Characterization and inactivation of the membrane-bound polyol dehydrogenase in *Gluconobacter oxydans* DSM 7145 reveals a role in *meso*-erythritol oxidation

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The growth of *Gluconobacter oxydans* DSM 7145 on *meso*-erythritol is characterized by two stages: in the first stage, *meso*-erythritol is oxidized almost stoichiometrically to L-erythrulose according to the Bertrand–Hudson rule. The second phase is distinguished from the first phase by a global metabolic change from membrane-bound *meso*-erythritol oxidation to L-erythrulose assimilation with concomitant accumulation of acetic acid. The membrane-associated erythritol-oxidizing enzyme was found to be encoded by a gene homologous to *sldA* known from other species of acetic acid bacteria. Disruption of this gene in the genome of *G. oxydans* DSM 7145 revealed that the membrane-bound polyol dehydrogenase not only oxidizes *meso*-erythritol but also has a broader substrate spectrum which includes C3–C6 polyols and d-gluconate and supports growth on these substrates. Cultivation of *G. oxydans* DSM 7145 on different substrates indicated that expression of the polyol dehydrogenase was not regulated, implying that the production of biomass of *G. oxydans* to be used as whole-cell biocatalysts in the biotechnological conversion of *meso*-erythritol to L-erythrulose, which is used as a tanning agent in the cosmetics industry, can be conveniently carried out with glucose as the growth substrate.

**INTRODUCTION**

*Gluconobacter oxydans* is one of the most important organisms in industrial biotechnology because of its ability to incompletely oxidize various sugars, sugar alcohols and sugar acids (De Muyck et al., 2007). The oxidation reactions are catalysed by membrane-bound dehydrogenases linked to the respiratory chain (Matsushita et al., 1994). As the active sites of these dehydrogenases face the periplasm, substrates need not be transported into the cytoplasm and the corresponding oxidation products accumulate in the culture medium. Moreover, most substrates are oxidized regio- and stereoselectively, yielding enantiomerically pure products at high yields, thus enabling efficient whole-cell biocatalytic production processes that are superior to chemical substrate conversion due to the absence of complicated and expensive protective chemistry reactions (Schweiger et al., 2007). Examples of the industrial application of *Gluconobacter* spp. are the production of L-sorbose, an intermediate of vitamin C synthesis (Adachi et al., 2003) and the conversion of 1-amino-D-sorbitol to 6-amino-L-sorbose for the synthesis of the antidiabetic drug Miglitol (Schedel, 2000).

All of the biochemically studied membrane-bound dehydrogenases are either quinoproteins, containing pyrroloquinoline quinone (PQQ) as prosthetic group, or flavoproteins, containing a covalently bound FAD molecule (Davidson, 2004; Matsushita et al., 1994). Additionally, some enzymes contain a haem c moiety, such as the quinohaemoprotein alcohol dehydrogenase (Kondo & Horinouchi, 1997). The reducing equivalents derived from the oxidation reactions are transferred via ubiquinone to a chinol oxidase of the bo3 type (Matsushita et al., 1987), with concomitant build-up of an electrochemical proton gradient across the cytoplasmic membrane. Therefore, the incomplete oxidation reactions provide energy for growth, while the cytoplasmic, NAD(P)-dependent dehydrogenases present in *Gluconobacter* spp. most likely provide precursors for biosynthetic pathways (Matsushita et al., 1994).

**Abbreviations:** DCIP, 2,6-dichlorophenol indophenol; Gm, gentamicin; Km, kanamycin; PMS, phenazine methosulfate; PQQ, pyrroloquinoline quinone; RLM RACE, RNA ligase-mediated rapid amplification of cDNA ends.

A supplementary figure, showing an alignment of the amino acid sequences of the SldB and SldA proteins of *G. oxydans* ATCC 621H (Gox0855) and *G. oxydans* DSM 7145, is available with the online version of this paper.
The membrane-bound quinoprotein glycerol dehydrogenase of the \textit{Gluconobacter suboxydans} strains IFO 3257 and IFO 3255, which contains PQQ as prosthetic group, has been shown to be a versatile enzyme, catalysing the oxidation of the sugar acid D-gluconate and the sugar alcohols glycerol, D-arabitol, D-mannitol and D-sorbitol (Matsushita \textit{et al.}, 2003). It is composed of the large SldA subunit (79.6 kDa), which contains the active site, and the small SldB subunit (14 kDa), which is essential for activity development and seems to act as a molecular chaperone (Shinjoh \textit{et al.}, 2002). The enzyme catalyses the regio- and stereoselective oxidation of its substrates according to the Bertrand–Hudson rule, which states that polyols with a cis arrangement of two secondary hydroxyl groups in D-configuration to the primary alcohol group (D-erythro configuration) are oxidized to the corresponding ketoses (Kulhanek, 1989). Also among these substrates is the tetritol meso-erythritol, which is oxidized to the corresponding ketose l-erythrulose (Matsushita \textit{et al.}, 2003). L-Erythrulose is commonly used as tanning agent and constitutes a precursor for the production of l-erythrose, a derivative of which, dideoxyerythrose, has shown some anti-HIV activity (Tschamber \textit{et al.}, 1996).

Despite the fact that \textit{Gluconobacter oxydans} is used for the industrial conversion of meso-erythritol to l-erythrulose, the utilization and oxidation of erythritol by this species has not been studied in detail. In this study we have shown that the membrane-bound glycerol dehydrogenase catalyses meso-erythritol oxidation in \textit{G. oxydans} DSM 7145, and that both meso-erythritol and l-erythrulose are utilized by \textit{G. oxydans} DSM 7145. Additionally, the genetic organization of the genes \textit{sldA} and \textit{sldB} was investigated.

\section*{METHODS}

\subsection*{Bacterial strains and growth conditions.} All strains and plasmids and their relevant characteristics are listed in Table 1. \textit{Escherichia coli} strains were grown in Luria–Bertani medium (Sambrook \textit{et al.}, 1989) at 37 °C and 150 r.p.m. \textit{G. oxydans} DSM 7145 and its derivatives were routinely grown in a complex medium containing 5 g yeast extract \(1^{-1}\), 3 g tryptone \(1^{-1}\) and 50 mM D-mannitol (pH 6.0). When appropriate, D-mannitol was replaced by 50 mM D-glucose. Growth was recorded by measuring the OD\textsubscript{600} in a UV-Vis spectrophotometer (Amersham). Growth tests were performed in complex medium, using cultures pre-grown on the respective substrate as inoculum. The following substrates were tested at final concentrations of 50 mM: D-mannitol, D-glucose, glycerol and meso-erythritol. A mixture of D-glucose and D-mannitol was added at a final concentration of 25 mM each. Antibiotics were used at the following concentrations: kanamycin (Km) 50 μg ml\textsuperscript{-1}, cefoxitin (50 μg ml\textsuperscript{-1}) and gentamicin (Gm) 50 μg ml\textsuperscript{-1} (\textit{G. oxydans}) or 10 μg ml\textsuperscript{-1} (\textit{E. coli}).

\subsection*{Resting cell experiments.} \textit{G. oxydans} DSM 7145 was grown to stationary phase (OD\textsubscript{600} \(\approx 1.1\)) in 300 ml complex medium with 50 mM D-glucose. The cells were harvested by centrifugation at 10000 r.p.m. and subsequently washed twice with 10 mM sodium phosphate buffer (pH 6.2). The pellets of 150 ml culture were resuspended in 100 ml 10 mM sodium phosphate buffer (pH 6.2) containing either 50 or 200 mM meso-erythritol, transferred to a 1 l flask and incubated at 30 °C, 150 r.p.m. for 24 h.

\subsection*{DNA manipulations.} Routine molecular biology experiments were carried out with commonly used standard procedures. Genomic DNA from \textit{G. oxydans} DSM 7145 for PCRs and Southern blot analysis was prepared using the MasterPure DNA purification kit (Epicentre). \textit{Pfu} DNA polymerase (Fermentas) was used for amplification of fragments that were subsequently cloned. \textit{Taq} DNA polymerase (Fermentas) was employed in test reactions. Primers used in this study were listed in Table 2 and were deduced from the whole genome sequence of \textit{G. oxydans} ATCC 621H (Prust \textit{et al.}, 2005). Restriction enzymes (Fermentas), DNA ligase and antarctic phosphatase (New England Biolabs) were all used according to the manufacturers’ instructions.

\begin{table}[h]
\centering
\begin{tabular}{|l|l|l|}
\hline
\textbf{Strain or plasmid} & \textbf{Relevant characteristics} & \textbf{Source or reference} \\
\hline
\textit{E. coli} strains & & \\
XL-1 blue & recA\textsuperscript{−}, thi, hsdR1, supE44, relA1, lacF\textsuperscript{−}, proAB, lacIq, lacZAM15, Tn10[Tet] & Bullock \textit{et al.} (1987) \\
S17-1 & Sm\textsuperscript{R}, Tp\textsuperscript{R}, mod\textsuperscript{+}, res\textsuperscript{−}, thi, pro, recA\textsuperscript{−}, hsdR17, RP4-Tc::Mu-Km::Tn7 & Simon \textit{et al.} (1983) \\
Solopack & lacZAM15, endA, recA\textsuperscript{−}, Strep\textsuperscript{R}, cre & Stratagene \\
\textit{G. oxydans} strains & & \\
DSM 7145 & Type strain & Mason & Claus (1980) \\
sldA::Gm & DSM 7145 derivative, Gm\textsuperscript{R} inserted in sldA gene & This study \\
\hline
\textbf{Plasmids} & & \\
pSC-A & Cloning vector, Ap\textsuperscript{R} & Stratagene \\
pBBR-1 MCS2 & Broad-host-range vector, Km\textsuperscript{R} & Kovach \textit{et al.} (1995) \\
pBBR-1 MSC5 & Broad-host-range vector, Gm\textsuperscript{R} & Kovach \textit{et al.} (1995) \\
pK19mobsacB & Gene replacement vector, Km\textsuperscript{R}, sac\textsuperscript{B} & Schäfer \textit{et al.} (1994) \\
pSC-A::sldA & sldA genes in pSC-A, Ap\textsuperscript{R} & This study \\
pSC-A::sldA\textsuperscript{−}:Genta & sldA genes in pSC-A, sldA gene disrupted by Gm\textsuperscript{R} gene, Km\textsuperscript{R}, Gm\textsuperscript{R} & This study \\
pJV5 & pK19mobsacB derivative containing sldA genes, sldA gene disrupted by Gm\textsuperscript{R}, Km\textsuperscript{R}, Gm\textsuperscript{R} & This study \\
pJV8 & pBBR-1 MCS2 derivative containing sldB promoter fused to sldA gene, Km\textsuperscript{R} & This study \\
\hline
\end{tabular}
\caption{Strains used and constructed in this study.}
\end{table}

Abbreviations: Ap\textsuperscript{R}, ampicillin resistant; Gm\textsuperscript{R}, gentamicin resistant; Km\textsuperscript{R}, kanamycin resistant; Strep\textsuperscript{R}, streptomycin resistant.
Nucleotide sequence analysis. Sequencing was performed using an ABI Prism 3730XL sequencer (Applied Biosystems). The nucleotide sequences were determined on both DNA strands. Sequence data were analysed using the STADEN software package (Bonfield et al., 1995). Homology searches and alignment analysis were performed using BLAST (Altschul et al., 1997) and CLUSTAL W (Larkin et al., 2007), respectively. Potential signal peptides and transmembrane helices were predicted with the SignalP 3.0 software (Bendtsen et al., 2004) and TMHMM software, respectively.

Southern blot analysis. Two micrograms of genomic DNA was digested with KpnI and electrophoresed on an 0.8 % agarose gel, transferred to a positively charged Hybond XL membrane (Amersham Biosciences), and hybridized with a probe generated by Southern blot analysis.

RT-PCR. RT-PCRs were performed using the OneStep RT-PCR kit (Qiagen) according to the instructions of the manufacturer and using 800 ng total RNA as template. To verify co-transcription of the sldBA genes, primers sldb_for and slda_w2 (Table 2) were used. Primer sldb_for binds at the 5' end of the sldb gene, while primer slda_w2 binds in the opposite direction starting at basepair 504 of the slda gene. A polycistronic mRNA was expected to yield a product of 924 bp.

Mapping of the sldBA transcription start site. RNA ligase-mediated rapid amplification of cDNA ends (RLM RACE) was used to determine the transcription start site of the sldBA genes, using the protocol of the manufacturer (FirstChoice RLM-RACE kit, Ambion). Two independent replicates were carried out, including a control without tobacco acid pyrophosphatase treatment. The generated cDNA was subsequently used in a nested PCR with Taq DNA polymerase (Fermentas) and the primers listed in Table 2. After column purification (Qiagen), products were cloned using a TOPO TA cloning kit (Invitrogen). A total of four colonies were sequenced, and the insert was sequenced in both directions.

Construction of a G. oxydans DSM 7145 slda mutant. To construct a G. oxydans DSM 7145 slda mutant by allelic replacement, the slda genes were amplified with forward primer sldb_for and reverse primer slda_rev (Table 2) from genomic DNA of G. oxydans DSM 7145 and cloned into plasmid pSC-A (Stratagene). The central 1.5 kb NotI fragment from the sldb insert in pSC-A: sldAB was then replaced with a 1 kb Gm-resistance cassette which had previously been amplified from plasmid pBBR-1 CM85 (Kovach et al., 1995) using primers Genta_1_for and Genta_2_rev (Table 2). The correct insertion of the Gm-resistance cassette in the same transcriptional direction as the sldb gene was confirmed by restriction endonuclease digestion. The insert was finally cloned between the HindIII and EcoRI sites of plasmid pK19mobsacB (Schäfer et al., 1994), resulting in plasmid pJV5. Plasmid pJV5 was transformed into E. coli S17-1 (Simon et al., 1983) and mobilized into G. oxydans DSM 7145. Single-crossover mutants were selected by plating on complex medium with Km. Double-crossover mutants were identified based on their Km/Cm phenotype.

Table 2. Primers used in this study

<table>
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<tr>
<th>Primer</th>
<th>Sequence (5’→3’)</th>
<th>Source or reference</th>
</tr>
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<td>sldb_for</td>
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<td>This work</td>
</tr>
<tr>
<td>sldb_rev</td>
<td>CGTTGCGACAGGCGAGTGCCGGAAG</td>
<td>This work</td>
</tr>
<tr>
<td>slda_for</td>
<td>GTCTGATCGCAGATCCCTTCTTCG</td>
<td>This work</td>
</tr>
<tr>
<td>slda_rev</td>
<td>CTGGTTCTCGTATACACCGGTAGC</td>
<td>This work</td>
</tr>
<tr>
<td>slda_w1</td>
<td>GTAGAGGCGGTACACCCACTTGATC</td>
<td>This work</td>
</tr>
<tr>
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</tr>
<tr>
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<tr>
<td>slda_w4</td>
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<tr>
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</tr>
<tr>
<td>sldb_v_for</td>
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<td>This work</td>
</tr>
<tr>
<td>slda_v_rev</td>
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<td>This work</td>
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<td>slda_p_for</td>
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<td>Ambion</td>
</tr>
<tr>
<td>5' RACE_inner</td>
<td>CGCGGATCCGGAACATCGGTGCTTGATG</td>
<td>Ambion</td>
</tr>
</tbody>
</table>

G. oxydans DSM 7145 total RNA was prepared from 40 ml cells grown to 40 % cell growth, and total RNA was prepared for RT-PCR analysis using the OneStep RT-PCR kit (Qiagen). The RNA ligase-mediated rapid amplification of cDNA ends (RLM RACE) was used to determine the transcription start site of the sldBA genes, using the protocol of the manufacturer (FirstChoice RLM-RACE kit, Ambion). Two independent replicates were carried out, including a control without tobacco acid pyrophosphatase treatment. The generated cDNA was subsequently used in a nested PCR with Taq DNA polymerase (Fermentas) and the primers listed in Table 2. After column purification (Qiagen), products were cloned using a TOPO TA cloning kit (Invitrogen). A total of four colonies were sequenced, and the insert was sequenced in both directions.
Construction of a complementation vector. To complement the sldA mutant, a 143 bp fragment containing the putative promoter region of the sldBA genes was amplified using primers sldB_prom_for and sldB_prom_rev (Table 2) and genomic DNA as template. Similarly, the sldA structural gene (2.2 kb) was amplified using primers sldA_compl_for and sldA_compl_rev (Table 2). Both fragments were fused in a long flanking homology PCR (Wach, 1996), and the obtained 2.3 kb fragment was subcloned into vector pSC-A (Stratagene). The insert was excised from pSC-A: sldAB_prom by EcoRI digestion and finally cloned between the EcoRI sites of pBBR-1 MCS2 (Kovach et al., 1995), resulting in plasmid pV8. The construct was transferred into G. oxydans DSM 7145 by biparental mating using E. coli S17-1.

Preparation of membrane fractions. G. oxydans DSM 7145 and G. oxydans DSM 7145 sldA::Gm were grown on 300 ml complex medium with D-glucose or D-glucose/D-mannitol to late exponential phase. Cultures were harvested by centrifugation (9000 r.p.m., 15 min), washed twice with 10 mM Tris/HCl buffer (pH 7.2) and resuspended in 10 ml of the same buffer per gram wet weight. Cells were lysed by twofold passage through a French press, and after centrifugation (11 000 r.p.m., 20 min) to remove intact cells, the supernatant (crude extract) was centrifuged at 100 000 g for 2 h. The resulting pellet was suspended in 10 mM Tris/HCl buffer (pH 7.2), centrifuged again (100 000 g, 60 min), resuspended in the same buffer and designated membrane fraction.

Protein determination. Protein concentrations were determined with a Bradford assay with the modification for determining protein volumes of 100 to 1800 μg (Bradford, 1976). BSA was used as standard.

Dehydrogenase assay. Dehydrogenase activities were assayed spectrophotometrically by following the reduction of 2,6-dichlorophenol indophenol (DCIP) at 578 nm using phenazine methosulfate (PMS) as a redox mediator. The reaction mixture contained enzyme solution, MacIlvaine buffer (pH 5.0), 25 mM substrate, 0.67 mM PMS and 0.1 mM DCIP. Reactions were started by addition of substrate and followed in a Varian Model 100 spectrophotometer. One unit of enzyme activity was defined as the amount of enzyme oxidizing 1 μmol substrate min⁻¹. The specific activity was calculated using a millimolar extinction coefficient for DCIP of 5.016 M⁻¹ cm⁻¹ at pH 5.0 and 578 nm.

Substrate/product analyses. Samples from cultures for the determination of meso-erythritol and l-erythulose were obtained by centrifugation at 13 000 r.p.m. for 10 min and subsequent freezing at −20 °C. meso-Erythritol and l-erythulose were quantified by HPLC using a CarboPac MA1 or PA1 column (Dionex). Sample volumes of 100 μl were injected and the temperature was kept constant at 25 °C. Each run was carried out isocratically using 480 mM (CarboPac MA1) or 250 mM (CarboPac PA1) NaOH elution buffer. meso-Erythritol and l-erythulose peaks were detected electrochemically after approximately 1.8 and 2.5 min, respectively (CarboPac MA1 10.8 and 26.8 min, respectively). Acetate was assayed enzymically as described by Bergmeier (1974) with an acetate detection kit (R-Biopharm) according to the instructions of the manufacturer.

RESULTS

Growth of G. oxydans DSM 7145 on meso-erythritol-containing medium

As shown in Fig. 1, G. oxydans DSM 7145 grew at a growth rate of 0.51 h⁻¹ and to a final optical density of 1.82. HPLC analysis of culture supernatants revealed that meso-erythritol was nearly quantitatively oxidized to l-erythulose within the first 8 h of the experiment, which coincided with an increase in optical density from 0.05 to 0.8. However, the extracellular l-erythulose concentration decreased by approximately 60% in a second growth phase from t8 to t24, where a further increase in optical density was observed (0.8–1.82). To identify reaction products secreted in the second growth phase, culture supernatants were analysed by HPLC and GC-MS analysis. These analyses identified acetate acid as the main reaction product (data not shown), which was also confirmed enzymically. Acetic acid starts to accumulate as the supplied meso-erythritol is completely oxidized. While the extracellular l-erythulose concentra-

![Fig. 1. Growth and substrate/product analysis of G. oxydans DSM 7145 on complex medium supplemented with 50 mM meso-erythritol. A representative experiment is shown. (a) Growth of the culture was followed spectrophotometrically after starting the culture at OD600 0.07. (b) Substrate consumption and product formation during growth were quantified as described in Methods. Symbols: ■, meso-erythritol concentration (mM); □, l-erythulose concentration (mM); ◇, acetate acid concentration (mM).]
tion decreased by 30 mM, only 10 mM acetic acid was detectable in the supernatant (Fig. 1b).

Resting cells of *G. oxydans* DSM 7145 rapidly converted 50 mM *meso*-erythritol to L-erythrulose within 6 h with a yield of 93% (Fig. 2). Interestingly, neither a decrease in extracellular L-erythrulose concentration nor an accumulation of acetic acid was observed in the resting cell experiments. Taken together, these results indicate that L-erythrulose consumption and acetic acid production can be attributed to growth of *G. oxydans* DSM 7145 on L-erythrulose.

**Sequence analysis of sldBA from *G. oxydans* DSM 7145**

As *meso*-erythritol oxidation was solely localized in membrane fractions of *G. oxydans* DSM 7145 (data not shown) it was hypothesized that an enzyme similar to the membrane-bound glycerol dehydrogenase of *G. suboxydans* (Matsushita et al., 2003) catalyses oxidation of *meso*-erythritol in *G. oxydans* DSM 7145. Therefore, potential homologues of the *sldBA* genes, encoding the glycerol dehydrogenase, were amplified. Not only the product sizes obtained, ~380 bp for *sldB*, ~2200 bp for *sldA*, but also the sequences of the *sldBA* genes of *G. oxydans* DSM 1745 and ATCC 621H were highly similar.

Based on the deduced amino acid sequences a complete identity of the SldB and a 99% identity of the SldA proteins of *G. oxydans* DSM 7145 and ATCC 621H were observed. Based on the structure of the *Methyllobacterium extorquens* methanol dehydrogenase (Ghosh et al., 1995) two highly conserved residues could be identified in the SldA amino acid sequence. Among these residues is Trp-340, which lies at the same position as Trp-243 of the methanol dehydrogenase, where this residue together with two sulfur atoms of a disulfide ring structure plays a key role in positioning the PQQ molecule. Interestingly, the Trp residue alone, and neither the two cysteine residues nor a histidine residue, which replaces the cysteine residues in the *E. coli* quinoprotein glucose dehydrogenase (Cozier & Anthony, 1995), was detectable in the SldA amino acid sequence. However, the SldA protein retains an Asp residue (Asp-404, Supplementary Fig. S1), conserved in all PQQ-dependent dehydrogenases, which corresponds to Asp-303 of the *M. extorquens* methanol dehydrogenase and is thought to be the catalytic base that initiates the reaction by abstraction of a proton from the substrate (Ghosh et al., 1995).

**Genetic organization of sldA and sldB in *G. oxydans* DSM 7145**

Sequencing of the *sld* genes revealed that the stop codon of the *sldB* gene (TGA) overlaps with the start codon (ATG) of the *sldA* gene, suggesting that the *sldBA* genes are organized in an operon. To analyse whether the *sldBA* genes are co-transcribed, an RT-PCR with primers spanning the entire *sldB* gene and the 5'-9 portion of the *sldA* gene was performed. As shown in Fig. 3, the expected ~920 bp fragment, originating from a polycistronic mRNA, was obtained. Additionally, the transcription start of the *sldBA* genes was mapped by 5'-RRLM RACE at the thymidine nucleotide 24 bp upstream of the *sldB* start codon, which further supports the notion that in *G. oxydans* DSM 7145 the *sldBA* genes are co-transcribed from a common promoter upstream of *sldB* (data not shown).

**Disruption of the sldA gene in *G. oxydans* DSM 7145**

To test the hypothesis that *meso*-erythritol oxidation in *G. oxydans* DSM 7145 is catalysed by the glycerol dehydrogenase, a mutant was constructed by chromosomal...
inactivation of the sldA gene. For inactivation, an internal 1.5 kb fragment of the sldA gene was replaced by a 1 kb Gm-resistance cassette. In this mutant, designated G. oxydans DSM 7145 sldA::Gm, more than 67% of the sldA gene was deleted. The successful disruption of the sldA gene and the absence of the vector in the chromosome were verified by PCR and Southern blot analysis (data not shown).

Growth of G. oxydans DSM 7145 and G. oxydans DSM 7145 sldA::Gm on different carbon sources

Growth of the mutant was monitored on complex medium supplemented with meso-erythritol and other carbon sources known to be utilized by G. oxydans DSM 7145. Disruption of sldA severely impaired growth of the resulting strain G. oxydans DSM 7145 sldA::Gm on complex medium with glycerol, meso-erythritol and D-mannitol. No growth was observed on meso-erythritol and D-mannitol, while growth on glycerol was slowed down by a factor of three. After 24 h the mutant reached an optical density on glycerol resembling that of the wild-type strain DSM 7145.

Growth of G. oxydans DSM 7145 sldA::Gm on D-glucose was slightly impaired and the mutant also reached a final optical density that was lower than that of the wild-type. On a mixture of 25 mM D-glucose/25 mM D-mannitol the growth rate of G. oxydans DSM 7145 sldA::Gm resembled that of the wild-type grown on D-glucose (0.65 h⁻¹) and also the final optical density was comparable with the value reached by G. oxydans DSM 7145 grown on D-glucose (OD₆₀₀ ~0.7). This seems noteworthy, because on D-glucose/D-mannitol the wild-type grew at a rate (0.46 h⁻¹) and to a final optical density (OD₆₀₀ ~2) comparable with the values obtained for cultivation on D-mannitol.

These results suggest that the glycerol dehydrogenase indeed oxidizes meso-erythritol in vivo, and in addition seems to have a broader substrate spectrum that also includes at least glycerol and D-mannitol.

Biochemical characterization of G. oxydans DSM 7145 sldA::Gm

To biochemically examine the effect of sldA disruption, membrane fractions of G. oxydans DSM 7145 and G. oxydans DSM 7145 sldA::Gm grown on complex medium with D-glucose to late exponential phase were prepared. These were subsequently used to assay the dye-linked dehydrogenase activities with different substrates. As shown in Fig. 4, sldA disruption did not negatively affect membrane-bound D-glucose oxidation. In G. oxydans DSM 7145 sldA::Gm, D-glucose oxidation was even slightly higher than in the wild-type. Apart from D-glucose, significant D-gluconate oxidation [0.18 U (mg protein)⁻¹, about 42% of the wild-type level] was retained in the membrane fraction of G. oxydans DSM 7145 sldA::Gm. On the other hand, oxidation of the tested polyols glycerol, meso-erythritol, D-arabitol, D-mannitol and D-sorbitol was significantly reduced in the membrane fraction of G. oxydans DSM 7145 sldA::Gm as compared with the wild-type membranes. Thus, the glycerol dehydrogenase from G. oxydans DSM 7145 not only oxidizes meso-erythritol but has a broad substrate spectrum that includes the sugar acid D-gluconate and the C3–C6 polyols glycerol, D-arabitol, D-mannitol and D-sorbitol.

Glycerol dehydrogenase activities in membrane fractions of cells grown on complex medium with 25 mM D-glucose/25 mM D-mannitol

To exclude the possibility that other membrane-bound dehydrogenases catalysing the oxidation of meso-erythritol are induced during growth on carbon sources other than D-glucose, G. oxydans DSM 7145 and G. oxydans DSM 7145 sldA::Gm were cultivated on complex medium with 25 mM D-glucose/D-mannitol to late exponential phase. Based on the data depicted in Fig. 4, SldA seems to be the main polyol dehydrogenase in G. oxydans DSM 7145. Oxidation of glycerol, meso-erythritol, D-arabitol, D-mannitol, D-sorbitol and D-gluconate was also clearly reduced in the membrane fraction of G. oxydans DSM 7145 sldA::Gm grown in a mixture of D-glucose/D-mannitol.

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**Fig. 3.** Genetic organization and operon analysis of the sldBA genes in G. oxydans DSM 7145. (a) Arrangement of the sldBA genes (grey arrows) in G. oxydans DSM 7145. (b) Operon analysis of the sldBA genes. cDNA synthesized from total RNA of cells grown either on D-glucose (lane 1) or on D-glucose/D-mannitol (lanes 2) was used as template in PCR experiments with primers sldB_for and sldA_w2 (Table 2). Negative controls without prior reverse-transcriptase treatment are shown in lanes 3 and 4, respectively. The product obtained from a PCR with genomic DNA is depicted in lane 6. Lanes 5 and 7 represent non-template controls of the PCRs. The predicted fragment size was 924 bp.

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**Biochemical characterization of G. oxydans DSM 7145 sldA::Gm**

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Moreover, Fig. 4 shows that the glycerol dehydrogenase seems to be expressed constitutively, irrespective of the utilized carbon source, because similar PMS-DCIP reductase activities were detected in membrane fractions of cultures grown on D-glucose and D-glucose/D-mannitol. In contrast, differences in membrane-bound D-glucose oxidation were observed. In wild-type membrane fractions, glucose dehydrogenase decreased with the D-glucose concentration in the medium, while membrane fractions of \textit{G. oxydans} DSM 7145 \textit{sldA}::Gm revealed elevated D-glucose oxidation rates.

**Complementation of \textit{G. oxydans} DSM 7145 \textit{sldA}::Gm**

To complement \textit{G. oxydans} DSM 7145 \textit{sldA}::Gm, a plasmid, pJV8, containing the putative \textit{sldB} promoter region fused to the \textit{sldA} gene was constructed. This construct efficiently restored growth of \textit{G. oxydans} DSM 7145 \textit{sldA}::Gm on complex medium with D-mannitol, meso-erythritol and glycerol (data not shown). Differences were observed in the final optical densities. While \textit{G. oxydans} DSM 7145 \textit{sldA}::Gm(pJV8) grown on glycerol and meso-erythritol reached values comparable with those of the vector control, only half of the final optical density of the control was reached when \textit{G. oxydans} DSM 7145 \textit{sldA}::Gm(pJV8) was cultivated on D-mannitol. Membrane fractions of the complemented mutant again oxidized glycerol, meso-erythritol, D-arabitol, D-mannitol, D-sorbitol and D-gluconate. The observed ratio of the dehydrogenase activities of the vector control and the complemented mutant was 0.7 for most substrates, except for D-gluconate, where the ratio was 0.89.

**DISCUSSION**

In this study it was shown that \textit{G. oxydans} DSM 7145 not only utilizes meso-erythritol but also \textit{l}-erythrulose as growth substrate, and that both substrates are metabolized by different pathways. Oxidation of meso-erythritol is membrane-associated, mediated by the glycerol dehydrogenase (discussed below) and results in nearly quantitative accumulation of \textit{l}-erythrulose in culture supernatants. Depletion of extracellular meso-erythritol leads to a global metabolic change from membrane-bound meso-erythritol oxidation to \textit{l}-erythrulose assimilation accompanied by acetate accumulation. In the cytoplasm, \textit{l}-erythrulose is most likely reduced to meso-erythritol by an NAD(P)\textsuperscript{+}-dependent dehydrogenase, as similarly discussed with ribitol dehydrogenase from \textit{G. suboxydans} IFO 12528 (Adachi \textit{et al.}, 2001), and then channelled into the pentose-phosphate pathway. Acetate is probably produced from the glyceraldehyde 3-phosphate generated in the pentose-phosphate pathway via pyruvate and acetaldehyde, as the genome sequence of \textit{G. oxydans} ATCC 621H reveals a missing acetate kinase pathway but the presence of a pyruvate decarboxylase and an NADP\textsuperscript{+}-dependent acetaldehyde dehydrogenase (Prust \textit{et al.}, 2005; Schweiger \textit{et al.}, 2007). \textit{Gluconobacter frateurii} CHM 43 has also been shown to grow on meso-erythritol and \textit{l}-erythrulose (Moonmangmee \textit{et al.}, 2002), but \textit{l}-erythrulose consumption linked to extracellular accumulation of acetic acid has not been previously reported.

Excretion of acetic acid by \textit{G. oxydans} DSM 7145 is most likely only a by-product of intracellular \textit{l}-erythrulose metabolism, because 30 mM \textit{l}-erythrulose was consumed but only 10 mM acetic acid was detectable in the culture.
supernatants (Fig. 1b). As has been shown for *E. coli* aerobic acetate production, this is a manifestation of an imbalance between glucose uptake and the demands for both biosynthesis and energy production (El-Mansi & Holmes, 1989). Thus, it can be assumed that l-erythulose cannot be channeled into the cytoplasmic pathways fast enough and therefore part of the internalized l-erythulose is converted to acetic acid.

A further physiological explanation of the observed biphasic metabolism of *meso*-erythritol could be that *G. oxydans* DSM 7145 first quickly oxidizes *meso*-erythritol to an unfavourable product, l-erythulose, thereby preventing growth and utilization of erythritol by other bacteria. Afterwards, l-erythulose is slowly utilized, similar to the hypothesis of l-sorbose utilization by *G. frateurii* CHM 43 (Soempohl et al., 2007).

As *meso*-erythritol oxidation was solely localized in membrane fractions of *G. oxydans* DSM 7145, it seemed reasonable that an enzyme similar to the membrane-bound glycerol dehydrogenase of *G. suboxydans* (Matsushita et al., 2003) catalyses *meso*-erythritol oxidation in *G. oxydans* DSM 7145. Sequencing of the identified homologues from strain DSM 7145 revealed not only that they are highly similar to the *sldBA* genes of *G. oxydans* ATCC 621H (gxx 0854–0855) (Prust et al., 2005) and *G. suboxydans* IFO 3255 (Miyazaki et al., 2002) but also that the genes seem to be organized in an operon (Fig. 3). Only few promoters of acetic acid bacteria have been characterized to date, so we decided to elucidate the mode of transcription of the *sldBA* genes. Our experiments showed that these two genes are indeed transcribed polycistronically from a promoter upstream of *sldb*. Co-transcription may also take place in *G. suboxydans* IFO 3255, as was speculated by Miyazaki et al. (2002), and may also occur in other *Gluconobacter* strains with a similar genetic organization of the *sldBA* genes. To test the hypothesis that *meso*-erythritol is a substrate of the membrane-bound glycerol dehydrogenase, the *sldA* gene was inactivated by insertion of a Gm-resistance gene. Growth experiments with *meso*-erythritol and other substrates known to be utilized by *G. oxydans* DSM 7145 indicated that *meso*-erythritol and other C3–C6 polyols but not D-glucose are substrates of the glycerol dehydrogenase. The broad substrate spectrum of the enzyme could be further confirmed by biochemical characterization of the mutant. While D-glucose oxidation was retained in membrane fractions of *G. oxydans* DSM 7145 *sldA::Gm*, oxidation of the C3–C6 polyols glycerol, *meso*-erythritol, D-arabitol, D-mannitol and D-sorbitol, and also of the sugar acid D-glucurate was significantly reduced. The substrate spectrum determined closely matches that of the glycerol dehydrogenases of *G. suboxydans* IFO 3255 and 3257, which have also been shown to catalyse the oxidation of some polyols and D-glucurate (Matsushita et al., 2003; Shinjoh et al., 2002).

The glycerol dehydrogenase seems to be the main enzyme involved in the oxidation of the substrates mentioned above, as the corresponding oxidation activities were also significantly reduced in membrane fractions of *G. oxydans* DSM 7145 *sldA::Gm* grown on a different carbon source. The residual oxidation of polyols can be attributed to other dehydrogenases present in the membrane fraction of *G. oxydans* DSM 7145, which most likely oxidize the SldA substrates at a low rate.

Interestingly, expression of the polyol dehydrogenase seems not to be regulated, as PMS-DCIP reductase activities measured in membrane fractions of cells grown on D-glucose (non-SldA substrate) did not increase by addition of the substrate D-mannitol to the growth medium (Fig. 4). Similarly, De Ley & Dochy (1960) and DeLey & Stouthamer (1959) concluded from the examination of D-glucose metabolism in *Acetobacter* spp. that expression of the enzymes involved is not regulated. Genome-wide transcription analysis of *G. oxydans* ATCC 621H further confirmed that most membrane-bound dehydrogenases are expressed constitutively, irrespective of the utilized carbon source (our unpublished results). Therefore, we conclude that for industrial production of l-erythulose, *G. oxydans* DSM 7145 can also be cultured on glucose-containing medium to obtain biomass, which then can be used in resting cell preparations to oxidize *meso*-erythritol to l-erythulose (Fig. 2).

In contrast to the glycerol dehydrogenase, differences were observed in membrane-bound D-glucose oxidation. In the wild-type background, membrane-bound D-glucose oxidation activity was lower in cultures grown on D-glucose/D-mannitol than in cultures grown on D-glucose. Additionally, elevated dye-linked glucose dehydrogenase activities were detectable in *G. oxydans* DSM 7145 *sldA::Gm* (Fig. 4). At present, the reasons for these differences are not clearly understood, as no differences in expression of the *sldA* gene and the *mgdh* gene, encoding the membrane-bound D-glucose dehydrogenase, were detectable (our unpublished results). Gupta et al. (1997) attributed elevated gluconate- and 2-keto-D-gluconate-oxidizing activities after transposon-induced inactivation of the membrane-bound glucose dehydrogenase in *G. oxydans* ATCC 9937 to a decontrol or activation of the genes encoding the respective enzymes. Such polar effects on the expression of genes distal to the insertion site have been described before (Kleckner et al., 1977) but can be ruled out in this case because neither in *G. oxydans* ATCC 621H nor in *G. oxydans* DSM 7145 are the *sldBA* and the *mgdh* genes organized in operons.

The ongoing work with *G. oxydans* DSM 7145 showed that this strain seems to be genetically similar to *G. oxydans* ATCC 621H. Nonetheless, physiological differences between the two strains were observed. With *G. oxydans* ATCC 621H, only a minor decrease in extracellular l-erythulose concentration was observed after the supplied *meso*-erythulose was depleted. Moreover, in contrast to *G. oxydans* ATCC 621H, the sacB selection strategy (Gay et al., 1985) could be applied in *G. oxydans* DSM 7145 to identify
double-crossover mutants. Based on these observations, sequencing of other *G. oxydans* genomes seems interesting in order to elucidate whether physiological differences can be traced back to genomic differences or whether other regulatory mechanisms are involved.

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