Peptidoglycan N-acetylglucosamine deacetylation decreases autolysis in *Lactococcus lactis*

Mickael Meyrand, Aida Boughammoura,† Pascal Courtin, Christine Mézange, Alain Guillot and Marie-Pierre Chapot-Chartier

INRA, Unité de Biochimie Bactérienne, UR477, 78350 Jouy-en-Josas, France

The gene *xynD* (renamed *pgdA*) of *Lactococcus lactis* IL1403 was shown to encode a peptidoglycan N-acetylglucosamine deacetylase. Inactivation of *pgdA* in *L. lactis* led to fully acetylated peptidoglycan, whereas cloning of *pgdA* on a multicopy plasmid vector resulted in an increased degree of peptidoglycan deacetylation, as shown by analysis of peptidoglycan constituent muropeptides. An increased amount of *N*-unsubstituted glucosamine residues in peptidoglycan resulted in a reduction of the rate of autolysis of *L. lactis* cells. The activity of the *L. lactis* major autolysin AcmA was tested on *L. lactis* cells or peptidoglycan with different degrees of de-*N*-acetylation. Deacetylated peptidoglycan exhibited decreased susceptibility to AcmA hydrolysis. This reduced susceptibility to AcmA did not result from reduced AcmA binding to peptidoglycan with an increasing degree of de-*N*-acetylation. In conclusion, enzymic *N*-acetylglucosamine deacetylation protects peptidoglycan from hydrolysis by the major autolysin AcmA in *L. lactis* cells, and this leads to decreased cellular autolysis.

**INTRODUCTION**

Peptidoglycan is the major cell wall component of Gram-positive bacteria, and ensures the stability and rigidity of the cell wall (Delcour et al., 1999). During growth, bacteria synthesize enzymes capable of hydrolysing their own peptidoglycan. These peptidoglycan hydrolases (PGHs) are required for cell separation after division and are involved in several other cellular processes that require peptidoglycan remodelling, such as peptidoglycan turnover and cell wall expansion (Smith et al., 2000). Under conditions which result in cessation of peptidoglycan synthesis, such as stationary phase or exposure to antibiotics, PGH activity may cause cellular autolysis, leading to the release of intracellular components.

Since PGHs are potentially lethal enzymes and are present in the cells during bacterial growth, it is usually assumed that their activities are regulated at the post-translational level (Shockman & Holtje, 1994; Smith et al., 2000). Different mechanisms of PGH control have been proposed, including proteolytic maturation (Buist et al., 1998; Poquet et al., 2000; Shockman, 1992), interaction with a specific modifier protein (Lazarevic et al., 1992), regulation by the membrane proton motive force (Calamita et al., 2001; Kemper et al., 1993), and interaction with secondary cell wall polymers such as teichoic acids (Palumbo et al., 2006; Wecke et al., 1997). Finally, structural modifications of the peptidoglycan substrate by *O*-acetylation (Pfeffer et al., 2006) or de-*N*-acetylation (Atrihi et al., 1999) may control the action of PGHs.

The peptidoglycan hydrolase complement of *Lactococcus lactis*, the model Gram-positive lactic acid bacterium, comprises five PGHs, including three *N*-acetylglucosaminidases (Buist et al., 1995; Huard et al., 2004, 2003) and one *γ*-D-glutaminyl-L-lysyl-endopeptidase (Redko et al., 2007). The autolysin AcmA is involved in cell separation and is the major effector of cellular autolysis in stationary phase (Buist et al., 1995). The AcmA protein has two domains: an N-terminal catalytic domain endowed with *N*-acetylglucosaminidase specificity (Steen et al., 2005a), and a C-terminal domain with three LysM modules involved in cell wall binding and which recognize peptidoglycan (Steen et al., 2003).

Our objective was to examine the impact of structural modifications of peptidoglycan on *L. lactis* cellular autolysis and on the activity of AcmA autolysin in the cells. Peptidoglycan consists of glycan strands made of alternating β-1,4-linked *N*-acetylglycosamine (GlcNAc) and *N*-acetylmuramic acid (MurNAc) which are cross-linked by short peptide chains. Its structure can be analysed by identification of the constituent muropeptides obtained after muramidase digestion. Recently, we performed a detailed analysis of *L. lactis* peptidoglycan structure and observed several deacetylated muropeptides (Courtin et al.,...
2006). A gene (xynD) encoding a putative peptidoglycan deacetylase was identified in the L. lactis IL1403 genome on the basis of sequence similarity with the peptidoglycan GcNAc deacetylase PgdA from Streptococcus pneumoniae (Vollmer & Tomasz, 2000). These peptidoglycan deacetylases belong to the carbohydrate esterase family 4 (CE4), which also includes chitin deacetylases, acetylxylan esterases and chito-oligosaccharide deacetylase [Psilinakis et al., 2005; Carbohydrate Active Enzymes database (http://www.cazy.org/); Coutinho & Henrissat, 1999]. In this study, we show that L. lactis xynD (renamed pgdA) encodes a peptidoglycan GcNAc deacetylase. In addition, we show that an increase in the degree of peptidoglycan de-N-acetylation results in decreased autolysis of L. lactis cells, due to a reduced susceptibility of deacetylated peptidoglycan to the major autolysin AcmA.

METHODS

Bacterial strains, plasmids and growth conditions. The bacterial strains and plasmids used in this study are listed in Table 1. Escherichia coli strains were grown at 37 °C in Luria–Bertani (LB; Difco) medium with shaking. L. lactis strains were grown in M17 medium (Difco) supplemented with 0.5 % (w/v) glucose at 30 °C. Growth and autolysis were monitored by measuring OD600 with a spectrophotometer (Uvikon XL, Bio-Tek Instruments). Plasmids were selected by addition of antibiotics as follows: for L. lactis, erythromycin (5 µg ml⁻¹), chloramphenicol (5 µg ml⁻¹); for E. coli, ampicillin (50 µg ml⁻¹), kanamycin (50 µg ml⁻¹), chloramphenicol (10 µg ml⁻¹).

General recombinant DNA techniques. Molecular cloning techniques were performed using standard procedures (Sambrook et al., 1989). Restriction enzymes (New England Biolabs), T4 DNA ligase (Epicenter), Taq DNA polymerase (Qbiogen) and the TripleMaster PCR System (Eppendorf) were used as recommended by the manufacturers. Oligonucleotides were purchased from Invitrogen. Plasmids were extracted using the QIAprep Spin Miniprep kit (Qiagen). PCR was performed with a GeneAmp 2400 PCR system (Perkin-Elmer). DNA sequences were determined with an Applied Biosystems 370A automated DNA sequencer, and with ABI PRISM dye terminator cycle sequencing and dye primer cycle sequencing kits (Perkin-Elmer). Preparation of competent cells and electrotransformation of L. lactis were carried out as described elsewhere (Holo & Nes, 1989).

Construction of the pgdA mutant and complementation of the mutant. The gene pgdA (xynD mutant) was inactivated in L. lactis strain IL6288 by single crossing-over (SCO) plasmid integration. An internal pgdA fragment was PCR-amplified with primers 5'-TACCTTGCTTATAGGAGCG-3' and 5'-CAGGCTTGCTTGTTCTC-3', using IL1403 DNA as template. The resulting 597 bp fragment was cloned into the pGEM-T Easy vector and sequenced. It was then cloned into the NcoI and SacI restriction sites of the pJIM2242

<table>
<thead>
<tr>
<th>Strains and plasmids</th>
<th>Relevant genotype or phenotype</th>
<th>Source or reference</th>
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</thead>
<tbody>
<tr>
<td><strong>E. coli strains</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGI</td>
<td>supE hsdA5 thi Δ(lac–proAB)</td>
<td>Studier &amp; Moffatt (1986)</td>
</tr>
<tr>
<td>BL21(DE3)</td>
<td>F− ompT hsdS rK32 mcrA gmr dcm</td>
<td>Invitrogen</td>
</tr>
<tr>
<td>BL21(DE3)pLysE</td>
<td>Cm', BL21(DE3) containing pLysE plasmid producing T7 lysozyme, an inhibitor of T7 RNA polymerase</td>
<td>This study</td>
</tr>
<tr>
<td>TIL933</td>
<td>Cm' Ap' Kan', BL21(DE3)pLysE containing pET11a-Kan</td>
<td>This study</td>
</tr>
<tr>
<td>TIL934</td>
<td>Cm' Ap' Kan', BL21(DE3)pLysE expressing AcmA with hexa-His-tag with pET11a-Kan plasmid</td>
<td>This study</td>
</tr>
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<td><strong>L. lactis strains</strong></td>
<td></td>
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<tr>
<td>IL1403</td>
<td>Plasmid-free strain</td>
<td>Chopin et al. (1984)</td>
</tr>
<tr>
<td>IL6288</td>
<td>IL1403 derivative cured of its six prophages</td>
<td>M.-C. Chopin*</td>
</tr>
<tr>
<td>TIL926</td>
<td>Em', IL6288 derivative, pgdA mutant obtained by SCO integration of pJIM2242 containing a 597 bp pgdA internal fragment</td>
<td>This study</td>
</tr>
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<td>This study</td>
</tr>
<tr>
<td>TIL926(pJIM)</td>
<td>Em' Cm', TIL926 derivative containing pJIM2246</td>
<td>This study</td>
</tr>
<tr>
<td>PA1001(pPA3)</td>
<td>Derivative of NZ9000 lacking acmA and htrA and containing pPA3 plasmid</td>
<td>Bosma et al. (2006)</td>
</tr>
<tr>
<td>MG1363acmaΔ1</td>
<td>Derivative of MG1363 carrying an internal deletion in acmA</td>
<td>Buist et al. (1995)</td>
</tr>
<tr>
<td><strong>Plasmids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pGEM-T Easy</td>
<td>Ap', cloning vector with T overhangs</td>
<td>Promega</td>
</tr>
<tr>
<td>pET11a</td>
<td>Ap', expression vector with T7 lac promoter</td>
<td>Novagen</td>
</tr>
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<td>pET11a-Kan</td>
<td>Ap' Kan', pET11a derivative with kanamycin-resistance cassette cloned into Cm' site</td>
<td>Chich et al. (1995)</td>
</tr>
<tr>
<td>pJIM2242</td>
<td>Em', derivative of pORI28 non-replicative vector in L. lactis</td>
<td>Guedon et al. (2001)</td>
</tr>
<tr>
<td>pJIM2246</td>
<td>Cm', high-copy lactococcal cloning vector</td>
<td>Renault et al. (1996)</td>
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<td>pJIMpgdA</td>
<td>Cm', pJIM2246 derivative carrying pgdA gene under control of its own promoter</td>
<td>This study</td>
</tr>
<tr>
<td>pPA3</td>
<td>Cm', pN78048 derivative containing c-myc, 3' end of acmA (nt 835–1492) under control of nisin-inducible promoter and usp45 signal sequence</td>
<td>Bosma et al. (2006)</td>
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*INRA, Génétique Microbienne, Jouy-en-Josas, France.
Plasmid vector, a non-replicative plasmid in *L. lactis* IL6288. Integration of this plasmid by SCO into the IL6288 chromosome was performed with helper plasmid pGhost8, as described elsewhere (Guedon et al., 2001). Erythromycin-resistant clone TIL926 was selected. Plasmid integration was verified by PCR and Southern blot hybridization. Completion of the IL6288 *pgdA*-negative mutant was obtained by cloning the *pgdA* gene into the pJIM2246 multicopy plasmid vector. A 1351 bp DNA fragment encoding *pgdA* with its putative promoter and terminator was amplified by PCR from IL4103 total DNA with primers 5′-AAACTGCGAGGATGTTAAGATAGGAGG-3′ (*Pst*I site underlined) and 5′-ATATGCGGCCGCTCAAGTTTCTCCATAAGTGTGC-3′ (*Not*I site underlined). The fragment was digested with *Pst*I and *Not*I and cloned into a *Pst*I/*Not*I-linearized pJIM2246 vector. The resulting plasmid was produced in *E. coli* TG1 and used to transform TIL926. The resulting strain was named TIL934. To induce expression of recombinant hexa-His-tagged AcmA, IPTG was added at a final concentration of 1 mM to the culture at an OD<sub>600</sub> of 0.6. The control strain BL21(DE3)pLysE containing the empty pET11a-Kan vector (TIL933) was treated in a similar way. Bacteria were grown at 37 °C until IPTG addition and were then transferred to 30 °C during the expression time (3 h) to avoid inclusion body formation. Cells were harvested by centrifugation and disrupted by one passage at a pressure of 1600 bar with a Basic Z Cell Disruption System (Constant Systems). The soluble fraction containing the recombinant protein was recovered after centrifugation at 15 000 g for 15 min at 4 °C. The hexa-His-tagged protein was purified on a His-Trap FF column (1 ml, Amersham Biosciences) according to the manufacturer’s instructions using a fast protein liquid chromatography system (Amersham Biosciences). Elution was carried out with an imidazole concentration gradient (20–500 mM in 15 min). Fractions were collected and analysed by SDS-PAGE and zymogram. Fractions containing AcmA eluted at an imidazole concentration between 300 and 400 mM.

**Cell wall peptidoglycan preparation.** Peptidoglycan from *L. lactis* strains was prepared as described previously (Courtin et al., 2006). Cells from a 500 ml exponentially growing culture (OD<sub>600</sub> 0.3) were chilled on ice and harvested by centrifugation (4200 g, 10 min, 4 °C). Cells were suspended in 20 ml deionized H<sub>2</sub>O and boiled for 10 min. They were then resuspended in 1 ml 5 % (w/v) SDS and boiled for 25 min. The pellet obtained by centrifugation at 20 000 g for 10 min was resuspended in 1 ml 4 % (w/v) SDS and boiled again for 15 min. Cell walls were recovered by centrifugation at 20 000 g for 10 min and washed six times with deionized H<sub>2</sub>O to remove SDS. To eliminate proteins, the cell wall pellet was treated with Pronase (2 mg ml<sup>−1</sup>) for 90 min at 60 °C, then by trypsin (200 μg ml<sup>−1</sup>) for 16 h at 37 °C. The pellet containing peptidoglycan was treated with 48 % hydrofluoric acid overnight at 4 °C to eliminate teichoic acids, washed twice with 0.25 M Tris/HCl, pH 8.0, and then four times with deionized H<sub>2</sub>O. The final pellet was freeze-dried and stored at −20 °C.

**Structural analysis of *L. lactis* peptidoglycan.** Purified peptidoglycan (4 mg dry weight in 500 μl) was digested with mutanolysin (Sigma; 2500 U ml<sup>−1</sup>) in 25 mM sodium phosphate buffer, pH 5.5, containing 0.1 % (v/v) Triton X-100 for 16 h at 37 °C. The fragment was digested with *Pst*I and *Not*I-linearized pJIM2246 vector. The resulting plasmid was produced in *E. coli* TG1 and used to transform TIL926 with its putative *pgdA* gene under the control of the T7 promoter with the lac operator. The resulting plasmid was produced in *E. coli* TG1 and used to transform *E. coli* BL21(DE3)pLysE. The resulting strain was named TIL934. To induce expression of recombinant hexa-His-tagged AcmA, IPTG was added at a final concentration of 1 mM to the culture at an OD<sub>600</sub> of 0.6. The control strain BL21(DE3)pLysE containing the empty pET11a-Kan vector (TIL933) was treated in a similar way. Bacteria were grown at 37 °C until IPTG addition and were then transferred to 30 °C during the expression time (3 h) to avoid inclusion body formation. Cells were harvested by centrifugation and disrupted by one passage at a pressure of 1600 bar with a Basic Z Cell Disruption System (Constant Systems). The soluble fraction containing the recombinant protein was recovered after centrifugation at 15 000 g for 15 min at 4 °C. The hexa-His-tagged protein was purified on a His-Trap FF column (1 ml, Amersham Biosciences) according to the manufacturer’s instructions using a fast protein liquid chromatography system (Amersham Biosciences). Elution was carried out with an imidazole concentration gradient (20–500 mM in 15 min). Fractions were collected and analysed by SDS-PAGE and zymogram. Fractions containing AcmA eluted at an imidazole concentration between 300 and 400 mM.

SDS-PAGE and renaturing SDS-PAGE (zymogram). SDS-PAGE was performed with 10 % (w/v) polyacrylamide separating gels. Renaturing SDS-PAGE was performed as previously described (Huard et al., 2003). The polyacrylamide gels contained 0.2 % (w/v) Micrococcus luteus ATCC 4698 (Sigma) or 0.4 % (w/v) *L. lactis* autolysed cells, or 0.08 % (w/v) *L. lactis* peptidoglycan as enzyme substrates. After sample migration in the gels, the gels were washed for 30 min in deionized H<sub>2</sub>O at room temperature and then incubated in 50 mM Tris/HCl, pH 7.0, containing 0.1 % (v/v) Triton X-100, overnight at 37 °C. The gels were subsequently washed for 30 min in deionized H<sub>2</sub>O, then stained with 0.1 % Methylene Blue in 0.01 % (w/v) KOH for 2 h at room temperature and destained in deionized H<sub>2</sub>O. Gel images were generated with a DcuScan T1200 scanner (Agfa-Gevaert).

**Protein identification by peptide mass fingerprinting (PMF).** Proteins were digested with trypsin and the masses of tryptic peptides were analysed by MALDI-TOF MS, as described previously (Guillot et al., 2003), with a Voyager DE STR instrument (Applied Biosystems) by the Plateau d’Analyses Protéomiques par Séquençage et Spectrométrie de Masse (PAPSS) at INRA, Jouy-en-Josas. Database searches were conducted with the MS-Fit software (http://prospector.ucsf.edu) either on an *L. lactis*-specific database containing protein sequences deduced from the genome sequence of *L. lactis* IL4103 or on the SWISS-PROT database.

**Triton X-100-induced autolysis in buffer solution.** *L. lactis* strains were grown in M17 medium to mid-exponential phase (OD<sub>600</sub> 0.8). Cells were harvested by centrifugation at 5000 g for 10 min at 4 °C, washed once with 50 mM potassium phosphate buffer, pH 7.0, and resuspended at an OD<sub>600</sub> of 1 in 50 mM potassium phosphate buffer, pH 7.0, supplemented with 0.05 % Triton X-100 (Cornett & Shockman, 1978). Cell suspensions were then transferred into 100-well sterile microplates and incubated at 30 °C. Autolysis was monitored by measuring the OD<sub>600</sub> of the cell suspensions with an automated incubator/optical density reader (Microbiology Workstation Bioscreen C, Labsystems).

**Assay of AcmA activity in *L. lactis* autolysed cells.** *L. lactis* autolysed cells were used as a substrate for measuring AcmA activity.
and were prepared as follows. *L. lactis* strains were grown in M17 medium up to the end of exponential phase. Cells were harvested by centrifugation at 5000 g for 15 min at 4 °C, washed once with 10 mM Tris/HCl, pH 7.5, at 4 °C, washed once with deionized H₂O, and freeze-dried. The dried samples were resuspended in deionized H₂O at 10% (v/v), autoclaved and stored at 4 °C.

Autoclaved cells were diluted in 25 mM Tris/HCl, pH 7, to OD₆₀₀ 0.5. Purified hexa-His-tagged AcmA (~1.5 μg ml⁻¹ final concentration) was added in a final volume of 1 ml, and the OD₆₀₀ of the cell suspension was monitored with a spectrophotometer (UVikon XL, Bio-Tek Instruments). The extent of autolysis was expressed as the percentage decrease in OD₆₀₀.

**Binding of c-Myc–PA fusion protein to peptidoglycan.** The c-Myc–PA (PA3) fusion protein corresponds to the cell wall binding domain of AcmA (PA; C-terminal 218 aa of AcmA) fused to a c-Myc epitope at its N terminus (Bosma et al., 2006). It was produced in the supernatant of strain *L. lactis* PA1001 (pPA3) (a kind gift of K. Leenhouts, BioMade, Groningen, The Netherlands). The strain was grown at 30 °C in M17 glucose medium containing 10 ng nisin ml⁻¹ to induce the production of c-Myc–PA fusion protein. The supernatant was recovered at the end of exponential phase growth and filtered through a 0.22 μm pore-size filter. Peptidoglycan from *L. lactis* PA1001 (pPA3) diluted 10, 20 or 50 times in culture supernatant of *L. lactis* MG1363 was added in a final volume of 1 ml, and the OD₆₀₀ of the cell suspension was monitored with a spectrophotometer (UVikon XL, Bio-Tek Instruments). The extent of autolysis was expressed as the percentage decrease in OD₆₀₀.

**RESULTS**

**Analysis of *L. lactis* pgdA sequence**

The gene *pgdA* (xymD) encodes a 372-residue protein with a putative N-terminal signal peptide, predicted by Psort software (http://psort.hgc.jp) to be uncleavable. The PgdA amino acid sequence exhibits 31% identity to the *S. pneumoniae* peptidoglycan GlcNAc deacetylase sequence (Vollmer & Tomasz, 2000). In addition, *L. lactis* PgdA contains a conserved zinc-binding triad (Asp-184, His-234, His-238) identified in the active site of its *S. pneumoniae* homologue (Blair et al., 2005). Northern blot analysis indicated that the *pgdA* gene is transcribed during the exponential growth phase in *L. lactis* IL1403 (data not shown). The transcript size (1.3 kb) indicated a monocistronic organization of the gene, in agreement with the detection of two putative rho-independent transcription terminators upstream and downstream of *pgdA*.

**L. lactis pgdA encodes a peptidoglycan GlcNAc deacetylase**

To investigate the role of *pgdA*, the gene was inactivated in *L. lactis* subsp. *lactis* strain IL6288. This strain is a derivative of IL1403 obtained after curing the six identified prophages (Chopin et al., 2001) from the chromosome (A. Aucouturier and M.-C. Chopin, personal communication). Inactivation of *pgdA* was obtained by SCO integration of the non-replicative vector pJIM2242 containing a 597 bp internal *pgdA* fragment.

The peptidoglycan structure of the IL6288 *pgdA* mutant (TIL926) was analysed and compared with that of the parental strain IL6288. After peptidoglycan digestion with mutanolysin, a muramidase, the resulting muropeptides were separated by HPLC (Fig. 1). Four peaks (indicated by arrows) present in the IL6288 muropeptide profile (Fig. 1a) were absent from the TIL926 muropeptide profile (Fig. 1b). These peaks (A, B, E, F) (Fig. 1c) were restored in the muropeptide profile of the complemented strain TIL926(pJIMpgdA), obtained by cloning *pgdA* into the multicopy plasmid vector pJIM2246. Also, three other minor peaks (C, D, G) appeared in the complemented mutant (Fig. 1c). Peaks A–G were analysed by MALDI-TOF MS. Their measured m/z values exhibited a 42 Da mass defect compared to the masses expected for the molecular sodiated ions corresponding to *L. lactis* fully acetylated muropeptides (Table 2). This 42 Da mass defect corresponds to the loss of one acetyl group. Thus, all the peaks A–G contained deacetylated muropeptides. From these results, we conclude that *pgdA* encodes a peptidoglycan deacetylase. The percentage of deacetylated muropeptides was calculated to be 9.8% in the parental strain IL6288 at the beginning of exponential growth, whereas it was 15.8% in the complemented strain TIL926(pJIMpgdA). These data indicate that *pgdA* is overexpressed in TIL926(pJIMpgdA), most probably because *pgdA* was cloned on a high-copy-number plasmid.

Peak A, containing the deacetylated monomer disaccharide tripeptide with Asn side chain (m/z 920.45), was subjected to MALDI-PSD analysis, which allowed the analysis of muropeptide fragment ions (Fig. 2). A fragment with m/z 760.6 corresponded to the loss of one glucosamine. Several other fragments resulted from the loss of one glucosamine (m/z 161), whereas no fragment corresponding to the loss of one GlcNAc (m/z 203) was observed. These results indicate that muropeptide A contains glucosamine instead of GlcNAc, and that deacetylation occurs on GlcNAc. Thus, the *L. lactis* *pgdA* gene encodes a peptidoglycan GlcNAc deacetylase.
Influence of peptidoglycan de-\(N\)-acetylation on lysozyme sensitivity

We tested the lysozyme sensitivity of IL6288 and its derivative strains by plating cultures of each strain on M17 agar plates containing lysozyme concentrations from 0 to 3 mg ml\(^{-1}\). The parental strain IL6288 was resistant to 1 mg lysozyme ml\(^{-1}\), whereas the \(pgdA\)-negative mutant TIL926 was sensitive to 1 mg ml\(^{-1}\). In contrast, the complemented strain TIL926(pJIM\(pgdA\)) with a higher

Table 2. Structures, molecular masses and quantities of deacetylated muropeptides

<table>
<thead>
<tr>
<th>Peak*</th>
<th>Observed m/z</th>
<th>Calculated ([M+Na]^+)†</th>
<th>(\Delta m)</th>
<th>Identification‡</th>
<th>Percentage§</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>IL6288</td>
<td>TIL926(pJIM(pgdA))</td>
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<tr>
<td>A</td>
<td>920.45</td>
<td>962.43</td>
<td>-41.98</td>
<td>Tri-N (deAc)</td>
<td>1.3</td>
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<tr>
<td>B</td>
<td>921.35</td>
<td>963.41</td>
<td>-42.06</td>
<td>Tri-D (deAc)</td>
<td>0.7</td>
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<tr>
<td>C</td>
<td>991.49</td>
<td>1033.47</td>
<td>-41.98</td>
<td>Tetra-N (deAc)</td>
<td>0.4</td>
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<tr>
<td>D</td>
<td>1062.42</td>
<td>1104.50</td>
<td>-42.08</td>
<td>Penta-N (deAc)</td>
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<tr>
<td>E</td>
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<td>G</td>
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<td>2947.36</td>
<td>-42.14</td>
<td>Tri-N-Tetra-N-Tetra-N (deAc)</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>9.8</td>
</tr>
</tbody>
</table>

*Peak identification refers to the chromatograms in Fig. 1.
†Calculated \([M+Na]^+\) corresponds to the non-deacetylated muropeptides from \(L.\ lactis\). Sodiated molecular ions were the most abundant ones in MALDI-TOF mass spectra for all muropeptides.
‡Tri, disaccharide tripeptide (L-Ala-D-iGln-L-Lys); Tetra, disaccharide tetrapeptide (L-Ala-D-iGln-L-Lys-D-Ala); Penta, disaccharide pentapeptide (L-Ala-D-iGln-L-Lys-D-Ala-D-Ala). Disaccharide=GlCNAC-MurNAc; D, Asp; N, Asn; deAc, deacetylation; iGln, isoGln.
§The percentage for each peak was calculated as the ratio of its area over the sum of all the peak areas.
degree of peptidoglycan deacetylation showed increased resistance to lysozyme and grew in the presence of 2 mg lysozyme ml\(^{-1}\), while the parent strain did not.

**Influence of peptidoglycan de-N-acetylation on cell separation and autolysis**

The growth rates of the pgdA-negative mutant and the wild-type strain were identical in M17 glucose medium, and the growth rates of the complemented strain TIL926(pJIMpgdA) and the control TIL926(pJIM) strain were identical in M17 glucose medium containing chloramphenicol. These results indicate that inactivation or overexpression of pgdA has no impact on bacterial growth rate. Microscopic observation of the different strains revealed that strain TIL926(pJIMpgdA) forms long chains of cells (Fig. 3c), unlike the parental strain IL6288 (Fig. 3a) and the pgdA-negative mutant TIL926 (Fig. 3b). The chain length for TIL926(pJIMpgdA) (15–20 cells) was shorter than that obtained with the MG1363 acmA mutant (50–100 cells per chain). The defect of cell separation in TIL926(pJIMpgdA) may result from the resistance of deacetylated peptidoglycan to endogenous autolysins.

Autolysis of the different strains after they had reached stationary phase was followed over 6 days. During this period, TIL926(pJIMpgdA) culture did not exhibit autolysis, as measured by the decrease in OD\(_{600}\) and behaved like the MG1363acmA mutant (data not shown). No difference in the rate and extent of autolysis was found among the wild-type IL6288 strain, the pgdA-negative mutant and the control strain TIL926(pJIM). For the three strains, the decrease in OD\(_{600}\) reached 10\% after 4 days, and then remained stable.

Autolysis was also compared after transfer of bacterial cells to 50 mM potassium phosphate buffer, pH 7.0, containing 0.05 \% Triton X-100. As shown in Fig. 4, the pgdA mutant TIL926 exhibited a similar initial autolysis rate to that of

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**Fig. 2.** MALDI-PSD analysis of reduced muropeptide A purified by reversed-phase HPLC (see Fig. 1). The [M + Na]\(^{+}\) parental ion (\(m/z\) 920.9) was selected for PSD analysis. (a) MALDI-PSD TOF mass spectrum of sodiated ions corresponding to fragments that issued from muropeptide A; (b) chemical structure determined for muropeptide A and fragmentation pattern. The dashed arrows indicate N-terminal fragment ions (a and b ions) and a C-terminal fragment ion (ion y) identified on the spectrum. Several fragments result from the loss of one glucosamine (\(m/z\) 161).
the parental IL6288 strain, but a higher final autolysis level. In contrast, strain TIL926(pJIMpgdA), with a higher degree of peptidoglycan de-N-acetylation, showed a reduced rate of autolysis compared to IL6288. The control strain TIL926(pJIM) exhibited an autolysis rate and a final extent of autolysis identical to those of TIL926 without plasmid (data not shown).

**Influence of GlcNAc deacetylation on peptidoglycan susceptibility to AcmA autolysin**

Since AcmA autolysin is the major enzyme involved in *L. lactis* autolysis and is involved in cell separation after cell division (Buist et al., 1995), we tested the activity of AcmA in vitro on peptidoglycan substrates with different degrees of de-N-acetylation.

AcmA without its putative signal sequence and with a C-terminal hexa-His-tag was produced in *E. coli* BL21(DE3)pLysE under control of the T7 promoter. After induction with IPTG, a low amount of recombinant AcmA-His was obtained (data not shown). The protein was purified by affinity chromatography on a His-Trap column. The major protein detected at 45 kDa in the purified fraction analysed by SDS-PAGE corresponded to AcmA-His (Fig. 5a, lane 1), as confirmed by PMF analysis. In addition, its activity could be detected by zymogram assay with *M. luteus* cells as substrate (Fig. 5b, lane 1). Three minor contaminant proteins were co-purified, and were identified by PMF as *E. coli* proteins not related to PGHs (Fig. 5a, lane 1). These contaminant proteins did not exhibit peptidoglycan-hydrolysing activity as checked by zymogram assay (Fig. 5b, lane 1). Thus, we used the partially purified AcmA-His for activity tests.

AcmA activity was first tested on autoclaved cells obtained from the three strains which exhibited different degrees of peptidoglycan de-N-acetylation: IL6288 (9.8 %), pgdA-negative mutant TIL926 (0 %) and complemented strain TIL926(pJIMpgdA) (15.8 %). Activity was measured by the optical density decrease of the cell suspensions. As shown...
In Fig. 6a, the highest activity was found towards cells originating from the negative mutant TIL926 with fully acetylated peptidoglycan. AcmA activity towards cells from TIL926(pJIMpgdA) with the highest degree of de-N-acetylation was lower than towards parental strain IL6288 cells. These results indicate that de-N-acetylation of peptidoglycan reduces its susceptibility to the autolysin AcmA.

We further confirmed this result by testing AcmA-His activity in a zymogram assay with purified peptidoglycan as substrate included into polyacrylamide gels. As shown in Fig. 6b, when the same amounts of AcmA-His were loaded on the gels, the activity band detected on peptidoglycan from the pgdA-negative mutant was more intense than that on peptidoglycan from TIL926(pJIMpgdA), confirming the lower activity of AcmA towards de-N-acetylated peptidoglycan compared to fully acetylated peptidoglycan.

**Influence of GlcNAc deacylation on AcmA binding to *L. lactis* peptidoglycan**

AcmA produced by *L. lactis* cells is found both attached to the cells and in the culture supernatant (Buist et al., 1995). It has to bind the peptidoglycan of the cell wall through its C-terminal LysM-containing domain to be able to lyse the cells (Steen et al., 2003). We investigated whether peptidoglycan deacylation influences substrate binding of AcmA.

First, using the zymogram technique, we compared the amount of AcmA bound to the cells and the amount present in culture supernatant for IL6288 and its derivative mutants. No difference was found in the intensity of the AcmA activity band on micrococci used as substrate between the pgdA mutant and wild-type IL6288 or the overexpressing strain (data not shown). Breakdown products of AcmA, which retained activity in the zymogram (Poquet et al., 2000; Steen et al., 2003), were barely detected in IL6288 and were present in similar amounts in its derivative mutants, indicating no difference in AcmA degradation among the tested strains.

Second, we examined whether peptidoglycan de-N-acetylation affects AcmA binding to purified peptidoglycan. AcmA consists of two domains: an active site domain and a C-terminal region containing three highly homologous repeats of 45 aa, named LysM domains, which bind peptidoglycan (Steen et al., 2003). To study the binding of AcmA to peptidoglycan with different degrees of de-N-acetylation, we used a fusion protein consisting of the C-terminal peptidoglycan-binding domain of AcmA fused to a c-Myc epitope (c-Myc–PA) at its N terminus (Bosma et al., 2006). Peptidoglycan extracted from IL6288, pgdA mutant TIL926 and pgdA-overexpressing strain TIL926(pJIMpgdA) was incubated with different concentrations of c-Myc–PA. The amount of fusion protein bound to each peptidoglycan was analysed by Western blotting with specific anti-c-Myc antibody (Fig. 7). A band with the expected molecular mass (28 kDa) was detected. Quantitative analysis of the immunodetected band in each sample (data not shown) indicated that equal amounts of c-Myc–PA bound to peptidoglycan from the wild-type, pgdA mutant and pgdA-overexpressing strains, with different degrees of deacylation. These results indicate that GlcNAc deacylation does not modify AcmA binding to peptidoglycan in strain TIL926(pJIMpgdA), but most probably affects the efficiency of peptidoglycan chain cleavage by AcmA.

**DISCUSSION**

The aim of the study was to evaluate the impact of peptidoglycan structural modification on *L. lactis* autolysis. We have identified a peptidoglycan deacetylase (PgdA) in *L. lactis* which deacetylates GlcNAc residues. We have shown that the increase of *N*-unsubstituted glucosamine residues in peptidoglycan results in decreased autolysis of...
L. lactis cells due to reduced susceptibility of the modified peptidoglycan to the hydrolytic activity of the L. lactis major autolysin AcmA.

GlcNAc deacetylation of peptidoglycan negatively influences the hydrolytic activity of AcmA, which is a glucosaminidase, able to hydrolyse β-1,4-glycosidic bonds between GlcNAc and MurNAc. Deacetylation of peptidoglycan aminosugars has previously been shown to affect the hydrolytic activity of PGHs with different specificities, either positively or negatively. For example, de-N-acetylation of peptidoglycan GlcNAc confers resistance to lysozyme, an exogenous muramidase, upon several bacterial species, such as S. pneumoniae (Vollmer & Tomasz, 2000), Bacillus cereus (Hayashi et al., 1973), Listeria monocytogenes (Boneca et al., 2007) and L. lactis (this study). In contrast, a muramidase purified from Clostridium acetobutylicum has been found to act on non-acetylated peptidoglycan alone (Crouch et al., 1992).

Also, the S. pneumoniae LytA amidase has a higher activity towards non-modified S. pneumoniae peptidoglycan with a high degree of deacetylation than towards chemically acetylated peptidoglycan (Vollmer & Tomasz, 2000). In B. cereus, glycosidases have been identified with a preference for either peptidoglycan with N-unsubstituted glucosamine or peptidoglycan with acetylated aminosugars (Kawagishi et al., 1980).

AcmA consists of two domains: an active site domain and a C-terminal region containing three highly homologous repeats of 45 aa, named LysM domains, which bind peptidoglycan. We found that equal amounts of AcmA C-terminal domain bound to peptidoglycan with the different degrees of de-N-acetylation tested (15.8% in the pdgA-overexpressing strain vs 0% in the pdgA-negative mutant). Thus, the reduced autolysis of L. lactis cells with an increased degree of peptidoglycan deacetylation does not seem to result from reduced AcmA binding to the cell wall peptidoglycan substrate. The decreased autolysis therefore probably results from reduced efficiency of cleavage by AcmA of GlcNH2–MurNAc bonds compared to GlcNAc–MurNAc bonds.

The degree of peptidoglycan GlcNAc deacetylation in L. lactis strain IL6288 (9.8%) was low compared to that observed in S. pneumoniae (over 80% in strain R36A; Vollner & Tomasz, 2000), B. cereus (40–100%; Hayashi et al., 1973) and L. monocytogenes (50%; Boneca et al., 2007). However, this appears to be sufficient to modulate the sensitivity of L. lactis cells to lysozyme and to AcmA autolysis.

The autolysis of L. lactis is of special interest with respect to its use as a starter in dairy fermentations. It has been shown that bacterial autolysis during cheese ripening enhances the contribution of intracellular enzymes to cheese flavour formation (Lortal & Chapot-Chartier, 2005). For another proposed application of L. lactis, i.e. its use as a delivery vehicle for antigens and therapeutic molecules in the digestive tract of humans and animals (Nouaille et al., 2003), autolysis is also a critical parameter to consider for optimal delivery of molecules (Grangette et al., 2004). The autolytic properties of L. lactis have been observed to be strain-dependent (Lortal & Chapot-Chartier, 2005). In this study, we observed that the degree of peptidoglycan deacetylation influences autolytic properties. Variation in the degree of peptidoglycan deacetylation could be one of the factors that contributes to the variability of autolytic properties among natural strains.

Since PGHs are potentially lethal enzymes for the cells that produce them, their activities are thought to be regulated at the post-translational level (Shockman & Höltje, 1994; Smith et al., 2000). This regulation could involve different factors. With respect to AcmA, previous studies have already revealed two mechanisms involved in the control of its activity in L. lactis cells. First, AcmA is found to bind to peptidoglycan through its LysM domains at specific loci in the cell wall, around the poles and septum of the cells, whereas AcmA binding on the whole cell surface is hindered by some cell wall constituents, most probably by lipoteichoic acids (Steen et al., 2003). Second, it has been shown that a decrease of the level of d-Ala substitution on lipoteichoic acids leads to increased autolysis through an indirect effect that results from the decreased degradation of AcmA by the extracellular housekeeping protease HtrA (Steen et al., 2005b). The degree of peptidoglycan de-N-acetylation could constitute a third mechanism of control of AcmA in cells by decreasing the susceptibility of peptidoglycan to AcmA.

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