppm) and a singlet representing an olefinic proton at 6.23 ppm, which is consistent

| Table 1: Kinetic Parameters for MIF, PmMIF, and PmMIF Mutants$^a$ |
|------------------|-----------------|-----------------|---------------------|
| enzyme | substrate | $k_{cat}$ (s$^{-1}$) | $K_m$ (µM) | $k_{cat}/K_m$ (M$^{-1}$ s$^{-1}$) |
| MIF | 1 | 114 ± 13 | 499 ± 116 | 2.3 × 10$^3$ |
| MIF | 3 | 147 ± 14 | 239 ± 57 | 6.2 × 10$^3$ |
| PmMIF | 1 | 0.31 ± 0.03 | 235 ± 61 | 1.3 × 10$^3$ |
| PmMIF | 3 | 0.05 ± 0.004 | 93 ± 28 | 5.4 × 10$^3$ |
| P1A-PmMIF | 1 | 0.01 ± 0.002 | 96 ± 55 | 1.0 × 10$^3$ |
| E60C-PmMIF | 1 | 1.27 ± 0.13 | 229 ± 57 | 5.5 × 10$^3$ |
| E60S-PmMIF | 1 | 2.44 ± 0.33 | 399 ± 111 | 6.1 × 10$^3$ |
| G97N-PmMIF | 1 | 0.24 ± 0.02 | 479 ± 76 | 5.0 × 10$^3$ |
| W106V-PmMIF | 1 | 0.57 ± 0.06 | 238 ± 66 | 2.4 × 10$^3$ |

$^a$The steady-state kinetic parameters were determined at 22°C in 20 mM NaH$_2$PO$_4$ buffer, pH 6.5. Errors are standard deviations from each fit.
with the enol form (Figure 2A). The enzymatic conversion of the enol form yields the keto form, as indicated by changes in the chemical shifts of the aromatic protons (to 7.02–7.04 and 6.78–6.79 ppm) and the appearance of a singlet at 3.91 ppm, which corresponds to the methylene protons. After a 30 min incubation period, the ratio of keto:enol is $\sim 2$ (Figure 2C). For comparison, a 30 min incubation period in the absence of enzyme yields a keto:enol ratio of $\sim 0.5$ (Figure 2B). These observations confirm that PmMIF has low-level tautomerase activity and demonstrate that 4 is the product of the PmMIF-catalyzed conversion of 3.

Since the N-terminal proline is expected to be important for the tautomerase activity of PmMIF (see below), we located the hexahistidine tag at the C-terminus of PmMIF. However, it remained possible that the hexahistidine tag could influence the tautomerase activity of PmMIF. To eliminate this concern, the native PmMIF protein without a fusion tag was also expressed and purified to homogeneity. Analysis of the kinetic properties of purified native PmMIF, using 1 as the substrate, yielded kinetic parameters ($k_{cat} = 0.22 \text{ s}^{-1}$, $K_m = 317 \mu\text{M}$, and $k_{cat}/K_m = 6.9 \times 10^2 \text{ M}^{-1} \text{ s}^{-1}$) very similar to those measured for the hexahistidine-tagged PmMIF. The sum of these observations shows that PmMIF has a tautomerase activity, but the activity is not as robust as that of MIF.

**Inactivation of PmMIF by 3-Bromopyruvate.** We investigated whether the tautomerase activity of PmMIF is sensitive to 3-bromopyruvate, an active site-directed irreversible inhibitor of MIF that covalently modifies the catalytic Pro-1 residue (47). After a 1 h incubation period (at 22 °C) with 3-bromopyruvate, the PmMIF sample (which was used as a control) had $\sim 5\%$ residual activity. Incubation of PmMIF or MIF without inhibitor under the same conditions had no effect on activity. Gel filtration chromatography did not result in recovery of enzyme activity, indicative of covalent modification.

To confirm the covalent modification of PmMIF and MIF, the two protein samples were treated with 3-bromopyruvate, reduced by NaBH$_4$, and analyzed by ESI-MS. The observed monomer masses of modified PmMIF (13395 ± 3 Da) and modified MIF (13529 ± 3 Da) are in good agreement with the masses expected for the monomer labeled by a single lactyl group and reduced by NaBH$_4$ (13395 and 13527 Da, respectively) (47). These results show that 3-bromopyruvate is responsible for the irreversible inhibition of both PmMIF and MIF and provide further evidence indicating that PmMIF is responsible for the observed tautomerase activity.

**Kinetic Properties of the P1A Mutant of PmMIF.** Kinetic, site-directed mutagenesis, NMR, and crystallographic analyses identified Pro-1 as the critical active site base for the tautomerase activity of MIF (19, 20, 47–49). To assess the importance of Pro-1 for the tautomerase activity of PmMIF, the P1A mutant was constructed, overproduced in E. coli BL21-(DE3), and purified to homogeneity using the immobilized metal affinity chromatography protocol developed for the wild-type MIF sample (which was used as a control) had $\sim 5\%$ residual activity. Incubation of PmMIF or MIF without inhibitor under the same conditions had no effect on activity. Gel filtration chromatography did not result in recovery of enzyme activity, indicative of covalent modification.

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3We also observed that prolonged incubation of PmMIF and MIF at 22 °C (in the presence of 3-bromopyruvate) gives multiple labeling events per monomer, which may result from the partial denaturation of the proteins under these conditions.
enzyme. The kinetic properties of the P1A mutant were analyzed using 1 as the substrate. The P1A mutant showed a 30-fold decrease in $k_{\text{cat}}$ and a 2.4-fold decrease in $K_m$, resulting in a 13-fold decrease in $k_{\text{cat}}/K_m$ (Table 1). These results provide additional evidence indicating that PmMIF is responsible for the observed activities and that Pro-1 is critical for activity.

**Oxidoreductase Activity of PmMIF.** It has previously been reported that MIF functions as an oxidoreductase and reduces small molecule disulfides such as 2-hydroxyethyl disulfide (HED) $(25, 26)$. This activity is based on a thioredoxin-like Cys-X-X-Cys motif (Figure 1B). We investigated whether PmMIF (with and without hexahistidine tag) can catalyze the reduction of HED. The results show that PmMIF does not reduce this disulfide. This is not surprising in view of the lack of the Cys-X-X-Cys motif in PmMIF (Figure 1B) and the very low level reductase activity of MIF (which was used as a control).

We next investigated whether the introduction of a Cys-X-X-Cys motif into PmMIF would give the enzyme the ability to reduce HED. The motif was introduced by constructing two different mutants: the single mutant E60C and the quadruple mutant T56C/C57A/Y58L/V59C. In the latter mutant, the motif is identical and in the same position in the alignment as that of MIF, whereas in the single mutant the Cys-X-X-Cys motif is shifted by one amino acid position (Figure 1B). In addition, we have mutated Glu-60 to the corresponding residue in MIF, yielding the E60S mutant. The three mutants were overproduced in E. coli BL21(DE3), purified to homogeneity, and assayed for their ability to reduce HED. As observed with wild-type PmMIF, the mutants did not exhibit detectable reductase activity.

The kinetic properties of the three mutants were also analyzed using 1 as the substrate. Replacement of Glu-60 with a cysteine or serine resulted in active enzymes with a surprisingly improved phenylpyruvate tautomerase activity (Table 1). The major effect of these mutations is observed in $k_{\text{cat}}$: there is a 4- and 8-fold increase in the $k_{\text{cat}}$ values for the E60C and E60S mutants, respectively. Analysis of the kinetic properties of the quadruple mutant yielded kinetic parameters very similar to those measured for wild-type PmMIF (not shown).

**Crystal Structure of PmMIF.** To enhance our understanding of the relationship between PmMIF and mammalian MIFs, we have determined the X-ray crystal structure of PmMIF at 1.63 Å resolution. The crystallographic R-factor for the final model was 16.4% ($R_{\text{free}}$ of 21.3%) (Table 2). PmMIF adopts a trimeric ring architecture similar to the other known MIF structures with each monomer composed of a four-stranded mixed β-sheet and two antiparallel α-helices stacked against the β-sheet on the outside of the trimer (Figure 3A). In the trimeric arrangement, the four-stranded β-sheet of each subunit is extended by two small β-strands contributed from the adjacent subunits. The overall trimeric structure of PmMIF is highly similar to that of the mammalian MIFs. A least-squares fit using Cα atoms from all three chains in the PmMIF trimer gives rmsd values of 0.83 and 0.95 Å against the structures of mouse MIF (PDB entry 1MFF) $(20)$ and human MIF (PDB entry 1MIF) $(22)$, respectively.

**Tautomerase Active Site of PmMIF.** To define the structural basis for the tautomerase activity of PmMIF, co-crystallization experiments with substrates 1 and 3 (and their keto isomers) (Scheme 1) were attempted. Although well-diffracting crystals were obtained at similar crystallization conditions as before, the derived electron density revealed no bound substrate in the active site. Hence, these co-crystallization experiments were unsuccessful. However, inspection of the $2F_o - F_c$ and $F_o - F_c$ difference Fourier maps revealed additional electron density near Pro-1 in all analyzed crystallographic data sets (from crystals grown in either the absence or presence of substrate), indicating the presence of a bound ligand. This electron density may be interpreted as a diethylene glycol molecule, small amounts of which are present in the crystallization precipitant PEG300 (up to 0.4% according to the manufacturer), or, alternatively, as the...
terminal units of a polyethylene glycol (PEG) molecule that protrudes into the active site, with its remainder being invisible due to disorder. The presumed diethylene glycol molecule or PEG terminus forms hydrogen-bonding interactions with Pro-1, Lys-32, and Ile-64 at the mouth of the putative active site cavity (Figure 3B).

To better define the tautomerase active site of PmMIF, we superimposed the structures of the active site regions of PmMIF and human MIF in complex with (p-hydroxyphenyl)enolpyruvate (3, Scheme 1) (Figure 3B). The structure of human MIF complexed with 3 (48) has identified the tautomerase active site and provided the essential structural information for the identification of the substrate interactions within the human MIF–substrate complex. In this complex, the catalytically important Pro-1 forms a hydrogen bond with C-3 of 3, Lys-32 and Ile-64 form hydrogen-bonding interactions with the carboxylate group, Asn-97 forms hydrogen bonds with the phenolic hydroxyl group, and Tyr-95 and Val-106 interact with the phenyl group of 3. Interestingly, four of the six active site residues that are interacting with the substrate (Pro-1, Lys-32, Ile-64, and Tyr-95) are conserved in PmMIF, both in sequence and in position. However, two residues, Asn-97 and Val-106, are not conserved and replaced by Gly-97 and Trp-106 in PmMIF (Figure 3B). The replacement of Asn-97 in human MIF by Gly-97 in PmMIF eliminates two side chain hydrogen bonds with substrate, assuming that substrate binds in the same orientation in the active site of PmMIF as compared to human MIF. The replacement of Val-106 in human MIF by the larger residue Trp-106 in PmMIF is potentially even more significant because Trp-106 partially fills the volume that is occupied by the phenyl group of the substrate in the human MIF–substrate complex (Figure 3B) (48). This suggests either that substrate has a different binding mode in PmMIF compared to human MIF, preventing a clash with Trp-106, or that conformational changes take place in PmMIF upon substrate binding, repositioning Trp-106 and generating the catalytically active state.

**Structure-Based Mutagenesis Studies of PmMIF.** The preceding comparison of the crystal structures of PmMIF and human MIF uncovered two unique active site residues in PmMIF, Gly-97 and Trp-106, that may contribute to its decreased tautomerase activity compared to human MIF. To investigate this possibility, these two active site residues in PmMIF have been mutated to the positionally conserved ones in human MIF. The two mutants (G97N and W106V) were overproduced in E. coli BL21(DE3), purified to homogeneity, and assayed for their two mutants (G97N and W106V) were overproduced in this possibility, these two active site residues in PmMIF have been tautomerase activity compared to human MIF. To investigate Gly-97 and Trp-106, that may contribute to its decreased MIF by Gly-97 and Trp-106 in PmMIF appears not to be DISCUSSION

We report herein the discovery and characterization of a cyanobacterial protein, designated PmMIF, that shares significant structural and functional similarities with the mammalian cytokine MIF. While several MIF homologues have been identified in eukaryotic parasites (27–35), where they are thought to play a role in modulating the host immune response, PmMIF is the first nonparasitic, bacterial MIF-like protein characterized in detail. Like eukaryotic MIFs, PmMIF is an active tautomerase, converting the substrates phenylenolpyruvate (1) and (p-hydroxyphenyl)enolpyruvate (3). The tautomerase activity levels are similar to those of MIF-like proteins from eukaryotic parasites, but much lower than those of human and mouse MIF.4 In contrast to several eukaryotic MIFs, however, PmMIF does not exhibit oxidoreductase activity.

The MIF family is one of the major families within the tautomerase superfamily, a group of structurally homologous proteins that are characterized by a β-α-β building block and a catalytic amino-terminal proline (Pro-1) (23, 24). Elucidation of the crystal structure of PmMIF (to 1.63 Å resolution) established that this cyanobacterial protein has the same overall β-α-β structural fold as previously characterized eukaryotic members of the MIF family. The importance of the conserved Pro-1 in catalysis was demonstrated by site-directed mutagenesis of PmMIF: the replacement of Pro-1 with an alanine resulted in an enzyme with strongly reduced tautomerase activity. Furthermore, reaction of PmMIF with 3-bromopyruvate, an active site-directed irreversible inhibitor of MIF that covalently modifies its catalytic Pro-1 residue (47), led to the alkylation of PmMIF and the concomitant loss of catalytic activity. The shared sequence identity and tautomerase activities and the conservation of the overall structural fold and catalytic Pro-1 residue firmly link PmMIF to the MIF family within the tautomerase superfamily. On the basis of these observations, we propose that PmMIF is part of the subfamily of bacterial β-α-β-fold proteins from which eukaryotic MIFs may have originated.

Although the overall trimeric structures are very similar, the putative active site region of PmMIF shows distinctive features from that of human and mouse MIF. Structural comparisons showed that four of the six active site residues implicated in substrate binding and/or catalysis in human MIF (Pro-1, Lys-32, Ile-64, and Tyr-95) are conserved in PmMIF (Figure 3B). However, two substrate-binding residues in human MIF, Asn-97 and Val-106, are replaced by Gly-97 and Trp-106 in PmMIF. These active site differences may reflect the different substrate specificities of cyanobacterial and human MIF, given that the physiological substrate of PmMIF has yet to be identified (see below). Notably, Trp-106 is fully conserved in the identified cyanobacterial MIF homologues, whereas the amino acid at position 97 is semiconserved, being either a glycine, glutamate, or asparagine (Figure 1A).

Surprisingly, mutation of Gly-97 and Trp-106 in PmMIF to their respective counterparts in human MIF had no significant influence on the level of phenylpyruvate tautomerase activity. This is quite remarkable given the fact that Trp-106, instead of the shorter Val-106, partially fills the volume that is occupied by the phenyl group of the substrate in the human MIF–substrate complex (Figure 3B) (48). One potential explanation for these observations is that conformational changes take place in PmMIF upon substrate binding, repositioning Trp-106 and thereby generating the catalytically active state of the enzyme. The notion that Trp-106 may occlude the binding pocket for

4The rate for the spontaneous nonenzymatic ketonization of 1 has not been reported. However, the rate for the uncatalyzed ketonization of enolpyruvate in phosphate buffer in D2O (∼2.0 × 10^{-1} s^{-1}) has been determined (30). Using this value and the $k_{cat}$ value for the PmMIF-catalyzed ketonization of 1 (Table 1), it can be roughly estimated that PmMIF affords a 150-fold rate enhancement. The actual rate enhancement might be somewhat different because 1 is more stable than enolpyruvate and because the ketonization of enolpyruvate in aqueous buffer will likely be severalfold faster than the reported rate in buffer in D2O.
aromatic substrates also prompted us to investigate whether alternative nonaromatic pyruvate derivatives may be processed by PmMIF. We have tested acetooacetate, oxaloacetate, and 2-hydroxymuconate as potential substrates for PmMIF, but no detectable tautomerase activity was observed. Work is in progress to explore additional pyruvate derivatives as possible substrates for PmMIF.

Another potential explanation for the lack of a significant kinetic effect of the W106V mutation is that the aromatic substrate has a different binding mode in PmMIF compared to human MIF. Support for this view comes from the interactions observed in the recently solved crystal structure of *Plasmodium yoelii* MIF (PyMIF) complexed with *(p-hydroxyphenyl)pyruvate* (4) (51). In the structure of the PyMIF—substrate complex, the substrate is bound in an orientation different from that observed in the structure of the human MIF—substrate complex. The change in the binding orientation in PyMIF prevents a clash between the substrate’s phenyl group and the large phenylalanine residue found at position 106. It has been postulated that this different substrate binding mode also accounts for the lower level of phenylpyruvate tautomerase activity of PyMIF (51).

Taken together, these observations implicate factors beyond the core set of six active site residues in MIF catalysis and substrate specificity. Hence, in-depth mechanistic, structural, and mutational studies of PmMIF are needed to identify the additional features necessary for a fully active phenylpyruvate tautomerase. In this context, it is important to emphasize that the PmMIF mutants E60C and E60S have surprisingly increased tautomerase activity levels (4- and 8-fold, respectively). Residue Glu-60 is located at the monomer—monomer interface within the trimer, quite far from the tautomerase active site, and the exact mechanism of the kinetic effects of the E60C and E60S mutations is unknown. Nonetheless, these findings suggest that the lower level of tautomerase activity of PmMIF may be the result of a combination of effects, including the suboptimal positioning of the substrate.

To obtain a better understanding of the catalytic mechanism of PmMIF, it would be highly desirable to have a crystal structure of PmMIF complexed with substrate at the active site. However, our attempts to crystallize PmMIF in complex with substrate I or 3 (or their keto isomers) using co-crystallization experiments have been unsuccessful so far. Our failure to obtain such a crystal structure could be due to a number of factors. We have considered the possibility that diethylene glycol, which is indicated as a possible ligand bound in the active site of PmMIF (Figure 3), could act as a competitive inhibitor and prevent substrate from binding. Hence, we have tested diethylene glycol as a potential inhibitor of PmMIF. In the presence of I (at 300 μM), the enzyme was only slightly inhibited (~15%) by 10 mM diethylene glycol. As the concentration of diethylene glycol in the crystallization solution is estimated to be ≤10 mM, we concluded that the possibility that diethylene glycol prevents substrate from binding is not very likely. Additional experiments are underway to obtain a structure of the enzyme—substrate complex, including soaking experiments and co-crystallization efforts using different crystalization conditions (in the absence of PEG).

In summary, the discovery of a new subgroup of cyanobacterial proteins in the MIF family, along with the structural and functional characterization of PmMIF, demonstrates that MIF-like proteins have a widespread distribution and are found not only in eukaryotic parasites but also in free-living bacteria. This invites speculation about the intrinsic physiological function of these MIF-like proteins. One important fundamental question concerns whether PmMIF exhibits immunostimulatory features similar to those of mammalian MIFs and MIF-like proteins found in parasitic nematodes and protozoa (27–34). In order to address this question, it will be necessary to test whether PmMIF can influence the functional responses of human immune cells and shows significant binding interaction with the human MIF receptor, CD74 (11, 12). Such efforts are being pursued in our laboratories and may help to establish whether parasitic MIF-like proteins could function as “accidental” effector molecules of the human immune response.

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**REFERENCES**


5The possibility that PmMIF has other activities in addition to its tautomerase activity cannot be excluded. Also note that the biological relevance of MIF’s tautomerase activities is unknown.
macrophage migration inhibitory factor (MIF) catalyzes a tautomer-
tion inhibitory factor (MIF) is a phenylpyruvate tautomerase. FEBS Lett. 417, 85–88.
dopachrome to 5,6-dihydroxyindole is a phenylpyruvate tautomerase. Mela
Mano Res. 7, 1–2.
inhibitory factor from rat liver. Nat. Struct. Biol. 3, 259–266.
tory, Cold Spring Harbor, NY.
tory, Cold Spring Harbor, NY.