Molecular characterization of a chromosomal region involved in the oxidation of acetyl-CoA to glyoxylate in the isocitrate-lyase-negative methylotroph *Methylobacterium extorquens* AM1

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A region on the *Methylobacterium extorquens* AM1 chromosome previously shown to complement a chemically induced mutant (PCT48) unable to convert acetyl-CoA into glyoxylate was characterized in detail in order to identify the gene(s) involved in the unknown pathway for acetyl-CoA oxidation. Six complete and two partial ORFs were identified by sequencing. Sequence comparisons suggested these might code for, respectively, a dehydrogenase of unknown specificity, a polypeptide of at least 15 kDa with unknown function, a coenzyme-B$_6$-linked mutase, a catalase, an alcohol dehydrogenase (ADH) of unknown function, a polypeptide of 28 kDa, a ketol-acid reductoisomerase and a propionyl-CoA carboxylase (PCC). Insertion mutations were introduced into each ORF in order to determine their involvement in C$_3$ and C$_4$ metabolism. Mutations in three genes, encoding the mutase, ADH and PCC, resulted in a phenotype characteristic of mutants unable to oxidize acetyl-CoA, i.e. they were C$_{-}$- and C$_{+}$-negative and their growth on these compounds was restored by the addition of glycolate or glyoxylate. Mutants in the genes thought to encode catalase and PCC were found to be deficient in the corresponding enzyme activity, confirming the identity of these genes, while physiological substrates for the mutase and ADH remain unidentified. This work, in which three new genes necessary for conversion of acetyl-CoA into glyoxylate were identified, is an intermediary step on the way to the solution of the unknown pathway for acetyl-CoA oxidation in isocitrate-lyase-negative methylotrophs.

**Keywords:** *Methylobacterium extorquens*, isocitrate-lyase-negative methylotrophs, serine cycle, acetyl-CoA oxidation, C$_3$ and C$_4$ metabolism

INTRODUCTION

*Methylobacterium extorquens* AM1 is a pink-pigmented serine cycle methylotroph able to grow on methanol and methylamine, and also on a variety of multicarbon substrates including ethanol, ethylamine, lactate, pyruvate, malonate, $\beta$-hydroxybutyrate and succinate (Peel & Quayle, 1961; Tsuji et al., 1990). For more than two decades, this organism has been used as a model for studying both the biochemistry and the genetics of the serine cycle utilized for assimilation of C$_3$ compounds at the level of formaldehyde (Salem & Quayle, 1971; Dunstan *et al*., 1972a, b; Dunstan & Anthony, 1973; Anthony, 1982; Chistoserdova & Lidstrom, 1992, 1994a-c). In the serine cycle, formaldehyde in the form of methylenetetrahydrofolate condenses with glycine to produce serine, which then undergoes transamination with glyoxylate, producing hydroxypyruvate, which in turn is reduced to D-glycerate. The latter is phosphorylated to phosphoglycerate, then transformed to phosphoenol pyruvate, which is carboxylated to produce malate and then malyl-CoA. This is then cleaved to glyoxylate and acetyl-CoA (Anthony, 1982). In the serine...
methylotrophs which lack isocitrate lyase (Icl"), such as *M. extorquens* AM1, the second molecule of glyoxylate must be regenerated from acetyl-CoA, but the biochemical pathway leading to such a conversion remains unknown (Anthony, 1982). Studies of the fate of carbon atoms originating from ethanol, acetate or methanol have indicated that a common pathway must operate that leads from acetyl-CoA to glyoxylate during assimilation of C₄ and C₅ compounds, and also multicarbon compounds like malonate and β-hydroxybutyrate (Salem & Quayle, 1971; Dunstan *et al.*, 1972a, b; Dunstan & Anthony, 1973).

The pathway of C₄ assimilation also remains unknown in other bacterial groups (Dawes & Sutherland, 1994). Elucidation of this pathway in methylotrophic bacteria might bring about greater understanding of the fate of acetyl-CoA in other Icl" organisms.

In *M. extorquens* AM1, three chromosomal fragments have been identified carrying genes encoding enzymes involved in assimilation of both C₄ and C₅ compounds and probably operating in the unknown pathway for glyoxylate regeneration. One of these, *orf4*, encodes a protein of unknown function and is located in a large cluster of C₄ genes that includes a number of serine cycle genes (Chistoserdova & Lidstrom, 1994c). Another gene, *glyA*, is located on a separate chromosomal fragment and encodes serine hydroxymethyltransferase. This enzyme apparently plays a dual role in *M. extorquens* AM1, firstly in the serine cycle and secondly in the oxidation of acetyl-CoA (Chistoserdova & Lidstrom, 1994b). The third chromosomal fragment not linked to the two fragments mentioned above has been shown to complement a number of chemically induced mutants such as PCT48 that are unable to grow on C₄ and C₅ compounds and are complemented by the addition of glycolate or glyoxylic acid (Stone & Goodwin, 1989; Smith & Goodwin, 1992; Smith *et al.*, 1995). PCT48 was shown to contain a deletion of 3.3 kb in this region (Smith & Goodwin, 1992). The goal of the present study was to characterize this last region in more detail.

**MATERIALS AND METHODS**

**Bacterial strains, plasmids and growth conditions.** *Escherichia coli* strains DH5α (Bethesda Research Laboratories) and S17-1 (Simon *et al.*, 1983) were used in this study. They were grown in LB medium in the presence of appropriate antibiotics as described by Maniatis *et al.* (1982). *M. extorquens* AM1 was grown in the minimal medium described previously (Harder *et al.*, 1973). Succinate (20 mM), methanol (100 mM), methylamine (20 mM), ethylamine (20 mM), formate (40 mM), pyruvate (40 mM) or β-hydroxybutyrate (20 mM) were used as substrates. Methanol induction of mutants was carried out as described by Dunstan *et al.* (1972b). The following antibiotic concentrations were used for *M. extorquens* AM1: tetracycline (Te), 10 μg ml⁻¹; kanamycin (Km), 100 μg ml⁻¹; and rifamycin, 50 μg ml⁻¹. The growth responses of mutants were tested on plates containing the substrates listed above in the presence or absence of supplements of glyoxylate (5 mM) or glycolate (20 mM).

**DNA-DNA hybridizations.** These were carried out with dried agarose gels as described by Meinkoth & Wahl (1984) at 68 °C. SSC (0.15 M NaCl, 0.015 M sodium citrate) was used at 6 × concentration for hybridizations and 0.5 × concentration for washes.

**DNA manipulations.** Plasmid isolation, *E. coli* transformation, restriction enzyme digestion, ligation, blunting ends with T4 DNA polymerase, or filling in ends with Klenow enzyme were carried out as described by Maniatis *et al.* (1982). The chromosomal DNA of *M. extorquens* AM1 was isolated by the procedure of Saito & Miura (1963).

**DNA sequencing.** The DNA sequence of both strands was determined with an Applied Biosystems automated sequencer by the Caltech Sequencing Facility.

**Computer analysis.** Translation and analyses of DNA and DNA-derived polypeptide sequences were carried out using PC/Gen (Genoft, Geneva) or Genetic Computer Group (Wisconsin) programs.

**Enzyme assays.** Enzyme activities were determined in *M. extorquens* AM1 crude extracts prepared as described previously (Chistoserdova & Lidstrom, 1992). All measurements were done at room temperature (26 °C) in a total volume of 1 ml. Hydroxypropyruvate reductase (HPR) was assayed as described by Chistoserdova & Lidstrom (1991). Catalase was assayed by following *A*₄₃₀ (Beers & Seizer, 1952). Propionyl-CoA carboxylase (PCC) was assayed by following the appearance of ADP. The reaction mixture contained 50 mM Tris/HCl, pH 7.5; 3 mM ATP; 10 mM MgCl₂; 3 mM propionyl-CoA; 0.2 mM NADH; 3 mM phosphoenolpyruvate (PEP); 20 units pyruvate kinase (PK); 7 units lactate dehydrogenase (LDH) and crude extract containing 0.1–0.3 mg protein. Methylmalonyl-CoA mutase (MCM) was measured by disappearance of ADP in a discontinuous assay coupling MCM and PCC reactions. For this assay, PCC was overexpressed by introduction of cloned *pccA* (see Results). The reaction mixture contained, in 0.5 ml 50 mM Tris/HCl, pH 7.5; 0.5 mM ADP, 5 mM MgCl₂, 3 mM succinyl-CoA, and crude extract containing 0.1–0.3 mg protein. The reaction was allowed to proceed for 5–10 min, after which the remaining ADP was measured in LDH reaction by the addition of 0.5 ml of the following mixture: 50 mM Tris/HCl, pH 7.5; 3 mM PEP; 0.2 mM NADH; 20 units PK; and 7 units LDH. Spectrophotometric methods (Kalb & Bernlohr, 1977; Whitaker & Granum, 1980) were used for protein determination.

**Isoelectrofocusing.** Crude cell extracts were isoelectrofocused in a pH range of 3–9 or 4–6.5 using PhastSystem as described by the manufacturer (Pharmacia-Biotech). For alcohol dehydrogenase (ADH) assays, gels were stained using a reaction mixture consisting of a buffer (potassium phosphate, pH 7.0; Tris/HCl, pH 7.5–8.0; or pyrophosphate, pH 9.0) plus 1 mM NAD or NADP, 1 mM nitro blue tetrazolium, 0.5 mM phenazine methosulfate and 1–10 mM substrate (ethanol, 2-propanol, glycerol, acetaldehyde, propionaldehyde, glycolaldehyde, glycolate or glyceralate). Catalase was visualized by incubating gels in a buffered (pH 7.0) 3% (v/v) solution of hydrogen peroxide and noting the appearance of bubbles.

**Matings.** Triparental or biparental matings between *E. coli* and *M. extorquens* AM1 were performed overnight on nutrient agar at 30 °C. Cells were then washed with sterile medium and plated on selective medium at appropriate dilutions. In triparental matings, pRK2013 (Ditta *et al.*, 1985) was used as a helper plasmid. Rifamycin was used for *E. coli* counter-selection.
Amino acid sequence comparisons

The amino acid sequences deduced from complete and partial ORFs found in the region under study were compared against the protein database. The first (partial) ORF showed similarity with a number of dehydrogenases, including 3-oxoacyl-[acyl-carrier-protein] reductase (about 35% identity; Klein et al., 1992; Slabas et al., 1992), glucose 1-dehydrogenase (about 32% identity; Lampel et al., 1986; Heilmann et al., 1988), acetoacetate (diacetyl) reductase (about 25% identity; Blomqvist et al., 1993) and 1-acetoacetate-CoA reductase (about 23% identity; Peoples & Sinskey, 1989). This gene was designated xdh, for unknown dehydrogenase. No significant similarity to known protein sequences was found for the second ORF, which was designated orf1. The polypeptide deduced from the third ORF showed high identity with subunits of MCM from both prokaryotic and eukaryotic sources (about 35%; Francalanci et al., 1986; Jansen et al., 1989; Wilkemeyer et al., 1990), and has been designated meaA (Smith et al., 1995). The next ORF, transcribed divergently from meaA, was shown to encode a polypeptide highly similar to catalase subunits from various sources (Murthy et al., 1981; Schroeder et al., 1982; Bell et al., 1986; Furuta et al., 1986; Ort et al., 1990; Bol et al., 1991) with identities ranging from 40 to 57%, and was designated adhA. The polypeptide translated from the next ORF, transcribed divergently from adhA, did not reveal strong identity to known proteins and was designated orf2. The putative product from the seventh ORF was shown to bear high similarity to 1-acetoacetate-CoA reductase (also known as 1-butyrate-CoA reductase) from bacteria and yeasts, with identities ranging from 32 to 54% (Daniels et al., 1992; Godon et al., 1992), and was designated adhC. The last (partial) ORF in the region encodes a polypeptide highly similar to the β-subunit of mammalian PCC (about 60% identity; Kraus et al., 1986; Lamhonwah et al., 1986), and was designated pccA.
Acetyl-CoA oxidation genes in a methylotroph

Fig. 2. Nucleotide and translated amino acid sequences of the 285 bp HindII-EcoRI fragment (a) and 8988 bp EcoRI-HindII fragment (b) of the M. extorquens AM1 chromosome region surrounding meaA. The coding DNA strands are shown. Hairpins are underlined and stop codons are indicated by asterisks.

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Construction of insertion mutations

Insertion mutations were generated in all the ORFs identified in the region under study. The strategy for introduction of specific mutations was based on the exchange of DNA via homologous recombination in vivo between the wild-type gene and a gene that had been inactivated by an insertion mutation in vitro (Ruvkun & Ausubel, 1981). The 1.3 kb Km\(^{r}\) cassette originating from pUC4K (Vieira & Messing, 1982) was employed, cut by appropriate restriction enzymes. The Km\(^{r}\) cassette was always inserted in the orientation such that the direction of transcription of the aph gene coincided with the direction of transcription of the interrupted gene. This has been shown in the past to create non-polar insertions (Chistoserdova & Lidstrom, 1994a, c; Chistoserdov et al., 1994). Plasmids in which corresponding genes had been interrupted by the insertion were then ligated with the suicide vector pACYC61 (Chistoserdov et al., 1994). The resulting plasmids were transformed into E. coli S17-1 to produce donors, which were mating with M. extorquens AM1. Km\(^{r}\) M. extorquens AM1 progeny were routinely obtained on plates containing succinate as the growth substrate, except in the case of mutations in ilvC, when supplements of valine and isoleucine (1 mg ml\(^{-1}\) or 5 mg ml\(^{-1}\), respectively) were also added. Colonies resistant to Km were checked for their resistance to Tc. Te\(^{r}\) colonies were assumed to be double-crossover recombinants, while Te\(^{s}\) colonies were assumed to be single-crossover recombinants. In all cases, the identity of the mutants was confirmed by hybridization of chromosomal DNA with corresponding specific probes and pUC4K DNA in comparison with the wild-type DNA (data not shown). Specific sites of insertions into the region are as follows (noted by asterisks in Fig. 1): Mutations 6211 and 6112KHI are, approximately in the middle (EcoRI site) and in the end (Tthl11I site) of xab, respectively. Mutation 61EP2 is a 3\(\beta\)l deletion of approximately 0.3 kb involving the 5\(^{\prime}\) terminus of orf1. Mutation 61MC1M is in the Smal site approximately in the middle of mecA. Mutation 6128Km is in katA (PstI site at position 939, Fig. 2b). Mutation 61ADH is in adbA (BsaAI site at position 1684). Mutation 6132 is in the region separating adbA and orf2 (NruI deletion of 360 bp, positions 3287 and 3676, Fig. 2b). Mutation 61OR2 is in orf2 (EcoRI site at position 4507). Mutation 61EPKm and 61ICP are in ilbC (AraI deletion of 190 bp, positions 5076 and 5266, and insertion into PstI, position 5488, respectively). Mutation 6111H is in the region separating ilbC and pecB (BsaAI site at position 6797). Mutation 61PCC is in pecB (SmaI site at position 7805).

Phenotypic analysis of insertion mutants

Up to 300 recombinants from each mating were tested for resistance to Tc in order to separate single-crossover (Te\(^{c}\)Km\(^{r}\)) and double-crossover (Te\(^{c}\)Km\(^{r}\)) recombinants. Mutations in only four genes produced double-crossover recombinants (with a frequency of 10–50% in relation to the total number of recombinants): mecA, katA, adbA and pecA (Fig. 1). One of the insertions introduced into an intergenic site (mutation 6132) also resulted in double-crossover recombinants. Mutations in the other seven sites, including one mutation in an intergenic site (6111H) produced only single-crossover recombinants. Since those types of crossover events regenerate a functional target gene, this implies that these gene products are vital for growth of M. extorquens AM1 on succinate. It is not clear why mutation 6111H did not result in double-crossover recombinants, since past experience with insertions of the Km\(^{r}\) cassette in M. extorquens AM1 did not cause polar effects (Chistoserdova & Lidstrom, 1994a–c; Chistoserdov et al., 1994). All single-crossover mutations were able to grow on both C\(_{4}\) and C\(_{3}\) compounds (up to 300 colonies tested for each mutation event).

Growth responses have been determined for double-crossover recombinant insertion mutants in mecA, adbA, katA and pecA. Mutants in katA grew normally on C\(_{4}\) (methanol and methylamine) and C\(_{3}\) (ethanol and ethylamine) compounds, while mutants in adbA, mecA and pecA lost the ability to grow on C\(_{4}\) and C\(_{3}\) compounds, and also on \(\beta\)-hydroxybutyrate, indicating that their products are required for both C\(_{4}\) and C\(_{3}\) metabolism. All mutants grew normally on pyruvate. Glyoxylate and glycolate have been used previously as supplements to characterize mutants in the unknown pathway of oxidation of acetyl-CoA to glyoxylate (Dunstan et al., 1972a, b; Dunstan & Anthony, 1973; Salem & Quayle, 1971; Salem et al., 1973). These compounds were tested for the ability to restore growth of the mutants on methanol, formate, ethylamine and \(\beta\)-hydroxybutyrate. Both supplements were able to restore growth of the mutants on C\(_{4}\) and C\(_{3}\) compounds and on \(\beta\)-hydroxybutyrate. Mutants in mecA and adbA regained the ability to grow on C\(_{4}\) and C\(_{3}\) compounds when the 13.5 kb HindIII fragment was introduced in a broad-host-range vector, pRK310 (Ditta et al., 1985), while mutants in pecA were complemented by an overlapping 5.6 kb PstI fragment isolated by hybridization and cloned into pRK310. This PstI fragment must therefore contain the complete pecA.

Activity of catalase in katA mutants

Activity of catalase was measured in a few representative katA mutants and in wild-type M. extorquens AM1 grown on methanol and succinate. In both the wild-type M. extorquens AM1 and the mutants, high levels of catalase activity were found, which in general seemed to be higher on succinate than on C\(_{4}\) compounds (approximately 100 and 60 nmol min\(^{-1}\) (mg protein\(^{-1}\))\(^{-1}\), respectively). These data suggested that M. extorquens AM1 may have multiple genes responsible for the synthesis of catalase. To prove the identity of the mutation in katA, we separated proteins on isoelectricfocusing gels using crude extracts from the wild-type cells of M. extorquens AM1, from two representatives of katA mutants, CAT38 and CAT42, and from CAT38 carrying a plasmid containing cloned katA (pLC310.SS) and observed catalase activity by immersing the gels in a hydrogen peroxide solution. Two activity bands with pI values of approximately 4.6 and 5.0 were present in the wild-type extract, and also in the extract of CAT38(pLC310.SS), while only one (the less acidic) band
Table 1. Activities of PCC, MCM and HPR in wild-type M. extorquens AM1, pccA and meaA insertion mutants, and in mutants carrying cloned pccA and meaA.

Measurements were done in triplicate and values were within ±25% of each other.

<table>
<thead>
<tr>
<th>Strain</th>
<th>Activity [nmol min⁻¹ (mg protein)⁻¹]</th>
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<tr>
<td></td>
<td>PCC</td>
</tr>
<tr>
<td></td>
<td>Succ*</td>
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<tr>
<td>Wild-type</td>
<td>25</td>
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<tr>
<td>Wild-type (pLC310.84)</td>
<td>65</td>
</tr>
<tr>
<td>PCC50</td>
<td>0</td>
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<tr>
<td>PCC54</td>
<td>0</td>
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<tr>
<td>PCC50(pLC310.84)</td>
<td>55</td>
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<tr>
<td>MCM1(pLC310.84)</td>
<td>50</td>
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<tr>
<td>MCM28(pLC310.84)</td>
<td>45</td>
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<tr>
<td>MCM28(pLC310.SS84)</td>
<td>60</td>
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<tr>
<td>MCM28(pLC310.SS84)</td>
<td>55</td>
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*, Not measured.
† Cells grown on methanol or, in the case of methanol-negative strains, grown on succinate, washed and incubated with methanol as described by Dunstan et al. (1972).

was present in the katA mutants (data not shown). Although the calculated pI for the product of katA is 6.1, the corresponding activity band shows a pI of approximately 4.6. This difference could be due to the quaternary structure of catalase, which is usually composed of four subunits (Murthy et al., 1981).

Activity of PCC in pccA mutants

PCC activity was measured in the wild-type M. extorquens AM1 cells and in two representatives of pccA mutants, PCC50 and PCC54. Cells from succinate-grown cultures or cultures grown on succinate and then induced with methanol (Dunstan et al., 1972b) were employed. The activity of HPR has also been used as a positive control for induction of serine cycle enzymes by methanol. Similar levels of PCC were found in wild-type M. extorquens AM1 grown on methanol or succinate. PCC activity was not found in pccA mutants. When a plasmid carrying cloned pccA (pLC310.84) was introduced into the pccA mutants, PCC activity was found at increased levels, in accordance with the presence of multiple copies of the gene in these strains (Table 1).

Activity of MCM in meaA mutants

Since meaA appeared to be similar to genes encoding subunits of MCM, the presence of MCM was first checked in the meaA mutants and in the wild-type cells. Since the assay we used involved PCC as a coupling enzyme, the latter was overexpressed by the introduction of plasmids carrying pccA (pLC310.84 carrying the 6·5 kb PstI fragment containing entire pccA cloned into pRK310) or both meaA and pccA (pLC310.SS84 carrying the 18·5 kb HindIII-PstI fragment). The activity was found at similar levels in mutant and wild-type cells grown on succinate or induced with methanol, and it did not seem to be overexpressed in strains carrying plasmids with cloned meaA (Table 1).

Search for ADH activity

The specificity of the product of adbA is unknown, but the enzyme reveals highest similarity with ADHs having specificity for short-chain alcohols (Russell et al., 1983; Russell & Hall, 1983; Young & Pilgrim, 1985; Gwynne et al., 1987; Saliola et al., 1990), which are most active on ethanol. ADHs are usually readily stained in gels (Megnet, 1967). We isoelectrofocused cell-free extracts of the wild-type M. extorquens AM1, two representatives of adbA mutants, ADH70 and ADH76, and ADH70 carrying pLC310.SS (the 13·5 kb HindIII fragment cloned into pRK310), in which the adbA product should be overexpressed. The gels were stained in various conditions, employing the following alcohols and aldehydes: ethanol, 2-propanol, glycerol, acetaldehyde, propionaldehyde, glycolaldehyde, glycolate and glycerate. As many as ten specific bands could be detected using the substrates above, and at least two of these seemed to be induced by C₆ substrates (with pI values of approximately 6.5 and 7.5). However, none of the bands disappeared in the adbA mutants (data not shown). Thus, the identity of adbA remains unknown.
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DISCUSSION

In most aerobic organisms able to utilize acetate, the main assimilatory mechanism is the glyoxylate cycle, which is characterized by the presence of two enzymes: isocitrate lyase and malate synthase, in addition to enzymes of the tricarboxylic acid cycle. This pathway has been found in many bacteria, including Icl- serine methylotrophs, fungi, algae and protozoa (Dawes & Sutherland, 1994). Icl- serine methylotrophs, exemplified by M. extorquens AM1, lack isocitrate lyase, and the pathway used for assimilation of acetate, which also operates during growth on C1 compounds and β-hydroxybutyrate, remains unknown. It has been shown previously using 14C-labelled C1 and C2 compounds that glycolate, glyoxylate, malate and an unidentified compound (compound X) must be intermediates in this unknown pathway (Dunstan et al., 1972a, b; Dunstan & Anthony, 1973). These conclusions were confirmed by the isolation of mutants unable to utilize C1 and C2 compounds and β-hydroxybutyrate, which were complemented by the addition of glycolate or glyoxylate (Dunstan et al., 1972a, b; Dunstan & Anthony, 1973; Salem & Quayle, 1971; Salem et al., 1973). However, a pathway that converts acetyl-CoA to glyoxylate in this strain has never been identified. In this study we have approached the problem using molecular genetic analysis. A fragment of the M. extorquens AM1 chromosome previously used to complement such a mutant, PCT48, was sequenced in order to identify the gene defective in this mutant and possibly other genes involved in the pathway. Three genes specifically involved in the unknown pathway have been identified, the one defective in PCT48 (meaA) encoding a coenzyme B12-linked mutase and two new genes (metA and adhA) encoding respectively PCC and an ADH with an as yet unknown function. Mutants in metA, pccA and adhA have the expected phenotype, i.e. they are C1- and C2-negative, and are complemented on these substrates by glycolate or glyoxylate. These three genes, although found within a single DNA fragment, are obviously not co-transcribed and are separated from each other by non-coding DNA regions and by genes whose involvement in C1 and C2 metabolism we were not able to prove, since mutants in them were only obtained as single-crossover recombinants with C1- and C2-positive phenotypes. In addition to the newly identified genes apparently involved in the unknown part of the serine cycle, we have previously shown that serine hydroxymethyltransferase and the product of an unidentified gene (orf4) are probably involved in this pathway (Chistoserdova & Lidstrom, 1994b, c). Phenotypes of mutants in glyA and orf4 are different from the phenotypes of the mutants described here, since they were only complemented on C2 compounds by glycolate, and not by glyoxylate.

A metabolic pathway, the 3-hydroxypropionate cycle, has been described in which acetyl-CoA is converted into glyoxylate, which would involve PCC (Strauss & Fuchs, 1993). In this pathway, acetyl-CoA is carboxylated and reductively converted via 3-hydroxypropionate to propionyl-CoA, which is carboxylated and converted via succinyl-CoA to malyl-CoA. The latter is cleaved to acetyl-CoA and glyoxylate. A different pathway was proposed to operate in the serine methylotroph Prostaminobacter ruber (Shimizu et al., 1984), in which glyoxylate could be regenerated from acetyl-CoA by using part of the tricarboxylic acid cycle to convert acetyl-CoA to α-ketoglutarate. The latter is then carboxylated to methylmalonyl-CoA and transformed to succinyl-CoA, which can be regenerated in another part of the tricarboxylic acid cycle to produce oxaloacetate, the acceptor for the next molecule of acetyl-CoA. None of the above pathways, however, would require any NAD-linked ADH, or a mutase other than MCM or serine hydroxymethyltransferase.

Two sequential reactions involving MCM and PCC are parts of both pathways described above. These are also shown to participate in β-oxidation of fatty acids and in degradation of branch-chained amino acids (Gottschalk, 1979). Both activities are present in M. extorquens AM1, but only PCC is proven to be specifically involved in the unknown pathway for regeneration of glyoxylate. meaA apparently encodes a mutase different from MCM, and MCM is not able to substitute for its activity. The physiological substrate for the alternative mutase and consequently its role remain unknown.

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