The key role of the mycolic acid content in the functionality of the cell wall permeability barrier in *Corynebacterineae*

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Recently, it has been shown that trehalose and mycolic acids are essential for the growth of *Mycobacterium tuberculosis*, the causative agent of tuberculosis, and *Mycobacterium smegmatis*, and important but not indispensable to the survival of *Corynebacterium glutamicum*. Therefore, to investigate the function of mycolic acids in both the permeability of the cell wall to small nutrients and antibiotics, and the excretion of amino acids by *C. glutamicum*, a trehalose-deficient mutant of the L-lysine producer ATCC 21527, designated LPΔtreSΔotsAΔtreY, was constructed. By using different carbon sources in either the presence or the absence of external trehalose, a set of endogenously trehalose-free LPΔtreSΔotsAΔtreY cells that exhibited various mycolate contents was generated. The results showed that the structure of the arabinogalactan of these different cell types of LPΔtreSΔotsAΔtreY was not affected when the mycolic acid layer was either missing or impaired. Nevertheless, cells were more susceptible to antibiotics, and the permeability of their cell walls to glycerol was increased. Interestingly, a concomitant increase in the excretion of both L-lysine and L-glutamate was also observed, indicating that the mycolic acid content of the permeability barrier (and not only the peptidoglycan and/or the arabinogalactan) is implicated in the glutamate excretion process.

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INTRODUCTION

Mycolic acids, very-long-chain (C30–C90) α -alkyl, β -hydroxy fatty acids, are major and specific constituents of a distinct group of Gram-positive bacteria, classified in the suborder *Corynebacterineae*, which includes the causative agents of the human diseases tuberculosis and leprosy, *Mycobacterium tuberculosis* and *Mycobacterium leprae*, respectively, and comprises other genera such as *Corynebacterium*, *Rhodococcus* and *Nocardia*. This bacterial group is unusual in that, like Gram-negative bacteria, its members contain an outer permeability barrier that may explain both the limited permeability of their cell walls and the general insusceptibility of these bacteria to toxic agents (Brennan & Nikaido, 1995; Daffé & Draper, 1998). In mycobacteria and corynebacteria, this permeability barrier consists of a bilayer composed of mycolic acids and other lipids. In the innermost monolayer, the mycoloyl residues are covalently linked to the cell wall arabinogalactan. The outermost

monolayer is composed of various glycolipids, including trehalose monomycolate and trehalose dimycolate.

The composition and amounts of mycolic acids have been shown to affect the virulence, growth rate, colony morphology and permeability of *M. tuberculosis* (Dubnau *et al.*, 2000; Glickman *et al.*, 2000; Liu *et al.*, 1996; Yuan *et al.*, 1998). To further investigate the molecular bases of these biological processes, it is important to manipulate the mycolate content of mycobacteria, which includes the construction or isolation of mutants whose cell walls are free from mycolates. No such certified strain is currently available, due to the essentiality of enzymes involved in mycolate biosynthesis for the growth of mycobacteria (Portevin *et al.*, 2004; Vilcheze *et al.*, 2000). Interestingly, the analysis of a wild-type derivative of *Corynebacterium glutamicum* defective in trehalose biosynthesis has revealed that this strain is also unable to synthesize mycolic acids outside the cell (Tropis *et al.*, 2005). Thus, although important for the growth rate and morphotype of corynebacteria, mycolates are not essential for the physiology of these bacteria (Tzvetkov *et al.*, 2003; Wolf *et al.*, 2003;

Abbreviations: GMCM, glucose monocorynomycolate; TDCM, trehalose dicorynomycolate; TMCM, trehalose monocorynomycolate.

Gande *et al.*, 2004; Portevin *et al.*, 2004, 2005; Tropis *et al.*, 2005). In *C. glutamicum*, the absence of the outer permeability layer slows bacterial growth and changes the surface properties of the trehalose-free wild-type derivative CglΔtreSΔotsAΔtreY, but it is possible to partially or completely restore the wild-type mycolate synthesis by growing the mutant with either glucose or maltose as a carbon source, or by adding trehalose to the sucrose-based medium (Tropis *et al.*, 2005). It was thus interesting, using a ΔtreSΔotsAΔtreY corynebacterial strain, to address the question of how the mycolate content influences, besides the cell-surface properties, the permeability of the *C. glutamicum* cell wall.

METHODS

Bacterial strains and cultivation conditions. *C. glutamicum* cells were incubated at 30 °C under aerobic conditions in brain heart infusion (BHI) medium or CGXII medium (Keilhauer *et al.*, 1993). To meet the auxotrophy of *C. glutamicum* ATCC 21527 (Nakayama *et al.*, 1973), CGXII medium was supplemented with 0.2 g L-leucine l⁻¹ and 0.4 g L-homoserine l⁻¹. Four percent sucrose or glucose was routinely used as a carbon source. When indicated, 2 % trehalose was added. In general, cells grown in rich medium were washed twice with PBS and used to inoculate CGXII medium. When they reached the exponential or early stationary phase, an aliquot of cells was used to inoculate the main CGXII cultures to initial OD₆₀₀ 0.5.

Construction of plasmids for the deletion of trehalose biosynthesis genes. In order to delete genes encoding the trehalose biosynthesis enzymes in the genome of *C. glutamicum* ATCC 21527, the method of allelic replacement was used (Schäfer *et al.*, 1994), which is based on the selection of a chromosomal deletion by two recombination events. For this purpose, competent ATCC 21527 cells were transformed with pK19mobsacB derivatives carrying a chromosomal fragment of *C. glutamicum*, with a deletion in *otsA*, *treS* or *treY*, as described by Wolf *et al.* (2003). Plasmid integration in the genome was verified by selecting kanamycin-resistant and sucrose-sensitive colonies. To promote re-excision of the plasmid DNA, positive clones grown overnight in Luria-Bertani (LB) broth (10 g tryptone l⁻¹, 10 g NaCl l⁻¹, 5 g yeast extract l⁻¹) containing 2 % glucose were plated on LB agar supplemented with 10 % sucrose at different dilutions, usually between 10⁻³ and 10⁻⁵. Kanamycin-sensitive and sucrose-resistant colonies obtained from the subsequent selection were tested by PCR to verify that the gene of interest carried the desired deletion in the genome. To generate the multiple gene deletion strain LPΔtreSΔotsAΔtreY, the single deletion strain LPΔtreS or the double deletion strain LPΔtreSΔotsA was used instead of ATCC 21527 for allelic replacement.

Quantification of internal trehalose and excreted amino acids. Analysis of the internal trehalose content was performed by GC, as described by Wolf *et al.* (2003). HPLC analysis was used for the quantification of excreted amino acids, as described by Wolf *et al.* (2003).

Extraction of non-covalently bound lipids and analysis of trehalose-linked corynomycolic acids. Lipids were extracted from wet cells for 16 h with chloroform/methanol (1:2, v/v) at room temperature; the cells were re-extracted with chloroform/methanol (1:1, v/v) for 16 h and chloroform/methanol (2:1, v/v) for 16 h. The three organic phases were pooled and concentrated by means of rotary evaporation. The crude lipid extracts were partitioned between the aqueous and organic phases arising from chloroform/water mixture (1:1, v/v). The lower organic phases were

collected and evaporated to dryness to yield the crude lipid extracts from each strain. Subsequently, 10 µg of lipids from each sample was comparatively examined using TLC on silica gel-coated plates (Durasil-25, 0.25 mm thick; Macherey-Nagel) developed with chloroform/methanol/water (30:8:1 or 65:25:4, by vol.). Glycolipids were detected by spraying plates with 0.2 % anthrone in concentrated H₂SO₄, followed by heating. The mycolate content of extractable lipids was determined in three independent experiments as follows: lipid extracts (100 mg) of the various strains were dried under vacuum and saponified (Daffé *et al.*, 1983), and the saponified products were acidified with 20 % H₂SO₄. The resulting fatty acids were extracted with diethyl ether, washed with water, converted to methyl esters with diazomethane, dried under vacuum, and weighed. The fatty acid methyl esters were separated from contaminants on a silica gel column irrigated with different concentrations of diethyl ether in petroleum ether (0, 5, 10, 20 and 100 %, v/v). Fractions were analysed by TLC, developed with dichloromethane. Lipids were detected by spraying plates with rhodamine B, and fractions containing mycolates were pooled and weighed.

Arabinogalactan-bound mycolic acids. The arabinogalactan-bound mycolic acids present in the delipidated cells, i.e. the material after the chloroform/methanol extraction (described above), were saponified with 40 % KOH in 2-methoxyethanol (1:7, v/v) at 110 °C for 3 h (Daffé *et al.*, 1983), and the solution was neutralized using 20 % H₂SO₄. The released mycolic acids were extracted with diethyl ether and methylated with diazomethane. The resulting fatty acid methyl esters were examined using TLC on silica gel-coated plates, developed as above. When significant amounts of fatty acids other than mycolic acids were present in the saponification products, mycolates were isolated by chromatography on a silica gel column, as described above, and weighed.

Isolation, purification and analysis of the cell wall arabinogalactan. Cell walls were prepared as previously described (Daffé *et al.*, 1990, 1993). Briefly, wet cells were resuspended in PBS (50 mM, pH 7.2) at a concentration of 5 g per 20 ml, and broken in a cell disrupter (2.7 kbar). After three cell-disrupter cycles, intact cells were removed by centrifugation (3000 g), and the supernatant containing the cell walls was centrifuged (27 000 g, 1 h). The resulting cell wall pellet was treated with aqueous 2 % SDS at 95 °C for 1 h and sedimented again at 27 000 g. Cell walls were washed twice with 80 % (v/v) acetone in water, and subsequently in water, to remove SDS, and lyophilized. The glycosyl composition of purified cell walls was determined by hydrolysing an aliquot with 2 M trifluoroacetic acid (CF₃COOH) for 2 h at 110 °C, followed by trimethylsilylation (Sweeley *et al.*, 1963) and GC analysis of the resulting products.

Cell walls were O-methylated by a slight modification of the Hakomori procedure (York *et al.*, 1986). Cell walls (100 mg) were suspended in 3 ml DMSO (Pierce), 300 µl 5.2 M dimethylsulfinyl carbanion was added, and the mixture was stirred for 5 h. An equimolecular amount of methyl iodide (CH₃I) (120 µl; Aldrich) was slowly added and the mixture was stirred for 2 h. Addition of the base and CH₃I was repeated twice, and a large excess (2 ml) of CH₃I was added at the end of the third cycle. After 2 h of stirring, the reaction mixture was partially evaporated with nitrogen, an equal volume of water was added, the mixture was dialysed and the retentate was lyophilized. Aliquot fractions of per-O-methylated cell walls were hydrolysed with 2 M CF₃COOH for 2 h at 110 °C, reduced with sodium tetradeuteroborate, and acetylated. The resulting per-O-methylated alditol acetates were analysed by GC/MS, as previously described (Daffé *et al.*, 1990, 1993). GC/MS of the partially O-methylated, partially O-acetylated alditols was performed on a Hewlett-Packard 5890 gas chromatograph connected to a Hewlett Packard 5989 mass selective detector. The temperature of the injector was 260 °C and that of the transfer line was

300 °C. The column was a 12 m HP-1 (Hewlett–Packard). The oven was programmed to hold at 60 °C for 3 min, followed by a rise of 20 °C min⁻¹ to 100 °C, and a rise of 8 °C min⁻¹ to 290 °C, and an 8 min hold. The mass spectrometer was set to scan from 50 to 500 Da.

For NMR analysis, purified cell walls were treated with 2 M NaOH (16 h, 80 °C) to cleave the phosphodiester link between arabinogalactan and peptidoglycan (Daffé *et al.*, 1990, 1993). The supernatant, which contained the soluble arabinogalactan, was obtained by centrifugation (27 000 g, 30 min), neutralized with acetic acid, and dialysed to remove salts. A precipitate formed during the treatment was removed by centrifugation. The supernatant was treated with ethanol (80 % in water), kept at 4 °C overnight to precipitate the polysaccharide that was recovered by centrifugation, and lyophilized. For ¹H- and ¹³C-NMR analysis, arabinogalactans were solubilized in ²H₂O (20 mg per 0.5 ml) and analysed at 600 and 150.9 MHz, respectively, on a Bruker Avance 600 MHz NMR spectrometer equipped with a TCI cryoprobe. ¹H decoupled ¹³C-spectra were obtained with a DEPT 135 pulse sequence in a DQD acquisition mode.

Antibiotic susceptibility tests. For quantitative determination of susceptibility to erythromycin, Etest strips containing the antibiotic were used (AB Biodisk). For this purpose, strains were pre-cultured overnight in CGXII containing glucose or sucrose as carbon source, and 2 % trehalose when indicated. On the next day, 25 ml of the same medium was inoculated with an aliquot of the overnight culture (OD₆₀₀ 1) and cultivated again for 24 h at 30 °C. On the next morning, the cell suspension was diluted to OD₆₀₀ 1 and spread with a cotton swab on CGXII agar plates containing the same carbon source and trehalose when indicated. Then, the Etest strips were applied. The plates were incubated at 30 °C for 2–3 days, after which, the MIC was determined.

Determination of glycerol transport rates. Prior to uptake measurements, cells of ATCC 21527 or LPΔtreSΔotsAΔtreY were grown twice in minimal medium supplemented with sucrose to ensure that LPΔtreSΔotsAΔtreY did not contain any mycolates in the cell wall. After 16 h of growth, cells of the second culture were harvested, washed once in 50 mM potassium phosphate buffer containing 20 mM NaCl and 10 mM glucose, before their use for uptake measurements. [¹⁴C]Glycerol (3.7 MBq ml⁻¹, 5.3 GBq mmol⁻¹) was purchased from PerkinElmer. [¹⁴C]Glycerol 20–100 μM (37 kBq ml⁻¹) was added to 1 ml 50 mM potassium phosphate buffer (pH 7.5) and 20 mM NaCl containing cells at OD₆₀₀ 3. Aliquots of cells (0.1 ml) were taken after 6, 12, 18, 24, 30 and 60 min, and were separated from the assay buffer by filtration. Subsequently, incorporated radioactivity was determined by liquid scintillation counting. The transport rates were expressed as nmoles glycerol accumulated min⁻¹ (mg cell dry weight)⁻¹.

Assay for glycerol kinase activity. Strain ATCC 21527 and its LPΔtreSΔotsAΔtreY mutant were grown to exponential phase, harvested twice in 50 mM potassium phosphate (pH 7.5) and suspended in 2 ml 50 mM Tris/HCl (pH 7.5), 10 mM MgCl₂, and disrupted by glass beads. The cell debris was removed by centrifugation in a microcentrifuge (12 000 r.p.m.) at 4 °C. The enzyme assays were carried out in 100 mM sodium phosphate (pH 6) according to the method of Kwakman & Postma (1994). The protein content in the assay was varied between 2 and 5 mg ml⁻¹.

RESULTS

Construction and phenotypical analysis of a trehalose-deficient L-lysine producer

It has recently been shown that *C. glutamicum*, like *M. tuberculosis*, possesses three different pathways for the

biosynthesis of trehalose, namely the OtsAB, TreS and TreYZ pathways (De Smet *et al.*, 2000; Tzvetkov *et al.*, 2003; Wolf *et al.*, 2003). These pathways use activated glucose-6-phosphate and UDP-glucose, maltose and maltodextrins, respectively, as substrates for trehalose biosynthesis. In order to construct a trehalose-deficient mutant of the L-lysine producer *C. glutamicum* ATCC 21527, the genes *otsA*, *treY* and *treS* were deleted stepwise from the genome of ATCC 21527 by allelic replacement. The resulting strain was designated LPΔtreSΔotsAΔtreY. The analysis of the cytosolic trehalose content revealed that the parental strain ATCC 21527 had a concentration of 47 μmol (g cell dry mass)⁻¹, whereas in LPΔtreSΔotsAΔtreY, no trehalose was detectable at all, which agrees with previously published data on the CglΔtreSΔotsAΔtreY mutant strain derived from the type strain ATCC 13032 of *C. glutamicum* (Wolf *et al.*, 2003).

We have recently shown that the trehalose-deficient CglΔtreSΔotsAΔtreY is also unable to accumulate mycolates when grown on sucrose-based minimal medium, proving that endogenously synthesized trehalose is an essential precursor for the production of detectable mycolic acids in *C. glutamicum* (Tropis *et al.*, 2005). By the addition of glucose or maltose, or by supplementing the sucrose-based medium with trehalose, it is possible to completely or partially restore mycolate production, and manipulate to some extent the composition of the extractable mycolic acids (Tropis *et al.*, 2005). In order to modulate the composition of the cell wall of the trehalose-deficient L-lysine producer, LPΔtreSΔotsAΔtreY and its parental strain ATCC 21527 were grown in either sucrose- or glucose-based minimal medium in the presence or absence of trehalose. Lipid analysis of both strains revealed that with sucrose as a substrate no mycolic acids were detectable in the mutant strain, whereas in the presence of trehalose, mycolates were produced and found linked to trehalose in extractable lipids and attached to arabinogalactan (Fig. 1A, Table 1). Trehalose monocorynomycolates (TMCs; Puech *et al.*, 2000) represent the major mycolate-containing glycoconjugates in the extractable lipids of both the parental strain and the trehalose-free mutant grown in medium supplemented with the disaccharide. This observation is in agreement with the data obtained from the wild-type strain of *C. glutamicum* and its derivative CglΔtreSΔotsAΔtreY (Tropis *et al.*, 2005), in which trehalose dicorynomycolates (TDCs; Puech *et al.*, 2000) represent minor glycoconjugates under these cultivation conditions. The use of glucose as a carbon source leads to the synthesis of significant amounts of glucose monocorynomycolates (GMCs; Puech *et al.*, 2000) in the mutant, which represents, however, a minor constituent in both the parental and mutant strain grown in glucose-based media supplemented with trehalose (Fig. 1A, Table 1). Compared to the L-lysine producer ATCC 21527 grown on minimal medium supplemented with glucose, the LPΔtreSΔotsAΔtreY mutant produced only half the quantity of both cell wall-linked and trehalose-containing mycolates (Table 1). It was

Fig. 1. Mycolate composition and growth of the lysine producer ATCC 21527 and its trehalose-free derivative LP Δ treS Δ otsA Δ treY in media with different carbon sources. (A) TLC of lipids extracted from strains grown on various carbon sources. Lipids from ATCC 21527 grown on glucose and trehalose (lane 2), glucose (lane 4), and sucrose and trehalose (lane 6), and lipids from the mutant grown on glucose and trehalose (lane 1), sucrose (lane 3), and sucrose and trehalose (lane 5), are shown. Ten micrograms of lipid was loaded for each sample. PI, phosphatidyl inositol; PIM, phosphatidyl inositolmannoside. (B) Effect of sucrose (left panel) and glucose (right panel) on growth. ATCC 21527 in medium without trehalose (■) or with 2% trehalose (○), and LP Δ treS Δ otsA Δ treY in medium without trehalose (▲) or with 2% trehalose (*), are shown. The results shown are representative of at least two independent measurements with identical results.

thus possible to modulate the mycolate content of the LP mutant by growing cells in defined minimal medium with different carbon sources.

In order to investigate the influence of the mycolic acid composition on the physiology of ATCC 21527 and LP Δ treS Δ otsA Δ treY cells, we first determined the growth behaviour of the mutant (Fig. 1B). For this purpose, cells were grown in minimal medium containing either sucrose or glucose as a carbon source. In a second step, trehalose, which cannot be taken up by *C. glutamicum* (Tropis *et al.*, 2005), was added to the different cultures in a concentration of 2%, in order to complement the defect in mycolic acid synthesis. Compared to the parental strain ATCC 21527, the growth of LP Δ treS Δ otsA Δ treY on either sucrose- or

glucose-based minimal medium was severely impaired. Not only was the growth rate lowered, but also the final yield of cell mass was reduced. This effect was more pronounced when sucrose was used as a carbon source. If sucrose-based medium was supplemented with 2% trehalose, the growth defect was partly rectified, whereas growth was more or less identical to that of the parental strain ATCC 21527 when cells were grown in glucose-based medium supplemented with trehalose (Fig. 1B).

Influence of corynomycolate production on the excretion of amino acids

The ATCC 21527 and LP Δ treS Δ otsA Δ treY strains were able to excrete L-lysine into the medium. Under our growth

Table 1. Quantification of corynomycolates of ATCC 21527 and LPΔtreSΔotsAΔtreY

The corynomycolates that composed the lipids extracted from bacterial cells with organic solvents (extractable lipids) and those that remained attached to delipidated cells (wall-linked corynomycolates) were determined after saponification of these materials, followed by methylation of the resulting fatty acids, purification of the corynomycolates by chromatography on silica gel columns, and weighing, as described in Methods. The percentages were determined relative to the masses of extractable lipids and delipidated cells. The values are the means of at least three independent experiments. WT, ATCC 21527; ΔSAY, LPΔtreSΔotsAΔtreY.

Carbon source	Wall-linked corynomycolates		Corynomycolates in extractable lipids	
	WT	ΔSAY	WT	ΔSAY
4 % Sucrose	1.0 ± 0.1 %	0.0	34 ± 2 %	0.0
4 % Glucose	0.7 ± 0.1 %	0.4 ± 0.1 %	45 ± 2 %	20 ± 2 %
2 % Sucrose + 2 % trehalose	0.9 ± 0.1 %	0.8 ± 0.1 %	40 ± 2 %	43 ± 2 %
2 % Glucose + 2 % trehalose	0.5 ± 0.1 %	0.7 ± 0.1 %	42 ± 2 %	54 ± 2 %

conditions, a final yield of up to 43 ± 2 mM was reached after growth on sucrose. Since ATCC 21527 and LPΔtreSΔotsAΔtreY showed large differences in the growth rate, and consequently in the mass of cells that were able to excrete L-lysine, we compared the amount of L-lysine produced per gram of cell dry mass. This revealed that when glucose was used as carbon source, almost no difference was observed between the trehalose-free LPΔtreSΔotsAΔtreY and the parental strain, in terms of productivity of lysine (Fig. 2). In sharp contrast, when sucrose was used as a carbon source, LPΔtreSΔotsAΔtreY cells excreted threefold more lysine [9 mmol (g cell dry mass)⁻¹] than did the parental strain [3 mmol (g cell dry mass)⁻¹]. Adding 2 % trehalose to the medium resulted in decreased excretion of lysine by mutant cells, to the level of that of the parental strain (Fig. 2).

In standard growth conditions, *C. glutamicum* does not excrete L-glutamate into the medium; L-glutamate efflux can be induced by applying certain treatments, e.g. the

addition of penicillin, Tween 60 or ethambutol (Eggeling & Sahm, 2003; Kimura, 2005; Radmacher *et al.*, 2005). However, it is well known that the treatment of sensitive bacteria with ethambutol, by inhibiting arabinosyl transferases (Belanger *et al.*, 1996), also decreases their mycolate content (Takayama *et al.*, 1979). Since we showed that, depending on the carbon source, the trehalose deficiency of LPΔtreSΔotsAΔtreY led to a severe change in the mycolic acid content of the corynebacterial cell wall, we analysed the L-glutamate content of the medium of LPΔtreSΔotsAΔtreY and the parental strain ATCC 21527 grown on various carbon sources. Independent of the chosen carbon source, the ATCC 21527 strain did not excrete L-glutamate. In contrast, the loss of mycolate biosynthesis in the cell wall led to a significant accumulation of L-glutamate in the medium (Fig. 3). Interestingly, the production of mycolates in a glucose-based medium was not sufficient to abolish the excretion of glutamate, whereas it was possible to reduce drastically the L-glutamate excretion by adding 2 % trehalose to sucrose- or glucose-containing medium. It was

Fig. 2. Dependence of L-lysine excretion by the lysine producer ATCC 21527 and its trehalose-deficient derivative LPΔtreSΔotsAΔtreY upon the carbon source of the medium. (A), sucrose; (B), glucose. ATCC 21527 in medium without trehalose (■) or with 2 % trehalose (○), and LPΔtreSΔotsAΔtreY in medium without trehalose (▲) or with 2 % trehalose (*), are shown. The results presented are the means of at least three independent measurements.

Fig. 3. Dependence of L-glutamate excretion by the lysine producer ATCC 21527 and its trehalose-deficient derivative LPΔtreSΔotsA-ΔtreY upon the carbon source of the medium. (A) sucrose; (B) glucose. ATCC 21527 in medium without trehalose (■) or with 2% trehalose (○), and LPΔtreSΔotsA-ΔtreY in medium without trehalose (▲) or with 2% trehalose (*), are shown. The results presented are the means of at least three independent measurements.

thus concluded that the mycolate content, as opposed to the production of these lipids, is important to switch off the stimulus for L-glutamate excretion.

Structural features of the arabinogalactans of the L-lysine producer and mutant strains

Taken together, the results of the excretion of amino acids were consistent with the fact that the changes in mycolic acid composition provoked changes in excretion of both L-lysine and L-glutamate in strain LPΔtreSΔotsAΔtreY. Thus, it seemed reasonable to postulate that the content and composition of the mycolic acid layer directly influence the permeability of the cell wall. Nevertheless, since it has been reported that inhibition of arabinogalactan synthesis by treatment with ethambutol also results in an increased excretion of glutamate (Radmacher *et al.*, 2005), it remained possible that the increased excretion of amino acids by the mutant strain was a consequence of changes in the structure of the cell wall arabinogalactan, which may have followed the deficiency in mycolate. In addition, such a comparative analysis should have given important information on the sequence of events during the building of the mycoloylated cell wall. Accordingly, cell walls from both the parental and corynomycolate-deficient strains were isolated and purified (Daffé *et al.*, 1990, 1993). Per-O-methylation of the cell walls, followed by acid hydrolysis, reduction and O-acetylation, resulted in the production of partially O-methylated, partially O-acetylated alditols that were then analysed by GC/MS to determine the glycosyl linkage composition of the purified cell walls. No obvious qualitative or quantitative difference was seen between the compositions of the purified cell walls from the two origins; they were composed of t-Ara₆, 2-Ara₆, 5-Ara₆, 2,5-Ara₆, 3,5-Ara₆, t-Gal₆, 5-Gal₆, 6-Gal₆, 5,6-Gal₆ and t-Rha₆. This composition was identical to that found in the type strain of *C. glutamicum* (Alderwick *et al.*, 2005), and similar to

those of other corynebacteria (Puech *et al.*, 2001) and related genera (Daffé *et al.*, 1993).

To decipher the structural features of the arabinogalactans from the parental and mutant LP strains, the polysaccharides were released from the cell walls by means of alkaline hydrolysis (Daffé *et al.*, 1990, 1993) and were comparatively analysed. As expected from the glycosyl composition, the ¹H-NMR spectra of the arabinogalactans from the two strains were superimposable (data not shown) and similar to those of mycobacteria and rhodococci, but different from those of nocardiae (Daffé *et al.*, 1990, 1993). Anomeric proton signals of the arabinogalactans were seen at δ 5.0–5.3, consistent with the presence of α- and/or β-furanosyl residues and/or α-pyranosyl units (Daffé *et al.*, 1993). Resonances of the other sugar protons were grouped at δ 4.3–3.6. Since ¹³C-NMR has proved to be an excellent investigative tool, both as an aid to structural determination and in fingerprinting for taxonomic purposes (Daffé *et al.*, 1990, 1993), the arabinogalactans from the two isogenic strains were analysed comparatively by this technique (Fig. 4).

The ¹³C-NMR spectra of the arabinogalactans from the two LP strains were superimposable (Fig. 4) and had many similarities with those from other *Corynebacterineae* (Daffé *et al.*, 1993). Based on the previous assignments deduced from the spectra of *M. tuberculosis* (Daffé *et al.*, 1990) and other *Corynebacterineae* (Daffé *et al.*, 1993), resonances attributable to the C-1s of t-β-Ara_f and 2-linked-α-Ara_f of the non-reducing end of the arabinogalactan molecules were seen at 101–102 p.p.m. and 106–107 p.p.m., respectively. The resonances of the C-2s of 2-linked-α-Ara_f were identified at δ 87–89, while that of the C-5 of t-β-Ara_f was seen at 64 p.p.m. (Daffé *et al.*, 1990, 1993). Importantly, the signals of C-1s of 2-linked-α-Ara_f of *C. glutamicum* (δ 106–107) were more complex than those of all arabinogalactans examined

Fig. 4. ^{13}C -NMR (DEPT mode) spectra of the cell-wall arabinogalactans from the lysine producer ATCC 21527 (A) and $\text{LP}\Delta\text{treS}\Delta\text{otsA-}\Delta\text{treY}$ mutant (B) strains. The polysaccharides were solubilized in $^2\text{H}_2\text{O}$ (20 mg per 0.5 ml) and analysed at 150.9 MHz on a Bruker Avance 600 MHz NMR spectrometer equipped with a TCI cryoprobe.

so far; an observation that is consistent with the complexity of the corresponding C-2s (δ 87–90). Furthermore, two groups of resonances of C-2s of 2-linked- α -Ara_f were observed. The major asymmetrical pair signals were seen at 87.8 and 88.1 p.p.m., whereas the minor series were observed at 89.0 and 89.3 p.p.m. This correlates with the occurrence of an asymmetrical pair of signals attributable to C-1s of t- β -Ara_f (δ 101–102). This suggests the occurrence of specific combinations of t- β -Ara_f and 2-linked- α -Ara_f residues, different from those of the non-reducing tri- and penta-arabinosyls found in the arabinogalactans of other *Corynebacterineae* (Daffé *et al.*, 1990, 1993). Further detailed structural studies of the polysaccharides of corynebacterial origin are clearly needed. The furanoid nature of the remaining Ara and Gal residues was also obvious from the chemical shift values of the C-1 resonances (δ 108–110). The resonances of primary alcohol carbons of unsubstituted C-5s of α -Ara_f and C-6s of β -Gal_f were observed at δ 61–62, whereas those of 5- and 3,5-Ara_f and 6- and 5,6-Gal_f were seen at δ 67.8. These assignments were based on the glycosyl linkage composition and ^{13}C -NMR spectroscopy in the DEPT mode (Fig. 4), in agreement with previously published data (Daffé *et al.*, 1990, 1993). The signal at 103.3 p.p.m., absent from the NMR spectra of the various arabinogalactans analysed so far, was attributed to the resonance of t-Rha_p, a glycosyl residue that has so far been found to be specific to the arabinogalactan of *C. glutamicum*. It was thus concluded that the gross structure of the arabinogalactan of the LP strain is not affected by mutations that result in a total lack of production of trehalose and mycolates. It follows that the enhanced excretion of amino acids by the LP mutant strain was attributable to the absence of the mycolate layer, the restoration of which fully abolished the observed excess excretion.

Influence of mycolate content on the susceptibility of *C. glutamicum* to antibiotics

The integrity of the mycolic acid layer has been shown to be important for the resistance of *M. tuberculosis* to antibiotics (Brennan & Nikaido, 1995; Daffé & Draper, 1998). Thus, we investigated whether the absence of mycolic acids or variations in the mycolic acid content of the *C. glutamicum* cell wall resulted in a higher susceptibility to antibiotics. For this purpose, cells grown on liquid minimal medium (with either sucrose or glucose as a carbon source) were spread on agar plates containing the same growth medium, and the MIC of the hydrophobic compound erythromycin was determined (Fig. 5). Analysis of the susceptibility of the parental lysine producer and the mutant strains to the antibiotic clearly showed that the mycolate deficiency of $\text{LP}\Delta\text{treS}\Delta\text{otsA}\Delta\text{treY}$ resulted in a higher permeability of the cell wall, independent of the carbon source. Similar results were also obtained with the hydrophilic ethambutol (data not shown), proving that the mycolates act as a permeability barrier, at least for antibiotics.

Glycerol transport rates in relation to production of mycolic acids

Glycerol is a membrane-permeable substance that can enter the cells of *Corynebacterineae* by diffusion across their thick cell walls that contain the mycolic acid layer as a second membrane-like structure, and their plasma membranes. It has been shown that the diffusion of glycerol can be used as a marker of the permeability of the mycobacterial cell wall (Bardou *et al.*, 1998; Jackson *et al.*, 1999). Thus, in order to characterize the function of the mycolic acid layer in *C. glutamicum*, the velocity of glycerol transport was determined in the ATCC 21527 and $\text{LP}\Delta\text{treS}\Delta\text{otsA}\Delta\text{treY}$ strains grown on sucrose-containing minimal medium. Under

Fig. 5. MIC of erythromycin for the lysine producer ATCC 21527 and LPΔtreSΔotsAΔtreY, depending on the carbon source in the medium. Black bars, ATCC 21527 in medium without trehalose; white bars, ATCC 21527 in medium with 2% trehalose; grey bars, LPΔtreSΔotsAΔtreY in medium without trehalose; hatched grey bars, LPΔtreSΔotsAΔtreY in medium with 2% trehalose. The results presented are the means of at least three independent measurements.

these conditions, the LPΔtreSΔotsAΔtreY strain was, in contrast to the wild-type cells, completely free of cell wall-located mycolic acids (see above), and thus free of the outer permeability membrane-like structure in the cell wall (Puech *et al.*, 2000; Portevin *et al.*, 2004; Tropis *et al.*, 2005).

At a concentration range of 30–100 μM, glycerol transport by the corynebacterial cells by diffusion depended linearly on the glycerol concentration. In the LPΔtreSΔotsAΔtreY strain, the transport rate was approximately three times higher than that in its parental ATCC 21527 strain (Fig. 6), indicating that the loss of mycolic acids indeed facilitates the

Fig. 6. Transport of [¹⁴C]glycerol by diffusion in ATCC 21527 (■) and LPΔtreSΔotsAΔtreY (○) cells cultivated in the minimal medium CGXII with 4% sucrose. The results presented are the means of at least three independent measurements.

diffusion of glycerol into the cell, in agreement with previous data (Puech *et al.*, 2000). In order to exclude the possibility that the mutant strain has a higher glycerol kinase activity that results in a faster conversion of glycerol to glycerol phosphate, and thus in a higher concentration gradient of non-phosphorylated glycerol across the membrane, we determined the glycerol kinase activity of cells used for the transport assay. Both strains exhibited comparable glycerol kinase activities of $0.25 \pm 0.01 \mu\text{mol min}^{-1} (\text{g cell dry mass})^{-1}$, which were 100-fold higher than the glycerol transport rates. Thus, it was concluded that the observed differences in the rate of transport of glycerol by the strains were attributable to their different mycolate contents.

DISCUSSION

We have recently established the importance of trehalose biosynthesis for the production of detectable amounts of mycolic acids in *C. glutamicum*, by showing that a derivative of the type strain ATCC 13032, which is not able to synthesize trehalose (Wolf *et al.*, 2003), is devoid of cell wall mycolic acids when sucrose is used as carbon source (Tropis *et al.*, 2005). Interestingly, this defect is partly rectified when sucrose is exchanged by glucose or a carbon source possessing a terminal α-D-glucopyranosyl unit (Tropis *et al.*, 2005). Under these conditions, the mycolates have been shown to be synthesized and to esterify both the sugar used as carbon source, in the form of monomycolate, and the cell wall-linked arabinogalactan (Tropis *et al.*, 2005). Using this knowledge, we manipulated the cell wall composition of LPΔtreSΔotsAΔtreY, a trehalose-deficient derivative of the L-lysine-producing *C. glutamicum* strain ATCC 21527, by adding different carbon sources for growth. The mutant cells varied in their cell wall composition, from being completely devoid of any detectable mycolates, to having a mycolate composition quantitatively similar to that of the parental strain. Accordingly, it was possible to investigate the influence of the presence and amount of mycolates in *C. glutamicum* on the permeability of the cell wall to both uptake and excretion of different substances.

To ensure that mycolates, as opposed to the whole cell wall core, which includes arabinogalactan and peptidoglycan, are the sole parameter concerned in these studies, we showed that the absence of mycolates had no influence on the production and structural features of the cell wall arabinogalactan. In mycobacteria, in which the cell wall polysaccharide represents the major mycolate-containing compound (Brennan & Nikaido, 1995; Daffé & Draper, 1998), mycolic acids are found esterifying the four primary alcohol groups of half (two-thirds in *M. tuberculosis*) of the non-reducing terminal penta-arabinosyl motifs of the polysaccharide (McNeil *et al.*, 1991). There are at least two possible explanations for these structural characteristics: either the whole arabinogalactan is synthesized and transferred to the cell wall compartment prior to the selective and specific mycoloylation of some motifs, or it is the mycoloylated penta-arabinosyl motifs that are added to

the arabinogalactan during its synthesis. Based on our results and on the similarities in the cell wall composition and architecture between mycobacteria and corynebacteria, the first hypothesis seems more likely. This hypothesis is further strengthened by the fact that we have recently shown that the biosynthesis of TCM, the likely precursor molecule for the formation of cell wall-linked mycolates, takes place within the cell wall and not in the cytoplasm (Tropis *et al.*, 2005). Therefore, by modulating the amount and composition of the mycolates in the trehalose-free mutant by varying the carbon source, the effects of the membrane-like mycolic acid layer on permeability could be evaluated.

The effects exerted by the composition of the mycolate layer on the excretion of amino acids could be important for biotechnological purposes, if they can be used as a tool to increase the productivity of *C. glutamicum* strains used for amino acid synthesis. Indeed, the investigation of the L-lysine production of strain LP Δ treS Δ otsA Δ treY revealed that, after fermentation in sucrose medium, a threefold higher productivity [g L-lysine (g cell dry mass)⁻¹] was detected in comparison to that in strain ATCC 21527. This indicates that the mycolate layer may in fact contribute to the efficient excretion of a charged amino acid like L-lysine. The effect can be explained by the following assumption: due to the hydrophobic character of the outer membrane-like mycolic acid layer in the parental strain ATCC 21527, L-lysine has to pass through the cell wall via the cation-selective porin PorA, which has recently been described in *C. glutamicum* (Lichtinger *et al.*, 2001; Costa-Riu *et al.*, 2003). If this permeability barrier is missing in the trehalose-free mutant, L-lysine may be excreted faster. As the L-lysine excretion was decreased to the level of the parental strain in cells grown on glucose, this implies that half of the mycolate content is sufficient to restore the permeability barrier for this amino acid. In addition, these results show that mycolate deficiency may in fact serve as a tool to increase product yields, although the observed severe growth impairment would have to be overcome.

The LP Δ treS Δ otsA Δ treY strain, but not the parent strain ATCC 21527, was able to excrete L-glutamate spontaneously into the medium. This effect in LP Δ treS Δ otsA Δ treY was almost completely reversed if trehalose was added to the medium. Although the general mechanism of L-glutamate efflux is rather poorly understood, a common feature of several of these manipulations is to affect the integrity of the cell wall of *C. glutamicum* (Eggeling & Sahm, 2003; Daffé, 2005; Radmacher *et al.*, 2005). While it could not be determined in previous experiments whether the trigger for L-glutamate excretion originated from a change in the plasma membrane and/or the outer membrane-like mycolic acid layer, our data demonstrate that the lack of mycolate is sufficient to induce glutamate excretion. For this process, however, the amount of mycolates seems to be more critical than for the excretion of lysine. The growth of the LP mutant on glucose, which led to the production of half the quantity

of the mycolates produced by the parental strain, and abolished L-lysine excretion, still resulted in the excretion of glutamate. Nevertheless, further work is required to reveal whether a change in the structure of the cell wall is both sufficient and a direct reason for the induction of glutamate excretion, or whether the disordering of the cell wall is somehow detected by the cell, which in turn leads to a particular cellular response, ultimately resulting in glutamate excretion. In this context, it should be noted that a decrease in the activity and expression level of 2-oxoglutarate dehydrogenase, which is the key enzyme for the carbon flux within the TCA cycle, has been observed after the induction of glutamate excretion (Kawahara *et al.*, 1997; Kataoka *et al.*, 2006). The resulting shift in the ratio between the carbon flux via 2-oxoglutarate dehydrogenase and that via glutamate dehydrogenase may also be a factor which contributes to glutamate excretion.

In order to define the impact of the mycolic acid layer on the permeability of the cell wall in the *Corynebacterineae* in more detail, we studied changes in uptake activities in the *C. glutamicum* strain LP Δ treS Δ otA Δ treY. These investigations are only possible to a limited extent in mycobacteria, due to the impossibility of generating viable mycolate-free mycobacterial strains. We used glycerol, a membrane-permeable substance that is known to diffuse across the thick cell wall of *Corynebacterineae*, as a marker for the permeability of the cell wall, as established previously for both mycobacteria (Bardou *et al.*, 1998; Jackson *et al.*, 1999) and corynebacteria (Puech *et al.*, 2000). We determined the velocity of glycerol diffusion by the ATCC 21527 and LP Δ treS Δ otsA Δ treY strains of *C. glutamicum* grown on sucrose-containing minimal medium, conditions in which the LP Δ treS Δ otsA Δ treY strain was completely free of cell wall-linked and trehalose-containing mycolic acids. We showed that diffusion of glycerol in LP Δ treS Δ otsA Δ treY was approximately three times faster than that in its parental strain ATCC 21527, indicating that the loss of mycolic acids indeed facilitates the transport of glycerol into the cells. This was not attributable to a higher glycerol kinase activity in the mutant, which would have resulted in a faster conversion of glycerol to glycerol phosphate, and thus to a higher driving force for inward diffusion of non-phosphorylated glycerol across the membrane, since the parental and mutant strains exhibited comparable glycerol kinase activities that were 100-fold higher than the glycerol transport rates.

In mycobacteria, the mycolate layer is of unusual thickness and low fluidity. These properties are thought to result in high resistance to most of the common antibiotics (Brennan & Nikaido, 1995). Although the mycolic acid layer in *C. glutamicum* is thinner than that in mycobacteria, due to a shorter chain length of the mycolic acids, susceptibility to antibiotics can also be used as a measure of permeability in *C. glutamicum*. By using erythromycin, we intended to ensure that the permeability of the cell wall, and not that of the plasma membrane, determined the inhibitory effect. This macrolide antibiotic was selected as an example of a

large hydrophobic molecule that has to pass through the cell wall of the parent strain by diffusion across the hydrophobic lipid bilayer, and not through the hydrophilic channels of porins, as recently shown for penicillin G (Costa-Riu *et al.*, 2003). Analysis of the susceptibility of the parental and mutant lysine-producer strains to erythromycin showed that the mycolate deficiency of LP Δ treS Δ otsA Δ treY resulted in a higher permeability of the cell wall, proving that the mycolates act as a permeability barrier for this antibiotic.

In conclusion, we showed that modulation of the content of the mycolic acid layer of *C. glutamicum* can be used to analyse the function of the outer membrane-like structure. Cells with a reduction in mycolate content showed a higher permeability for substances taken up into the cells or excreted into the culture medium. Based on the observation that the structure of the arabinogalactan layer was not affected when the mycolic layer was either missing or impaired, the detected permeability changes can be solely attributed to the mycolic acid layer of the cell wall.

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REFERENCES

- Alderwick, L. J., Radmacher, E., Seidel, M., Gande, R., Hitchen, P. G., Morris, H. R., Dell, A., Sahm, H., Eggeling, L. & Besra, G. S. (2005). Deletion of Cg-emb in corynebacterianae leads to a novel truncated cell wall arabinogalactan, whereas inactivation of Cg-ubiA results in an arabinan-deficient mutant with a cell wall galactan core. *J Biol Chem* **280**, 32362–32371.
- Bardou, F., Raynaud, C., Ramos, C., Lanelle, M.-A. & Lanelle, G. (1998). Mechanism of isoniazid uptake in *Mycobacterium tuberculosis*. *Microbiology* **144**, 2539–2544.
- Belanger, A. E., Besra, G. S., Ford, M. E., Mikusova, K., Belisle, J. T., Brennan, P. J. & Inamine, J. M. (1996). The *embAB* genes of *Mycobacterium avium* encode an arabinosyl transferase involved in cell wall arabinan biosynthesis that is the target for the antimycobacterial drug ethambutol. *Proc Natl Acad Sci U S A* **93**, 11919–11924.
- Brennan, P. J. & Nikaido, H. (1995). The envelope of mycobacteria. *Annu Rev Biochem* **64**, 29–63.
- Costa-Riu, N., Burkovski, A., Krmer, R. & Benz, R. (2003). PorA represents the major cell wall channel of the Gram-positive bacterium *Corynebacterium glutamicum*. *J Bacteriol* **185**, 4779–4786.
- Daff, M. (2005). The cell envelope of corynebacteria. In *Handbook of Corynebacterium glutamicum*, pp. 121–148. Edited by L. Eggeling & M. Bott. Boca Raton, FL: CRC Press.
- Daff, M. & Draper, P. (1998). The envelope layers of mycobacteria with reference to their pathogenicity. *Adv Microb Physiol* **39**, 131–203.
- Daff, M., Lanelle, M. A., Asselineau, C., Levy-Frebault, V. & David, H. (1983). Intrt taxonomique des acides gras des Mycobactries: proposition d'une mthode d'analyse. *Ann Microbiol* **134**, 241–256 (in French).
- Daff, M., Brennan, P. J. & McNeil, M. (1990). Predominant structural features of the cell wall arabinogalactan of *Mycobacterium tuberculosis* as revealed through characterization of oligoglycosyl alditol fragments by gas chromatography/mass spectrometry and by ¹H and ¹³C NMR analyses. *J Biol Chem* **265**, 6734–6743.
- Daff, M., McNeil, M. & Brennan, P. J. (1993). Major structural features of the cell wall arabinogalactans of *Mycobacterium*, *Rhodococcus*, and *Nocardia* spp. *Carbohydr Res* **249**, 383–398.
- De Smet, K. A., Weston, A., Brown, I. N., Young, D. B. & Robertson, B. D. (2000). Three pathways for trehalose biosynthesis in mycobacteria. *Microbiology* **146**, 199–208.
- Draper, P. (1998). The outer parts of the mycobacterial envelope as permeability barriers. *Frontiers Biosci* **3**, D1253–D1261.
- Dubnau, E., Chan, J., Raynaud, C., Mohan, V. P., Lanelle, M. A., Yu, K., Quemard, A., Smith, I. & Daff, M. (2000). Oxygenated mycolic acids are necessary for virulence of *Mycobacterium tuberculosis* in mice. *Mol Microbiol* **36**, 630–637.
- Eggeling, L. & Sahm, H. (2003). The cell wall barrier of *Corynebacterium glutamicum* and amino acid efflux. *J Biosci Bioengin* **92**, 201–213.
- Gande, R., Gibson, K. J., Brown, A. K., Krumbach, K., Dover, L. G., Sahm, H., Shioyama, S., Oikawa, T., Besra, G. S. & Eggeling, L. (2004). Acyl-CoA carboxylases (accD2 and accD3), together with a unique polyketide synthase (Cg-pks), are key to mycolic acid biosynthesis in *Corynebacterianae* such as *Corynebacterium glutamicum* and *Mycobacterium tuberculosis*. *J Biol Chem* **279**, 44847–44857.
- Glickman, M. S., Cox, J. S. & Jacobs, W. R., Jr (2000). A novel mycolic acid cyclopropane synthetase is required for cording, persistence, and virulence of *Mycobacterium tuberculosis*. *Mol Cell* **5**, 717–727.
- Jackson, M., Raynaud, C., Lanelle, M. A., Guilhot, C., Laurent-Winter, C., Ensergueix, D., Gicquel, B. & Daff, M. (1999). Inactivation of the antigen 85C gene profoundly affects the mycolate content and alters the permeability of the *Mycobacterium tuberculosis* cell envelope. *Mol Microbiol* **31**, 1573–1587.
- Kataoka, M., Hashimoto, K.-I., Yoshida, M., Nakamatsu, T., Horinouchi, S. & Kawasaki, H. (2006). Gene repression of *Corynebacterium glutamicum* in response to the conditions inducing glutamate overproduction. *Lett Appl Microbiol* **42**, 471–476.
- Kawahara, Y., Tanaka, T., Ikeda, S., Shimizu, E., Nakamatsu, T. & Nakamori, S. (1997). Relationship between the glutamate production and the activity of 2-oxoglutarate dehydrogenase in *Brevibacterium lactofermentum*. *Biosci Biotechnol Biochem* **61**, 1109–1112.
- Keilhauer, C., Eggeling, L. & Sahm, H. (1993). Isoleucine synthesis in *Corynebacterium glutamicum*: molecular analysis of the *ilvB-ilvN-ilvC* operon. *J Bacteriol* **175**, 5595–5603.
- Kimura, E. (2005). L-Glutamate production. In *Handbook of Corynebacterium glutamicum*, pp. 439–463. Edited by E. Eggeling & M. Bott. Boca Raton, FL: CRC Press.
- Kwakman, J. H. & Postma, P. W. (1994). Glucose kinase has a regulatory role in carbon catabolite repression in *Streptomyces coelicolor*. *J Bacteriol* **76**, 2694–2698.
- Lichtinger, T., Riess, F. G., Burkovski, A., Engelbrecht, F., Hesse, D., Kratzin, H. D., Krmer, R. & Benz, R. (2001). The low-molecular-mass subunit of the cell wall channel of the Gram-positive *Corynebacterium glutamicum*. *Eur J Biochem* **268**, 462–469.
- Liu, J., Barry, C. E., III, Besra, G. S. & Nikaido, H. (1996). Mycolic acid structure determines the fluidity of the mycobacterial cell wall. *J Biol Chem* **271**, 29545–29551.
- McNeil, M., Daff, M. & Brennan, P. J. (1991). Location of the mycolyl ester substituents in the cell walls of mycobacteria. *J Biol Chem* **266**, 13217–13223.

- Nakayama, K., Sagamihara, K. & Araki, K. (1973). Process for producing L-lysine. US patent no. 3, 708,395.
- Portevin, D., De Sousa-D'Auria, C., Houssin, C., Grimaldi, C., Chami, M., Daffé, M. & Guilhot, C. (2004). A polyketide synthase catalyzes the last condensation step of mycolic acid biosynthesis in mycobacteria and related organisms. *Proc Natl Acad Sci U S A* **101**, 314–319.
- Portevin, D., de Sousa-D'Auria, C., Montrozier, H., Houssin, C., Stella, A., Lanéelle, M. A., Bardou, F., Guilhot, C. & Daffé, M. (2005). The acyl-AMP ligase FadD32 and AccD4-containing acyl-CoA carboxylase are required for the synthesis of mycolic acids and essential for mycobacterial growth: identification of the carboxylation product and determination of the acyl-CoA carboxylase components. *J Biol Chem* **280**, 8862–8874.
- Puech, V., Bayan, N., Salim, K., Leblon, G. & Daffé, M. (2000). Characterization of the *in vivo* acceptors of the mycolyl residues transferred by the corynebacterial PS1 and the related mycobacterial antigens 85. *Mol Microbiol* **35**, 1026–1041.
- Puech, V., Chami, M., Lemassu, A., Lanéelle, M. A., Schiffler, B., Gounon, P., Bayan, N., Benz, R. & Daffé, M. (2001). Structure of the cell envelope of corynebacteria: importance of the non-covalently bound lipids in the formation of the cell wall permeability barrier and fracture plane. *Microbiology* **147**, 1365–1382.
- Radmacher, E., Stansen, K., Besra, G. E., Alderwick, L. J., Maughan, W. N., Hollweg, G., Sahm, H., Wendisch, V. F. & Eggeling, L. (2005). Ethambutol, a cell wall inhibitor of *Mycobacterium tuberculosis*, elicits L-glutamate efflux of *Corynebacterium glutamicum*. *Microbiology* **151**, 1359–1368.
- Schäfer, A., Tauch, A., Jäger, W., Kalinowski, J., Thierbach, G. & Pühler, A. (1994). Small mobilizable multi-purpose cloning vectors derived from the *Escherichia coli* plasmids pK18 and pK19: selection of defined deletions in the chromosome of *Corynebacterium glutamicum*. *Gene* **145**, 69–73.
- Sweeley, C. C., Bentley, R., Makita, M. & Wells, W. W. (1963). Gas-liquid chromatography of trimethylsilyl derivatives of sugars and related substances. *J Am Chem Soc* **85**, 2497–2507.
- Takayama, K., Armstrong, E. L., Kunugi, K. A. & Kilburn, J. O. (1979). Inhibition by ethambutol of mycolic acid transfer into the cell wall of *Mycobacterium smegmatis*. *Agents Chemother* **16**, 240–242.
- Tropis, M., Meniche, X., Wolf, A., Gebhardt, H., Strelkov, S., Chami, M., Schomburg, D., Krämer, R., Morbach, S. & Daffé, M. (2005). The crucial role of trehalose and structurally related oligosaccharides in the biosynthesis and transfer of mycolic acids in *Corynebacterineae*. *J Biol Chem* **280**, 26573–26585.
- Tzvetkov, M., Klopprogge, C., Zelder, O. & Liebl, W. (2003). Genetic dissection of trehalose biosynthesis in *Corynebacterium glutamicum*: inactivation of trehalose production leads to impaired growth and an altered cell wall lipid composition. *Microbiology* **149**, 1659–1673.
- Vilcheze, C., Morbidoni, H. R., Weisbrod, T. R., Iwamoto, H., Kuo, M., Sacchettini, J. C. & Jacobs, W. R., Jr (2000). Inactivation of the *inhA*-encoded fatty acid synthase II (FASII) enoyl-acyl carrier protein reductase induces accumulation of the FASI end products and cell lysis of *Mycobacterium smegmatis*. *J Bacteriol* **182**, 4059–4067.
- Wolf, A., Krämer, R. & Morbach, S. (2003). Three pathways for trehalose metabolism in *Corynebacterium glutamicum* ATCC13032 and their significance in response to osmotic stress. *Mol Microbiol* **49**, 1119–1134.
- York, W. S., Darwill, A. G., McNeil, M., Stevenson, J. T. & Albersheim, P. (1986). Isolation and characterization of plant cell walls and cell wall components. *Methods Enzymol* **118**, 3–40.
- Yuan, Y., Zhu, Y., Crane, D. D. & Barry, C. E., III (1998). The effect of oxygenated mycolic acid composition on cell wall function and macrophage growth in *Mycobacterium tuberculosis*. *Mol Microbiol* **29**, 1449–1458.

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