

# The CHAP domain of Cse functions as an endopeptidase that acts at mature septa to promote *Streptococcus thermophilus* cell separation

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**The CHAP domain of Cse functions as an endopeptidase that acts at mature septa to promote *S. thermophilus* cell separation.**



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|                               |  |

1 **The CHAP domain of Cse functions as an endopeptidase that acts at**  
2 **mature septa to promote *Streptococcus thermophilus* cell separation.**

3

4 Séverine Layec <sup>1</sup>, Joëlle Gérard <sup>2</sup>, Valérie Legué <sup>2</sup>, Marie-Pierre Chapot-Chartier<sup>3</sup>, Pascal  
5 Courtin<sup>3</sup>, Frédéric Borges <sup>1f</sup>, Bernard Decaris <sup>1</sup> and Nathalie Leblond-Bourget <sup>1\*</sup>

6

7 <sup>1</sup>Laboratoire de Génétique et Microbiologie, UMR INRA/UHP 1128, IFR 110, Nancy-  
8 Université, BP 239, 54506 Vandoeuvre-lès-Nancy, France.

9 <sup>f</sup> present address: LSGA- Laboratoire de Science et Génie Alimentaire, ENSAIA-INPL,  
10 BP172, 54506 Vandoeuvre-lès-Nancy, France.

11

12 <sup>2</sup>Génomique, Ecophysiologie et Ecologie Fonctionnelles, « Interaction Arbres/Micro-  
13 organismes », UMR INRA/UHP 1136, IFR 110, Nancy-Université, BP239, 54506 Vandoeuvre-  
14 lès-Nancy, France.

15

16 <sup>3</sup>INRA, UR477 Biochimie Bactérienne, F-78350 Jouy-en-Josas, France

17

18 \*Corresponding author : Phone: (33) 3 83 68 42 10

19 Fax : (33) 3 83 68 44 99

20 E-mail : bourget@nancy.inra.fr

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22 *S. thermophilus*

23

24 **SUMMARY**

25

26 Cell separation is dependent on cell wall hydrolases that cleave the peptidoglycan shared  
27 between daughter cells. In *Streptococcus thermophilus*, this step is performed by the Cse protein  
28 whose depletion resulted in the formation of extremely long chains of cells. Cse, a natural chimeric  
29 enzyme created by domain shuffling, carries at least two important domains for its activity: the  
30 LysM expected to be responsible for the cell wall-binding and the CHAP domain predicted to  
31 contain the active center. Accordingly, the localization of Cse on *S. thermophilus* cell surface has  
32 been undertaken by immunogold electron and immunofluorescence microscopies using of  
33 antibodies raised against the N-terminal end of this protein. Immunolocalization shows the presence  
34 of the Cse protein at mature septa. Moreover, the CHAP domain of Cse exhibits a cell wall lytic  
35 activity in zymograms performed with cell walls of *Micrococcus lysodeikticus*, *Bacillus subtilis* and  
36 *S. thermophilus*. Additionally, RP-HPLC analysis of muropeptides released from *B. subtilis* and  
37 *S. thermophilus* cell wall after digestion with the CHAP domain shows that Cse is an  
38 endopeptidase. Altogether, these results suggest that Cse is a cell wall hydrolase involved in  
39 daughter cell separation of *S. thermophilus*.

40 **INTRODUCTION**

41 Cell separation can be defined as the mechanism needed to disconnect the two new  
42 daughter sacculi after the cell division is completed (or at the very late step of cell division). This is  
43 still a poorly understood process that requires the involvement of cell wall hydrolases. Cell-  
44 separating hydrolases were mostly identified by phenotypic analysis, their absence resulting in the  
45 formation of chains of unseparated cells (Borges *et al.*, 2005; Buist *et al.*, 1995; Fukushima *et al.*,  
46 2006; Garcia *et al.*, 1999; Heidrich *et al.*, 2001; Margot *et al.*, 1998; Margot *et al.*, 1999; Yoshimura  
47 *et al.*, 2006) or in a highly aggregated phenotype (Kajimura *et al.*, 2005). In *Streptococcus*  
48 *thermophilus*, the deletion of *cse* led to a dramatic increase of the chain length indicating that Cse is  
49 the key *S. thermophilus* cell-separating enzyme (Borges *et al.*, 2005).

50 The Cse protein consists of four regions: a signal peptide and a LysM domain at its N-  
51 terminus, a catalytic domain at its C-terminus, both domains being separated by a central variable  
52 region (Borges *et al.*, 2005; Borges *et al.*, 2006). The LysM motif functions as a general  
53 peptidoglycan binding module (Eckert *et al.*, 2006; Steen *et al.*, 2005a) that may play important  
54 roles in appropriate localization and/or recognition of substrates (Fukushima *et al.*, 2006; Kajimura  
55 *et al.*, 2005; Steen *et al.*, 2005a; Yamamoto *et al.*, 2003).

56 The C-terminal catalytic domain of Cse carries a Cysteine, Histidine-dependent  
57 Amidohydrolases/Peptidases (CHAP) domain conferring to the protein a potential catalytic activity  
58 (Borges *et al.*, 2005; Layec *et al.*, 2008a). Point mutation of the conserved Cys and His residues or  
59 total deletion of this domain reveals that it retains cell wall hydrolase activity (Donovan *et al.*, 2006;  
60 Navarre *et al.*, 1999; Nelson *et al.*, 2006; Pritchard *et al.*, 2004; Yokoi *et al.*, 2005).

61 Among the *Firmicutes*, few bacterial and phage-encoded CHAP proteins have been  
62 characterized and participate either in cell division (Chia *et al.*, 2001; Mattos-Graner *et al.*, 2006;  
63 Ng *et al.*, 2004; Reinscheid *et al.*, 2001) daughter cell separation (Borges *et al.*, 2005; Kajimura *et al.*  
64 *et al.*, 2005) or in cell lysis (Donovan *et al.*, 2006; Huard *et al.*, 2003; Navarre *et al.*, 1999; Pritchard  
65 *et al.*, 2004; Yokoi *et al.*, 2005).

66

67 By analogy with other cell-separating enzymes and taking into account the involvement of  
68 Cse in cell disconnection, we postulate that Cse is a cell wall hydrolase probably acting at cell  
69 separation sites. However, there has been no direct evidence concerning either the Cse catalytic  
70 activity or its localization at the *Streptococcus thermophilus* cell surface. In this study, we provide  
71 genetic and biological evidence that Cse separates daughter cells by cleaving the bond between D-  
72 Ala of the stem peptide and L-Ala of the cross-bridge in *S. thermophilus* peptidoglycan at mature  
73 septa.

74

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75 **RESULTS**

76

77 **The LysM and CHAP domains are essential for Cse cell separating activity.**

78 To get more insight into the biological role of the LysM and CHAP domains of the Cse  
79 protein, in frame deletion mutants were constructed resulting in the *cse* $\Delta$ LysM and *cse* $\Delta$ CHAP  
80 mutant strains (Fig. 1A). Semi-quantitative RT-PCR was used to quantify the level of expression of  
81 *cse* alleles in the wild-type and the mutant strains. The level of expression of *gyrA* was included an  
82 internal housekeeping control to ensure that equivalent amounts of RNA were used for the RT-PCR  
83 analysis. As shown in Fig. 1B, there is no significant difference between the levels of expression of  
84 the different alleles.

85 Visual inspection of overnight standing HJL cultures revealed that turbidity in the cultured  
86 medium was only observed for the CNRZ368 control strain whereas the cells of the  $\Delta$ *cse*,  
87 *cse* $\Delta$ LysM and *cse* $\Delta$ CHAP mutants all flocculate at the bottom of the tube (Fig. 2A). To determine  
88 if the sedimentation properties of these mutants correlate with an increase of their chain length,  
89 aliquots of each culture were observed under light microscopy followed by the counting of the  
90 number of cells per chain. As observed in Fig. 2B, chains of the wild-type strain were rather small  
91 since 70% of them were constituted by less than 40 cells. By contrast, chains of the 3 *cse* deletion  
92 mutants were mostly composed of more than 201 cells. Complementation experiments were  
93 performed by transformation of the *cse* $\Delta$ LysM and *cse* $\Delta$ CHAP mutants with pNST260<sup>+</sup>::*cse*, a  
94 vector containing an intact copy of *cse* that we developed previously (Borges *et al.*, 2005).  
95 Complemented strains exhibited a wild-type phenotype with respect to the number of cells per chain  
96 and to the sedimentation property while the negative control maintained a mutant phenotype (data  
97 not shown). Thus, deletion of the LysM or the CHAP domain of the *cse* gene had a clear effect on  
98 the chain length indicating that both domains were required for Cse efficient cell separation activity.

99

100

101

102 **Cse is involved in late stage of cell division.**

103 Transmission electron microscopy of both the wild-type and the  $\Delta cse$  mutant revealed that  
104 they formed linear chains that appeared like linear necklaces of diplococcal cells (Fig. 3). As  
105 observed for *S. pneumoniae* (Morlot *et al.*, 2003), progression of the *S. thermophilus* septum  
106 synthesis is materialized by three kinds of septa (Fig. 3C and F): (i) nascent septum (a) located  
107 equidistant from the cell poles and initiated by the constriction ring, (ii) intermediate septum (b)  
108 generated by further constriction of the cell walls and (iii) mature septum (c) observed at the end of  
109 the division process and corresponding to an extension of the septum holding daughter cells  
110 together. No impairment of the septum formation was observed in the  $\Delta cse$  mutant suggesting that  
111 Cse had no role in cell wall synthesis at septa. The only difference between the  $\Delta cse$  mutant  
112 (Fig. 3A to C) and the wild-type strains (Fig. 3D to F) is the regularity of the cell morphology.  
113 Within the mutant, the chains of cells consist of a regular succession of diplococcus, a phenotype  
114 that corresponds to fully divided cells. A more irregular phenotype is observed in the wild-type  
115 suggesting that the processes of cell division and of disconnection of daughter cells could interfere.

116 Since deletion of *cse* led to a dramatic reduction of daughter cell separation and because  
117 the material linking daughter cells was expected to be peptidoglycan, we postulate that Cse acts as a  
118 late cell wall hydrolase that is able to bind *S. thermophilus* cell surface and separate divided cells.

119  
120 **Localization of Cse and its derivatives at *S. thermophilus* cell surface.**

121 In a previous study, we demonstrate that Cse is an extracellular protein whose export is  
122 signal peptide dependent (Borges *et al.*, 2005). Moreover, a search of the Conserved Domain  
123 Database shows that the N-terminal parts of Cse contain a LysM domain potentially involved in Cse  
124 attachment to the cell wall. Thus, to visualize the specific localization of Cse on the *S. thermophilus*  
125 cell surface, we utilized immunogold electron microscopy. To avoid the simultaneous detection of  
126 Cse and PcsB sharing the same C-terminal end (Borges *et al.*, 2005), antibodies were raised against  
127 a specific region (from 1 to 183 aa) of the Cse protein. As shown in Fig. 4, the labelled gold  
128 particles were localized on the fine link connecting daughter cells and within adjacent cell poles



129 (Fig. 4A and B). However, because of the darkness of the cells, we could not determine if labelled  
130 particles were present elsewhere. We used next immunofluorescence microscopy on the wild-type  
131 strain, and confirmed that Cse binding was highly localized at mature septa with no or little Cse  
132 protein at nascent septa (Fig. 5A2 and E2). Staining of the wild-type *S. thermophilus* cells with  
133 calcofluor fluorescent dye (Fig. 5, E4) which stains cell walls blue confirmed the specific binding of  
134 Cse to the peptidoglycan of the mature septa. No fluorescence was detected on the *cseΔlysM* mutant  
135 (Fig. 5C) or on the wild-type strain stained with preimmune serum (Fig. 5B) used as negative  
136 controls. Fluorescence analysis of the *cseΔVar* and *cseΔCHAP* mutants (Fig. S1C and Fig. 5D)  
137 showed that the Cse derivatives were capable of recognizing the same targets but surprisingly the  
138 patterns of fluorescence was more diffuse than that of the wild-type strain.

139

#### 140 **Cse is an endopeptidase.**

##### 141 **(i) The CHAP domain of Cse confers the cell wall hydrolytic activity.**

142 In a previous study, we tried to overexpress the full length Cse protein but our attempts  
143 failed. This time, only the CHAP domain of Cse (from position in aa 341 to 461) was expressed in  
144 *E. coli*. To facilitate the purification of the CHAP protein, a hexa-histidine tag was introduced at its  
145 N-terminus. On SDS-PAGE, the purified CHAP-His<sub>6</sub>-tagged protein gave a band of about 15 kDa  
146 estimated to be more than 96% pure (Fig. S2). This band corresponded to the cell-wall hydrolyzing  
147 band observed on zymogram and was also revealed by Western immunoblot analysis using an anti-  
148 His tag monoclonal antibody (Fig. S2). Zymograms were done using as substrates cells from  
149 *Micrococcus lysodeikticus* (data not shown), purified peptidoglycan from *B. subtilis* 168 HR  
150 (Fig. S2 and Fig. 6A) and from *S. thermophilus*  $\Delta$ *cse* mutant (Fig. S2 and Fig. 6B) and revealed that  
151 the CHAP domain carries a cell wall hydrolytic activity. The CHAP-His<sub>6</sub>-tagged protein activity  
152 was revealed with incubation buffer containing 0.2% Triton\_X100 at pH 4.0 or pH 4.5. No activity  
153 was detected at other pH (data not shown).

154

155

156 **(ii) Determination of the hydrolytic specificity of the CHAP domain of Cse on *B. subtilis***  
157 **peptidoglycan.**

158 In the literature, the CHAP domain of several phage-encoded lytic proteins displays an  
159 endopeptidase activity (Baker *et al.*, 2006; Donovan *et al.*, 2006; Navarre *et al.*, 1999; Nelson *et al.*,  
160 2006; Pritchard *et al.*, 2004; Yokoi *et al.*, 2005), but this domain is also reported to function as *N*-  
161 acetylmuramoyl-L-alanine amidase (Kajimura *et al.*, 2005; Llull *et al.*, 2006). To determine the  
162 hydrolytic specificity of Cse, the purified CHAP-His<sub>6</sub>-tagged protein was used to digest purified  
163 peptidoglycan of *B. subtilis* whose structure was established previously (Atrih *et al.*, 1999). After  
164 incubation, the digestion mixture was centrifuged and both soluble and insoluble materials were  
165 analyzed. No muropeptide or peptide could be detected in the soluble material when analyzed by  
166 RP-HPLC (data not shown) whereas an *N*-acetylmuramoyl-L-alanine amidase is expected to release  
167 peptide moieties from peptidoglycan as observed previously (Bourgeois *et al.*, 2009), this suggests  
168 that Cse does not present such specificity. The insoluble material was further digested with  
169 mutanolysin and the digestion products were analyzed by RP-HPLC. Comparison of the  
170 muropeptide profile of the peptidoglycan double digest with the muropeptide profile obtained by  
171 mutanolysin digestion of *B. subtilis* peptidoglycan (Fig. 6A), revealed a large increase of monomers  
172 in parallel with a clear decrease of dimers and trimers in the CHAP-His<sub>6</sub>-tagged protein treated  
173 sample. Especially, the amount of the major dimers, peaks 2 and 3, decreased strikingly in  
174 *B. subtilis* peptidoglycan treated with the CHAP-His<sub>6</sub>-tagged protein whereas the amount of several  
175 monomers in peaks 1, 4 and 5, increased clearly (Fig. 6A). These results indicate that Cse CHAP-  
176 domain is able to cleave bonds inside insoluble native *B. subtilis* peptidoglycan. Cleavages occur  
177 most probably inside the peptide moieties since the decrease of dimers and trimers is accompanied  
178 with an increase of monomers suggesting that the Cse CHAP-domain has endopeptidase activity  
179 (Table 1, Fig. 6A).

180

181

182

183 **(iii) Determination of CHAP hydrolytic bond specificity on *S. thermophilus* peptidoglycan.**

184 We then characterized further the hydrolytic bond specificity of Cse CHAP-domain on  
185 muropeptides derived from *S. thermophilus* peptidoglycan by mutanolysin digestion. Peptidoglycan  
186 was digested by mutanolysin and the resulting digestion products were separated by RP-HPLC.  
187 Three muropeptides characterized by MALDI-TOF mass spectrometry (Table 1, peaks 8, 9, 10 and  
188 Fig. S3) and purified by RP-HPLC (Fig. S4) were digested with the CHAP-His<sub>6</sub>-tagged protein to  
189 determine its cleavage site on *S. thermophilus* peptidoglycan. The resulting digestion products were  
190 analyzed by RP-HPLC. In Fig. 6B, the peaks with the highest retention times [peak 8 in (a) ; peak 9  
191 in (b) and peak 10 in (c)] correspond to the intact muropeptides indicating partial digestion.  
192 However, the others peaks [peak 6 in (a); peaks 6 and 7 in (b) and peaks 6 to 9 in (c)] are consistent  
193 with being the CHAP-His<sub>6</sub>-tagged protein digestion products. According to the retention times of  
194 each peak and their masses determined by MALDI-TOF MS (Table 1), muropeptide structures were  
195 proposed (Fig. S3). These results indicate that the CHAP-His<sub>6</sub>-tagged protein cleaved the peptidic  
196 bond between the D-Ala residue of the stem peptide and the L-Ala residue of the cross-bridge of  
197 *S. thermophilus* peptidoglycan (Fig. 6B). Thus, Cse has D,L-endopeptidase activity on  
198 *S. thermophilus* peptidoglycan.

199

200

201 **DISCUSSION**

202           Within the *Firmicutes*, only a few CHAP proteins have been characterized that function as  
203 cell wall hydrolases. Among them are PcsB/GbpB from *Streptococcus* involved in cell division  
204 (Chia *et al.*, 2001; Mattos-Graner *et al.*, 2006; Ng *et al.*, 2004; Reinscheid *et al.*, 2001), Sle1 from  
205 *Staphylococcus aureus* (Kajimura *et al.*, 2005) and Cse from *S. thermophilus* that are necessary for  
206 daughter cell separation (Borges *et al.*, 2005). Acmb from *Lactococcus lactis* contributes to cellular  
207 autolysis (Huard *et al.*, 2003). Six other phage-encoded CHAP proteins are involved in bacterial  
208 cell lysis (Donovan *et al.*, 2006; Llull *et al.*, 2006; Navarre *et al.*, 1999; Nelson *et al.*, 2006;  
209 Pritchard *et al.*, 2004; Rashel *et al.*, 2008; Yokoi *et al.*, 2005). Besides the variety of their roles,  
210 these proteins differ by the cleavage specificity of their CHAP domains that present either an  
211 endopeptidase or an *N*-acetylmuramoyl-L-alanine amidase activity.

212           The CHAP domains of the  $\phi 11$ ,  $\phi 12$ , B30, LysWMY and Cse proteins (Donovan *et al.*,  
213 2006; Navarre *et al.*, 1999; Pritchard *et al.*, 2004; Sass and Bierbaum, 2007; Yokoi *et al.*, 2005) and  
214 potentially that of Acmb have an endopeptidase activity (Huard *et al.*, 2003). Alternatively, the  
215 CHAP domain of the Sle1 and Skl proteins were demonstrated to function as *N*-acetylmuramoyl-L-  
216 alanine amidase (Kajimura *et al.*, 2005; Llull *et al.*, 2006). This indicates that there is no correlation  
217 between the cleavage specificity of the CHAP proteins and their biological functions.

218           In a previous study, the C-terminal end of Cse, including the CHAP domain, was  
219 demonstrated to be homologous with that of PcsB/GbpB (Borges *et al.*, 2005). Many attempts were  
220 done to demonstrate the potential cell wall hydrolytic activity of these enzymes, but all failed  
221 (Borges *et al.*, 2005 ; Ng *et al.*, 2004; Reinscheid *et al.*, 2001). This time, by over expressing the  
222 CHAP domain of Cse and by searching for optimal experimental conditions, we succeeded to  
223 demonstrate its endopeptidase activity. By zymogram, Cse activity was only detected at pH 4 - 4.5.  
224 Such low pH could exist in the cell wall matrix if we consider that like *B. subtilis* (Calamita *et al.*,  
225 2001), the cell wall of *S. thermophilus* could be protonated during growth.

226

227 The process of daughter cell separation can be view as an active process that takes place at  
228 the end or after the completion of the cell division process. Indeed, cells lacking cell-separating  
229 enzymes are inhibited only in cell separation and are not inhibited in cell division, with normal  
230 septa still being formed (Ohnishi *et al.*, 1999). The cell separation process requires dedicate cell  
231 wall hydrolases that cleave the sacculi connecting daughter cells. In their vast majority, cell-  
232 separating enzymes are composed of a unique CHAP, NLPC/P60 or Glucosaminidase (more rarely  
233 Glyco\_hydro\_25) catalytic domain (Layec *et al.*, 2008b). The catalytic domain diversity is  
234 correlated with the diversity of the peptidoglycan linkage that they cleave. For instance, AcmA  
235 from *L. lactis* (Buist *et al.*, 1995; Steen *et al.*, 2005a) and LytB from *S. pneumoniae* (De Las Rivas  
236 *et al.*, 2002; Garcia *et al.*, 1999) carry a glucosaminidase domain conferring the *N*-  
237 acetylglucosaminidase activity. Ami A, B and C from *E. coli* and Sle1 from *S. aureus* are *N*-  
238 acetylmuramoyl-L-alanine amidases. Aml from *S. mutans*, carrying a “Glyco\_hydro\_25” domain,  
239 presents a *N*-acetylmuramidase activity (Yoshimura *et al.*, 2006). At last, several cell-separating  
240 enzymes display an endopeptidase activity. That is the case of Cse from *S. thermophilus* (this study)  
241 and of LytE, LytF and CwIS (YolJ) from *B. subtilis* (Fukushima *et al.*, 2006; Margot *et al.*, 1998;  
242 Margot *et al.*, 1999). Collectively, all these data clearly show that evolution has selected several  
243 alternative enzymes exhibiting distinct catalytic activity to perform the daughter cell separation  
244 process.

245 All the cell-separating enzymes described so far are cell surface proteins and Cse does not  
246 escape this rule. Cse is thought to bind peptidoglycan via its LysM domain. The LysM domain is  
247 one of the most common attachment modules in bacterial cell-separating enzymes. Thus, AcmA  
248 from *L. lactis*, AltA from *E. faecalis*, Sle1 from *S. aureus*, LytE, LytF and CwIS from *Bacillus*  
249 contain 2 to 6 tandem repeats of the LysM motif (Eckert *et al.*, 2006; Fukushima *et al.*, 2006;  
250 Ishikawa *et al.*, 1998; Kajimura *et al.*, 2005; Margot *et al.*, 1998; Margot *et al.*, 1999; Ohnishi *et al.*,  
251 1999; Steen *et al.*, 2003). In addition to its role in cell wall-binding, LysM is important for  
252 biological functioning (Buist *et al.*, 2008). The chaining phenotype of the *cseΔlysM* mutant

253 corroborated these results since LysM was found to be necessary for efficient Cse cell-separating  
254 activity.

255 The location of only a few cell-separating enzymes has been studied so far but reveals that all of  
256 them are positioned only at cell separation sites (Fukushima *et al.*, 2006; Kajimura *et al.*, 2005;  
257 Steen *et al.*, 2003) and questions about the reasons leading to such exclusive location.

258 In the case of Cse, one explanation is to consider that the restricted binding of the enzyme would be  
259 ensured by its LysM domain. Another possibility is to consider that a specific mechanism targets  
260 Cse to its site of action. Recently, Carlsson *et al.* (2006) (Carlsson *et al.*, 2006) demonstrated that the  
261 signal sequence of M protein promotes secretion at the division septum, whereas that of PrtF  
262 preferentially promotes secretion at the old pole. Thus, the possibility that the Cse signal peptide  
263 (and potentially its LysM domain) governs its secretion to mature septum is not excluded.

264 Within Cse protein, other regions were found to be important for the correct and specific  
265 location of the Cse protein. Indeed, depletion of the CHAP domain (Fig. 5D) or of the Var region  
266 (Fig. S1C) led to a modification of the Cse localization on *S. thermophilus* cell walls. Although we  
267 cannot exclude a direct role for these regions on cell wall attachment and/or substrate recognition, it  
268 is also possible that the Cse $\Delta$ var and Cse $\Delta$ CHAP recombinant proteins make inadequate  
269 conformations resulting in an altered localization.

270 At last, not only the structure protein but also the cell wall constituents and probably its  
271 architecture possibly interfere with protein attachment. Indeed, studies of AcmA led to the  
272 conclusion that the binding of this autolysin over the entire surface is hindered by lipoteichoic acid  
273 a cell wall compound associated with glycan molecules (Steen *et al.*, 2005b).

274

275 Data from this study indicate that Cse is not involved in cell wall synthesis but only takes  
276 part in the very late stage of (or after) the cellular division to catalyse the separation of daughter  
277 cells. It demonstrates that cell separation is an active process that requires the action of dedicated  
278 cell wall hydrolases.

279 **EXPERIMENTAL PROCEDURES**280 **Bacterial strains, plasmids, media and growth conditions.**

281 Bacterial strains and plasmids used in this study are listed in Table S1. *S. thermophilus* CNRZ368  
282 and its derivatives were cultivated in milk medium, M17 (Terzaghi and Sandine, 1975) or HJL  
283 (Stingele and Mollet, 1996). Milk medium was used for strain storage, M17 for mutant generation,  
284 and Hogg Jago Lactose (HJL) for phenotypic analysis. When required, erythromycin (final  
285 concentration 2  $\mu\text{g}\cdot\text{ml}^{-1}$ ) was added. *S. thermophilus* strains containing pGh9 (Maguin *et al.*, 1992)  
286 or pNST260<sup>+</sup> derivatives were cultivated at 30°C when plasmid self-maintenance was required and  
287 at 42°C for selection of clones with the chromosome's integrated plasmid. Phenotypic analyses  
288 were all performed at 42°C. *S. thermophilus* CNRZ368 $\Delta\text{cse}$  mutant was cultured in HJL at 42°C  
289 and was used (i) as a substrate in renaturing SDS-PAGE and (ii) to prepare cell-wall extracts for the  
290 zymography assays. *E. coli* strains were grown in Luria-bertani (LB) medium (Sambrook *et al.*,  
291 1989) at 37°C with shaking. When required erythromycin or ampicillin was added to a final  
292 concentration of 150  $\mu\text{g}/\text{ml}$ . *E. coli* EC101 (Leenhouts, 1995) was used as a host of recombinant  
293 plasmids derived from pGh9. *E. coli* strain DH5 $\alpha$  was used as a host of pET15b derivatives, and  
294 *E. coli* strain BL21(DE3) (Stratagene) was used as a host to overexpress the LysM<sub>Cse</sub> and CHAP  
295 fusion (His<sub>6</sub>-tagged) proteins. *B. subtilis* 168 HR was cultured in LB medium at 37°C and was used  
296 to prepare cell-wall extracts for the study of (i) lytic activity by zymogram and (ii) hydrolytic  
297 activity.

298

299 **DNA and RNA manipulations**

300 Plasmids and primers used in this study are listed in Table S1 and Table S2, respectively.

301

302 **(i) Construction of *S. thermophilus* CNRZ368  $\text{cse}\Delta\text{LysM}$  and  $\text{cse}\Delta\text{CHAP}$  mutant strains.**

303 The LysM and the CHAP modules of the *cse* gene were deleted by allelic replacement as previously  
304 described (Thibessard *et al.*, 2004). To make deletions, the two regions flanking the LysM or CHAP



305 domains were independently amplified by PCR using the following primers pairs:  
306 del\_lysME5'/del\_lysMI5' and del\_lysMI3'/del\_lysME3' or del\_CHAPE5'/del\_CHAPI5' and  
307 del\_CHAPI3'/del\_CHAPE3', respectively (Table S2). The PCR products were digested by  
308 appropriate restriction enzymes, joined together and ligated with the plasmid pGh9 (Maguin *et al.*,  
309 1992). The ligation products were used to transform *E. coli* EC101. After transformation of  
310 *S. thermophilus* with the recombinant plasmid, deleted mutants displaying an *EcoRI* restriction site  
311 replacing 459 pb of the LysM module or 318 bp of the CHAP module were selected. Deletion  
312 mutants were checked by PCR, Southern hybridization and sequencing (data not shown).

313

#### 314 **(ii) cse $\Delta$ LysM and cse $\Delta$ CHAP complementation.**

315 The complementation of cse $\Delta$ lysM or cse $\Delta$ CHAP mutants was carried out by inserting the  
316 pNST260+::cse plasmid in their chromosome as previously described (Borges *et al.*, 2005).

317

#### 318 **(iii) RNA extraction and RT-PCR experiments**

319 Total RNA was isolated from bacterial cultures according to the protocol described earlier (Kieser  
320 *et al.*, 2000). The quantity and quality of the RNA samples were verified by agarose gel  
321 electrophoresis and by measuring their absorbance at 260 and 280 nm. Isolated RNAs were stored  
322 at -80°C. Reverse transcription was performed according to the manufacturer's instructions  
323 (MMLV-reverse transcriptase, Fermentas). RNA samples isolated from *S. thermophilus* cultures  
324 were used for semi-quantitative RT-PCR analysis of the *cse* and *gyrA* transcript levels followed by  
325 separation of the PCR products on 1.5% gel agarose electrophoresis and quantitation using Quantity  
326 One software (Bio-Rad).

327

#### 328 **(iv) Construction of the pET15b::lysM<sub>cse</sub> and pET15b::chap plasmids for LysM<sub>Cse</sub>- and 329 CHAP-His<sub>6</sub>-tagged proteins overexpression.**

330 *S. thermophilus* CNRZ368 DNA fragments encoding (i) the 5' end of *cse* including the cell wall-  
331 binding LysM module (from 1 to 549 bp) and (ii) the catalytic CHAP module (from 1021 to



332 1383 bp) of *cse* were amplified by PCR. The amplified DNA fragments were purified, double  
333 digested with *Nde*I and *Bam*HI, repurified, and fused in-frame to the 3'end His<sub>6</sub>-tagged of pET15b  
334 (Novagen), generating the pET15b::lysM<sub>cse</sub> and pET15b::chap plasmids, respectively (Table S1).  
335 The in-frame fusion was confirmed by DNA sequencing.

336

### 337 **Overexpression, purification of His<sub>6</sub>-tagged proteins and western blotting.**

338 Expression of the His<sub>6</sub>-tagged proteins was induced in *E. coli* BL21(DE3) containing  
339 pET15::lysM<sub>Cse</sub> or pET15b::chap by adding IPTG (to 1 mM final concentration) at OD<sub>600</sub> = 0.5 for  
340 4h at 28°C. For extraction, cells were harvested by centrifugation and disrupted on ice with a  
341 microtip of Sonifier 250 (Branson Ultrasonics). The soluble fraction containing the recombinant  
342 protein was collected by centrifugation at 14,000 rpm for 30 min at 4°C. The His<sub>6</sub>-tagged proteins  
343 were purified by a HiTrap chelating HP column according to the manufacturer's instructions (5ml,  
344 Amersham Biosciences). The LysM<sub>Cse</sub>- and CHAP-His<sub>6</sub>-tagged proteins have a predicted molecular  
345 mass of 21.5 kDa and 15.1 kDa, respectively. The purity of the His<sub>6</sub>-tagged proteins was confirmed  
346 by SDS-15% [wt/vol] polyacrylamide gel electrophoresis (PAGE) and was estimated >96% by  
347 Quantity One software (Bio-Rad). The LysM<sub>Cse</sub>-His<sub>6</sub>-tagged protein was used for antibodies  
348 generation; the CHAP-His<sub>6</sub>-tagged protein was used to demonstrate Cse enzymatic properties.

349 For Western blotting, proteins were transferred onto PVDF membrane (Roche) using a semi-dry  
350 blotting system (Bio-Rad) following standard protocols (Towbin *et al.*, 1992). To control the  
351 presence of the His-tag on the fusion proteins, immunodetection assays were performed using rabbit  
352 IgG against RGS-His tag (Qiagen, at dilution 1:2000). The ECL Western blotting detection was  
353 done according to the manufacturer's instructions (Roche) and visualized by FluorS'max (Bio-Rad).

354

355

356

357

358 **Cse immunolocalization.**

359 **(i) Production of anti-LysM<sub>Cse</sub> antibodies.**

360 Polyclonal anti-LysM<sub>Cse</sub> were obtained from New Zealand White Rabbit inoculated with a mixture  
361 of 500 µg of purified LysM<sub>Cse</sub>-His<sub>6</sub>-tagged protein and Freund's complete adjuvant (Sigma-Aldrich)  
362 followed by booster two times with LysM<sub>Cse</sub>-His<sub>6</sub>-tagged protein and incomplete adjuvant every  
363 three weeks. The purified LysM<sub>Cse</sub>-His<sub>6</sub>-tagged protein was separated by SDS-15% [wt/vol]  
364 polyacrylamide gel, cut from the gel, fragmented and used for immunization. The specificity of the  
365 LysM<sub>Cse</sub> antibodies was verified on the purified LysM<sub>Cse</sub>-His<sub>6</sub>-tagged protein (at dilution 1:10,000)  
366 and *S. thermophilus* total proteins extract (at dilution 1:5000) by Western blotting analysis. In the  
367 soluble fraction of *S. thermophilus* CNRZ368 cells extract, one approximately 45.5 kDa band  
368 compatible with Cse molecular mass without its signal peptide (theoretical molecular mass with  
369 signal peptide, 48.5 kDa) was detected with polyclonal anti-LysM<sub>Cse</sub> antibodies (data not shown).  
370 No band was discovered in *S. thermophilus* CNRZ368Δcse mutant cells extract, used as a negative  
371 control (data not shown).

372

373 **(ii) Preparation of *S. thermophilus* samples for Cse immunolocalization.**

374 After overnight growth at 42°C in HJL medium, samples (2 ml) of *S. thermophilus* were pelleted  
375 by centrifugation (3,000 rpm for 20 min at 4°C) and washed two times with 2 ml phosphate  
376 buffered saline (81 mM NaCl, 1.62 mM KCl, 0.9 mM KH<sub>2</sub>PO<sub>4</sub>, 4.8 mM K<sub>2</sub>HPO<sub>4</sub> [pH 7.2]; PBS  
377 buffer). The cell pellets were resuspended in 2 ml PBS buffer and fixed by addition of 4% [vol/vol]  
378 final concentration paraformaldehyde and 0.2% [vol/vol] final concentration glutaraldehyde for 3 h  
379 of incubation on ice. Cells were harvested by centrifugation and washed four times in 2 ml PBS  
380 buffer containing 0.05 M glycine. Cells were resuspended in 1 ml PBS buffer. A sample of 100 µl  
381 was centrifugated and resuspended in 50 µl PBS buffer containing polyclonal anti-LysM<sub>Cse</sub> primary  
382 antibodies and incubated for 12 h at 4°C with gentle rolling. After washing, cells were resuspended  
383 in 50 µl of PBS buffer containing Alexa fluor 488-conjugated anti-rabbit IgG antibodies (1:400)

384 (Molecular-Probes) and observed by Fluorescence Microscopy. For Transmission Electron  
385 Microscopy (TEM), cells were resuspended in 50  $\mu$ l of PBS buffer containing anti-rabbit IgG  
386 conjugated with 10 nm colloidal gold secondary antibodies (1:50) (Sigma-Aldrich). The  
387 fluorochrome calcofluor (Sigma-Aldrich) was used on *S. thermophilus* cells with a 0.01% [wt/vol]  
388 solution to reveal peptidoglycan.

389

### 390 **(iii) Microscopy.**

391 Immunofluorescence microscopy was performed with a Bio-Rad LRC Radiance 2100 (Elexience,  
392 Paris, France) confocal laser scanning microscope (CLSM), attached to Nikon TE2000-U inverted  
393 microscope, using an excitation at 488 nm from 100 mW argon ion laser and appropriate barrier  
394 filters. Cells were observed through x60 Nikon immersion oil plan apo (NA 1.40). Images were  
395 contrast enhanced in Adobe Photoshop (Adobe Systems Inc., Mountain View, USA). A sample of  
396 the bacterial cell suspension was deposited onto formvar carbon-coated copper nickel grids. Cells  
397 were examined with a Zeiss 902A transmission electron microscope at 80kV (magnification  
398 x 20,000 or x 30,000). *S. thermophilus* chaining phenotypes were observed with a Nikon  
399 OPTIPHOT microscope mounted with phase-contrast equipment "Ph". Cells were photographed  
400 with a Nikon coolpix 5400 digital camera.

401

### 402 **Cell wall hydrolase activity.**

#### 403 **(i) SDS-PAGE and zymography.**

404 Sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) were carried out as  
405 previously described with a protean II minigel system (Bio-Rad). Zymograms were performed with  
406 15% [wt/vol] polyacrylamide separating gels containing either lyophilized or autoclaved cells (from  
407 *M. lysodeikticus* ATCC4698 (Sigma, 0.2% [wt/vol]) or from *S. thermophilus* CNRZ368 $\Delta$ ce mutant  
408 (0.4% [wt/vol]) or purified peptidoglycan 0.08% [wt/vol] (from *S. thermophilus* CNRZ368 $\Delta$ ce  
409 mutant or *B. subtilis*). Peptidoglycan from *S. thermophilus* and *B. subtilis* 168 HR vegetative cells  
410 were prepared as described previously (Courtin *et al.*, 2006; Meyrand *et al.*, 2007).

411 After electrophoresis, gels were washed two times for 30 min. in 3% [vol/vol] Triton X-100 and  
412 then incubated in renaturation buffer overnight at 30°C. Proteins renaturation was performed with:  
413 25 mM sodium citrate/ 50 mM sodium phosphate (Huard *et al.*, 2003) or 50 mM KH<sub>2</sub>PO<sub>4</sub> buffer  
414 containing 0.2% [vol/vol] Triton X-100 at pH 3 to 7. The gels were stained with 0.1% [wt/vol]  
415 methylene blue in 0.01% [wt/vol] KOH for 4 h at room temperature and destained in deionized  
416 H<sub>2</sub>O. Gel images were generated with GS-800 Calibrated Densitometer Scanner (Bio-Rad).

417

418 **(ii) Determination of CHAP cell wall hydrolytic specificity.**

419 Peptidoglycan from *B. subtilis* 168 HR and *S. thermophilus* was extracted as described previously  
420 (Meyrand *et al.*, 2007). *B. subtilis* peptidoglycan (4 mg) was incubated overnight at 30°C with  
421 purified CHAP-His<sub>6</sub>-tagged protein (500 µg) in a final volume of 500 µl buffer (25 mM sodium  
422 citrate/ 50 mM sodium phosphate containing 0.2% Triton X-100 at pH 4.0). The sample was boiled  
423 for 3 min to stop the reaction and then centrifuged at 14,000 g for 15 min. The insoluble material as  
424 well as half of the soluble fraction, both recovered after incubation with CHAP-His<sub>6</sub>-tagged protein,  
425 were further treated with mutanolysin (2,500 U.ml<sup>-1</sup>) overnight at 37°C. A control digest of  
426 *B. subtilis* peptidoglycan was obtained by mutanolysin digestion as described (Courtin *et al.*, 2006).  
427 The soluble muropeptides obtained after the digestions were reduced with sodium borohydride and  
428 separated by reverse phase HPLC using a Hypersil ODS column (C18, 250 x 4.6 mm; 5 µm;  
429 ThermoHypersil-Keystone) at 50°C using ammonium phosphate buffer and a methanol linear  
430 gradient as described previously (Atrih *et al.*, 1999; Courtin *et al.*, 2006). Peaks were analysed  
431 without desalting by matrix-assisted laser desorption ionization time-of-flight (MALDI-TOF) mass  
432 spectrometry with a Voyager DE STR mass spectrometer (Applied Biosystems) as described  
433 previously (Courtin *et al.*, 2006).

434 *S. thermophilus* peptidoglycan was digested with mutanolysin overnight at 37°C and the  
435 resulting soluble muropeptides were reduced and separated by RP-HPLC as described previously  
436 (Hebert *et al.*, 2007). Three muropeptides were collected, dried in a Speed-vac concentrator under  
437 vacuum. The purified muropeptides were incubated with 50 µg of purified CHAP-His<sub>6</sub>-tagged

438 protein in a total volume of 200  $\mu$ l in the conditions described above for *B. subtilis* peptidoglycan.  
439 The reaction products were then analyzed by RP-HPLC and MALDI-TOF mass spectrometry as  
440 described above.  
441

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598 Acetylmuraminidase, Aml, involved in *Streptococcus mutans* cell separation. *Microbiol*  
599 *Immunol* **50**: 729-742.
- 600
- 601

602 **LEGEND FIGURES**

603

604 **FIG. 1. RT-PCR detection of *cse* transcripts.**

605 **A.** *cse* modular structure. The positions in nucleotides delimit the signal peptide (SP), the LysM cell  
606 wall-binding module, the central variable region (Var) and the catalytic CHAP module of  
607 *S. thermophilus* CNRZ368 *cse* gene. Arrows and hairpin loops symbolize putative promoters and  
608 putative rho-independent transcriptional terminators, respectively. **B.** Semi-quantitative RT-PCR  
609 assays were carried out to compare the level of expression of the different *cse* alleles (*cse*,  $\Delta cse$ ,  
610 *cse* $\Delta lysM$ , *cse* $\Delta var$  and *cse* $\Delta chap$ ). Semi-quantitative RT-PCR reactions were performed with *cse*  
611 locus specific primers (surlysM5' and Del\_lysMI5') referred in Table S2, yielding a product of  
612 110 bp in size. The internal housekeeping gene *gyrA* served as a reference point to detect relative  
613 difference in the integrity of individual RNA samples and was amplified using the *gyrA*5' and  
614 *gyrA*3' primers (Table S2), which yielded a product of 140 bp in size. As a negative control, all  
615 DNase RNA samples were subjected to PCR prior to RT analysis [- RT (*gyrA*)]. T(-), also  
616 corresponds to a negative control, using water as a PCR matrix. As positive control [T(+)], DNA  
617 samples extracted from the culture of each strains were subjected to PCR. For semi-quantitative  
618 analysis, the density ratios of the *cse* mutant allele versus the *cse* wild-type were calculated and  
619 used as an indication for the relative expression (*cse* = 100%;  $\Delta cse$  = 0%; *cse* $\Delta lysM$  = 99.3+/- 2.9%;  
620 *cse* $\Delta var$  = 94.7+/- 6.2% and *cse* $\Delta chap$  = 97.2+/- 8.2%).

621

622 **FIG. 2. Mutation of *cse* alters *S. thermophilus* cell separation.**

623 **A.** Picture of standing HJL cultures and phase contrast microscopy of the strains. Photographs were  
624 taken after 20 h of growth at 42°C in HJL medium. Magnification, x1,000. **B.** Chain length  
625 analysis. Cells were counted in stationary phase after 20 h of growth at 42°C in HJL medium. The  
626 error bars represent standard deviations of three independent experiments. The chain length analysis  
627 of the *cse* $\Delta Var$  mutant was reported in the following reference (Borges *et al.*, 2006).

628 **FIG. 3. *S. thermophilus* chaining phenotype observed by transmission electron microscopy**  
629 **(TEM).**

630 The  $\Delta cse$  mutant chaining phenotype is shown in panels A to C, that of the wild-type in D to F.  
631 Cells were visualized after 20 h of growth at 42°C in HJL medium. Arrowheads in panels C and F  
632 pointed distinct septa. Diplococcal dividing cells are characterized by the in-growth of the septum  
633 (nascent septum, a) initiated by the constriction ring located equidistant from the cell poles. The  
634 progression of the septal peptidoglycan synthesis is materialized by the further constriction of the  
635 cell walls (intermediate septum, b). At the end of the division process, diplococcal cells are held  
636 together by a thin peptidoglycan filamentous corresponding to an extension of the septum (mature  
637 septum, c). Bars = 0.5  $\mu\text{m}$ .

638  
639 **FIG. 4. Immunolocalization of Cse on *S. thermophilus* cell surface.**

640 The TEM pictures of the wild-type strain are shown in A to D and that of the  $\Delta cse$  mutant in E and  
641 F. Cells were successively probed with anti-LysM<sub>Cse</sub> rabbit polyclonal antibodies (A, B, C, E and F)  
642 or with preimmun serum (D) and with anti-rabbit IgG conjugated with 10 nm colloidal gold  
643 secondary antibody. The localization of Cse protein is indicated by the arrowheads pointed on gold-  
644 conjugates secondary antibodies (A to C). No labelling was observed on the negative controls (D to  
645 F). Bars = 0.1  $\mu\text{m}$ .

646  
647 **FIG. 5. Cse localizes on *S. thermophilus* CNRZ368 mature septa.**

648 CNRZ368 wild-type (A, B and E),  $cse\Delta\text{LysM}$  (C) and  $cse\Delta\text{CHAP}$  (D) cells are shown. Surface  
649 bound Cse and derivatives proteins were detected by immunofluorescence microscopy using anti-  
650 LysM<sub>Cse</sub> antibodies. Phase-contrast images (A1 to E1) and fluorescence images (A2 to B2 and E2 to  
651 E4) of the bacterial cells in the same field are shown. The arrowheads pointed mature septa. No  
652 fluorescence staining on the wild-type cell surface was observed using the preimmun serum (B2), as

653 well as on the *cse* $\Delta$ LysM mutant cells with the anti-LysM<sub>Cse</sub> antibodies (C2), as negative controls,  
654 (Bars = 25  $\mu$ m).

655 E2 shows a single-labeled with anti-LysM<sub>Cse</sub> antibodies that indicates the localization of Cse  
656 exclusively on mature septa (Bars = 5  $\mu$ m). E3 shows the fluorochrome calcofluor having an  
657 affinity for peptidoglycan. E4 is the result double-labelled.

658

659 **FIG. 6. Cse functions as an endopeptidase.**

660 **A.** RP-HPLC analysis of the muropeptides released from *B. subtilis* cell wall after incubation with  
661 mutanolysin (a) or the CHAP-His<sub>6</sub>-tagged protein and mutanolysin (b). **B.** RP-HPLC analysis of  
662 three different purified muropeptides from *S. thermophilus* (Table 1, Fig. S4) after digestion with  
663 the CHAP-His<sub>6</sub>-tagged protein. The numbers indicate the peaks analyzed by MALDI-TOF MS. The  
664 molecular ions *m/z* values are indicated in Table 1. The CHAP domain activity is visible as a clear  
665 hydrolysis band observed on a renaturing SDS-PAGE with 8  $\mu$ g of CHAP-His<sub>6</sub>-tagged protein in  
666 gel containing 0.08% [wt/vol] *B. subtilis* HR168 or *S. thermophilus* CNRZ368 $\Delta$ cse cell-wall as  
667 substrate.

668 The percentage of monomers corresponds to the sum of the area of the peaks corresponding to  
669 monomers over the sum of the areas of all peaks. The same was done for dimers and trimers. The  
670 percentage of each peak was calculated as the ratio of the peak area over the sum of areas of all the  
671 peaks identified by RP-HPLC.

672 Schematic structure of *S. thermophilus* cell-wall is illustrated. Arrow indicates the cleavage site of  
673 the CHAP-His<sub>6</sub>-tagged protein. GlcNAc, *N*-acetylglucosamine; MurNAc, *N*-acetylmuramic acid.

674

675 **FIG. S1. Immunolocalization of Cse protein derivatives on the cell surface of *S. thermophilus*.**

676 *S. thermophilus* CNRZ368 cells of the  $\Delta$ cse (A), the *cse* $\Delta$ CHAP (B) and the *cse* $\Delta$ Var (C and D)  
677 mutants are shown. Cells were visualized with a laser scanning confocal microscope. Phase-contrast  
678 images (A1 to D1) and fluorescence images (A2 to D2) of the bacterial cells are shown in the same



679 field. No fluorescence was detected on negative controls:  $\Delta$ cse cells with anti-LysM<sub>Cse</sub> antibodies  
680 (A2); from cse $\Delta$ CHAP to cse $\Delta$ var cells with preimmun serum (B2 and D2). C2 indicates the  
681 localization of Cse derivative protein using the LysM<sub>Cse</sub> antibodies. (Bars = 25  $\mu$ m)

682

683 **FIG. S2. Overexpression, purification, western-blotting and lytic activity of the CHAP-His<sub>6</sub>-**  
684 **tagged protein.**

685 SDS-15% polyacrylamide gel with Coomassie brilliant blue staining, Western blot obtained using  
686 RGS-His-tag antibodies raised against CHAP-His<sub>6</sub>-tagged protein and Cell wall hydrolytic activity  
687 of the CHAP-His<sub>6</sub>-tagged protein in renaturing SDS-15% polyacrylamide gel containing 0.08%  
688 [wt/vol] *B. subtilis* 168 HR or *S. thermophilus* CNRZ368 $\Delta$ cse peptidoglycan as substrate.  
689 Renaturing buffer contains 0.2% TritonX-100. The CHAP-His<sub>6</sub>-tagged protein activity is visible as  
690 cleaning zones in the gel (lanes 3, 4 and 5). Lanes 1 and 2, cell extract and supernatant of *E. coli*  
691 BL21(DE3) containing pET15b. Lanes 3 and 4, cell extract and supernatant of *E. coli* BL21(DE3)  
692 containing pET15b::chap. Lane 5, purified CHAP-His<sub>6</sub>-tagged protein. Lane MM, the molecular  
693 masses of standard proteins. The arrow indicates the position of purified CHAP-His<sub>6</sub>-tagged  
694 protein.

695

696 **FIG. S3. Schematic structure of the muropeptides from *S. thermophilus* obtained after**  
697 **mutanolysin digestion or after CHAP-His<sub>6</sub>-tagged protein and mutanolysin digestion.**

698 Numbers peaks on the chromatograms presented in Fig. 6 and Table 1.

699

700 **FIG. S4. Purity of *Streptococcus thermophilus* muropeptides.**

701 Chromatogram of the three muropeptides from *S. thermophilus* peptidoglycan before CHAP-His<sub>6</sub>-  
702 protein digestion. The molecular ions *m/z* values of peaks 8, 9 and 10 are indicated in Table 1 and  
703 their structures are illustrated in Fig. S3.

704

705



706

707 **Table S1.** Bacterial strains and plasmids used in this study.

| Strain or plasmid                     | Genotype/phenotype/ source   | Origin/reference   |
|---------------------------------------|--|--|
| <b><i>S. thermophilus</i> strains</b> |  |  |
| CNRZ368                               | Wild-type; isolated from yogurt.   | INRA-CNRZ, strain collection, France                       |
| CNRZ368Δcse                           | Derivative of CNRZ368 carrying a 1359 bp deletion in the <i>cse</i> gene   | (Borges <i>et al.</i> , 2005)                              |
| CNRZ368cseΔLysM                       | Derivative of CNRZ368 carrying a 459 bp deletion in the <i>cse</i> LysM Module   | This study   |
| CNRZ368cseΔVar                        | Derivative of CNRZ368 carrying a 345 bp deletion in the var- <i>cse</i> Region   | (Borges <i>et al.</i> , 2005)                              |
| CNRZ368cseΔCHAP                       | Derivative of CNRZ368 carrying a 318 bp deletion in the <i>cse</i> CHAP Module   | This study   |
| <b><i>E. coli</i> strains</b>         |  |  |
| EC101                                 | <i>supE hsd-5 thi Δ(lac-proAB) F'(traD6 proAB<sup>+</sup> lacI<sup>q</sup> lacZΔM15) repA<sup>+</sup></i> , derivative of TG1 strain (Sambrook <i>et al.</i> , 1989) | (Leenhouts, 1995; Sambrook <i>et al.</i> , 1989)           |
| DH5α                                  | F <sup>-</sup> , <i>endA1, gyrA96, thi-1, hsdR17(r<sub>K</sub><sup>-</sup>,m<sub>K</sub><sup>+</sup>), supE44, rel A1, M15, Δ(lacZYA-argF),U169</i>                  | (Sambrook <i>et al.</i> , 1989)                            |
| BL21(DE3)                             | <i>E. coli</i> B, F <sup>-</sup> , <i>dcm, ompT, hsdS(r<sub>B</sub><sup>-</sup>m<sub>B</sub><sup>-</sup>), galλ(DE3)</i>   | Stratagene   |
| <b><i>B. subtilis</i></b>             |  |  |
| 168 HR                                | <i>trpC2</i>   | (Kunst <i>et al.</i> , 1997)                               |
| <b>Plasmids</b>                       |  |  |
| pGh9                                  | Thermosensitive plasmid, used for gene replacement; Ery <sup>R</sup>   | (Biswas <i>et al.</i> , 1993; Maguin <i>et al.</i> , 1992) |
| pGh9 ::cseΔlysM                       | Derivative of pGh9 carrying a 1098 bp for LysM deletion  | This study   |
| pGh9 ::cseΔCHAP                       | Derivative of pGh9 carrying a 924 bp for CHAP deletion   | This study   |
| pNST260+                              | Derivative of pGh9 carrying a <i>int</i> gene coding a integrase and an <i>attI</i> from ICESr1, specific-site of recombinaison                                      | G. Guédon, personal communication                          |
| pNST260+ ::cse                        | pNST260+ with CNRZ368 <i>cse</i> gene, its putative promoter and terminator  | (Borges <i>et al.</i> , 2005)                              |
| pET15b                                | Expression vector for N-terminal His <sub>6</sub> -tagged fusion; Amp <sup>R</sup>   | Novagen  |
| pET15b :: lysM <sub>cse</sub>         | Derivative of pET15b carrying a 549 bp insert coding a LysM <sub>Cse</sub> His <sub>6</sub> -tagged protein  | This study   |
| pET15b :: chap                        | Derivative of pET15b carrying a 369 bp insert coding a CHAP His <sub>6</sub> -tagged protein   | This study   |

708

709

710 **Table S2.** Primers used in this study.

| Name  | Sequence (5' to 3') <sup>a</sup>                           | Restriction sites |
|---|--|-------------------|
| <b>Construction of <i>S. thermophilus</i> cseΔlysM mutant</b> |  |                   |
| Del_lysME5'   | CCC CCC CCA <b>AGC TTA</b> CAA GAT CAG TTT GGA AC          | <i>HindIII</i>    |
| Del_lysMI5'   | CCC CCC <b>GAA TTC</b> ACG TGC TGT CCA GTG A               | <i>EcoRI</i>      |
| Del_lysMI3'   | CCG <b>GAA TTC</b> GAT GCT ATT GAT CAT GTT AC              | <i>EcoRI</i>      |
| Del_lysME3'   | CCC <b>CCT GCA G</b> TGC GAT ATG TAT TAG GAG TT            | <i>PstI</i>       |
| <b>Construction of <i>S. thermophilus</i> cseΔchap mutant</b> |  |                   |
| Del_CHAPE5'   | CCC CCA <b>AGC TTG</b> ATG CTA TTG ATG CTA TTG ATC ATG TTA | <i>HindIII</i>    |
| Del_CHAPI5'   | CCG <b>GAA TTC</b> AGT TGA TGC ATA TTC GTA T               | <i>EcoRI</i>      |
| Del_CHAPI3'   | CCC CCC <b>GAA TTC</b> ATT TAT CCA TAA TGA GTA CA          | <i>EcoRI</i>      |
| Del_CHAPE3'   | CCC CCC <b>CTG CAG</b> CCT GTG GTT GAA G                   | <i>PstI</i>       |
| <b>Construction of pET15b::lysM<sub>cse</sub></b>             |  |                   |
| surlysM5'   | CCC CCC CCA <b>TAT G</b> TT ATC AAA ATC TAA AAC            | <i>NdeI</i>       |
| surlysM3'   | CCC <b>CGG ATC C</b> TT AAG CTG GAG TAT CTG ATG C          | <i>BamHI</i>      |
| <b>Construction of pET15b::chap</b>                           |  |                   |
| surchap5'   | CCC CCC CCA <b>TAT G</b> CT AGC AGC TAC ATA CGA ATA        | <i>NdeI</i>       |
| surchap3'   | CCC <b>CGG ATC C</b> TT ATG GAT AAA TAT AAT ATA CAG AA     | <i>BamHI</i>      |
| <b>gyrA gene expression</b>                                   |  |                   |
| gyrA5'  | GATGCCGTTAAATTGATGAT                                       | /                 |
| gyrA3'  | GAGCCTTTACCAGTTTCGTA                                       | /                 |

711

712 <sup>a</sup>Restriction sites are in boldface and underlined.

713 **Table 1:** Observed  $m/z$  values for sodiated molecular ions of muropeptides obtained after hydrolysis  
 714 of *B. subtilis* and *S. thermophilus* peptidoglycan.

715

| Peak<br><sup>a</sup>                     | [M+Na] <sup>+</sup><br>observed | Muropeptide identification <sup>b</sup>  |
|--|---------------------------------|--|
| <b><i>Bacillus subtilis</i></b>          |                                 |  |
| 1  | 852.3                           | DS-Tri (NH <sub>2</sub> )  |
| 2  | 1815.7                          | DS-Tri-DS-Tetra (NH <sub>2</sub> )   |
| 3  | 1814.7                          | DS-Tri (NH <sub>2</sub> )-DS-Tetra (NH <sub>2</sub> )  |
| 4  | 964.4                           | DS-Tetra   |
| 5  | 963.4                           | DS-Tetra (NH <sub>2</sub> )  |
| <b><i>Streptococcus thermophilus</i></b> |                                 |  |
| 6  | 1061.3                          | DS-Tetra –Ala Ala (NH <sub>2</sub> )   |
| 7  | 1132.4                          | DS- Penta – Ala Ala (NH <sub>2</sub> )   |
| 8  | 2081.9                          | DS- Tetra (NH <sub>2</sub> ) – Ala Ala – DS Tetra (NH <sub>2</sub> )– Ala Ala  |
| 9  | 2153.0                          | DS- Penta (NH <sub>2</sub> ) – Ala Ala – DS Tetra (NH <sub>2</sub> ) – Ala Ala   |
| 10                                       | 3173.3                          | DS- Penta (NH <sub>2</sub> ) – Ala Ala – DS Tetra (NH <sub>2</sub> ) – Ala Ala – DS Tetra (NH <sub>2</sub> ) – Ala Ala |

716

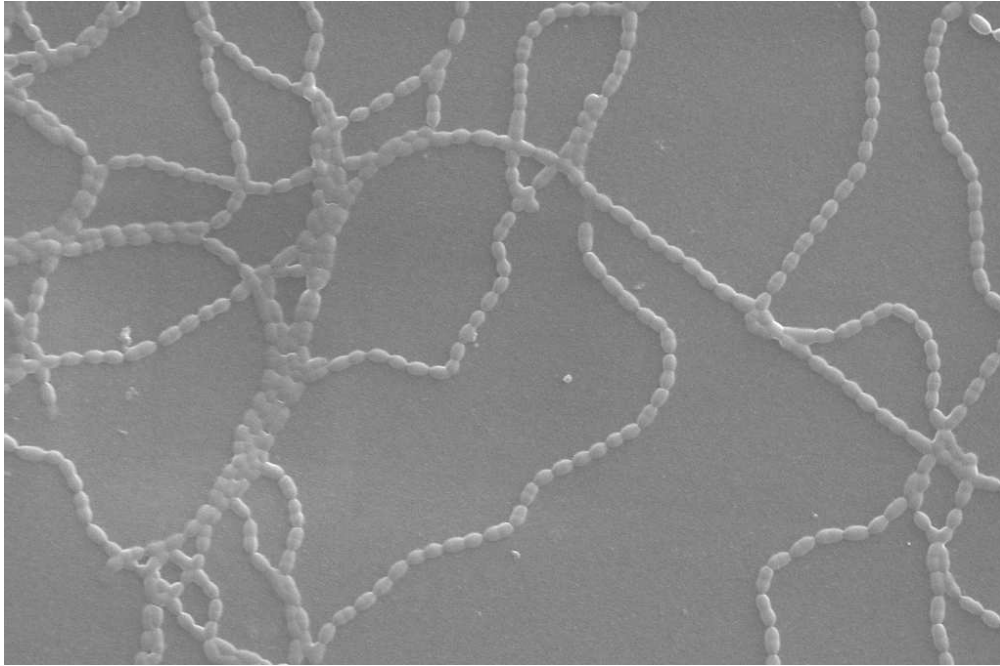
717 <sup>a</sup> Peak numbers refer to the peaks on the chromatograms presented in Fig. 6, which were analyzed  
 718 by mass spectrometry.

719 <sup>b</sup> DS, disaccharide GlcNAc-MurNAc (GlcNAc, *N*-acetylglucosamine; MurNAc, *N*-acetylmuramic  
 720 acid). Tri, tripeptide (L-Ala-D- $\gamma$ Glu-mDAP) from *B. subtilis*; Tetra, tetrapeptide (L-Ala-D- $\gamma$ Glu-  
 721 mDAP-D-Ala) from *B. subtilis* and (L-Ala-D- $\gamma$ Glu-L-Lys-D-Ala) from *S. thermophilus*; Penta,  
 722 pentapeptide (L-Ala-D- $\gamma$ Glu-L-Lys-D-Ala-D-Ala) from *S. thermophilus*.

723 NH<sub>2</sub> indicates the presence of an amidation on the peptide chain on mDAP from *B. subtilis*  
 724 according to (Atrih *et al.*, 1999) and most probably on D- $\gamma$ -Glu from *S. thermophilus*.

725

726



Scanning electron photograph of *Streptococcus thermophilus* csedeltaLysM mutant. The long chain phenotype indicates that the binding of Cse at cell surface is required for efficient cell separation.

Magnification, x 4,780

26009x17272mm (1 x 1 DPI)

Review

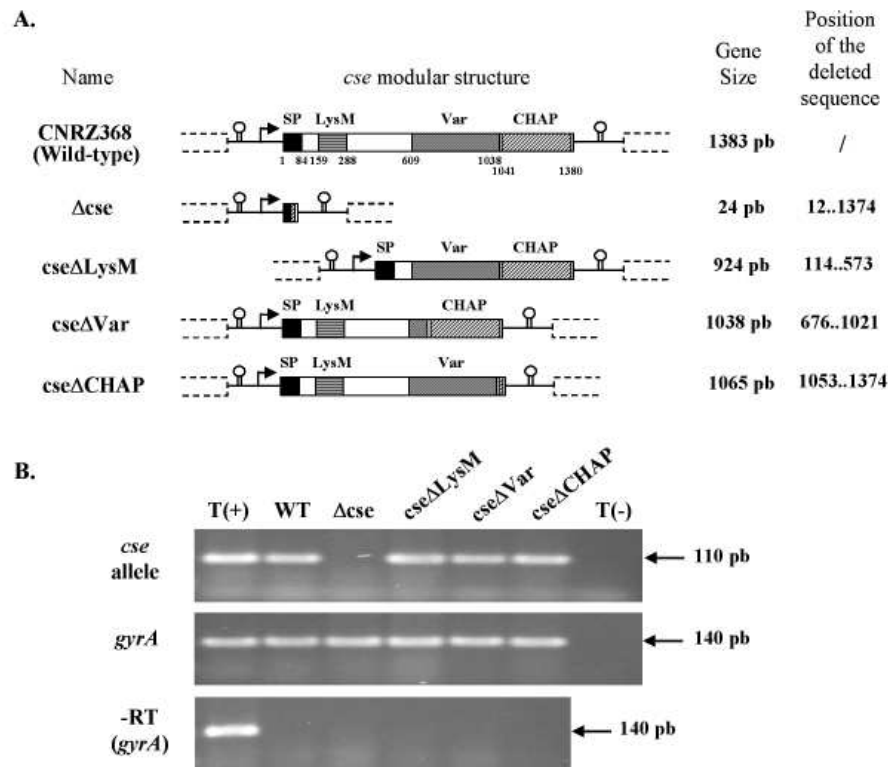
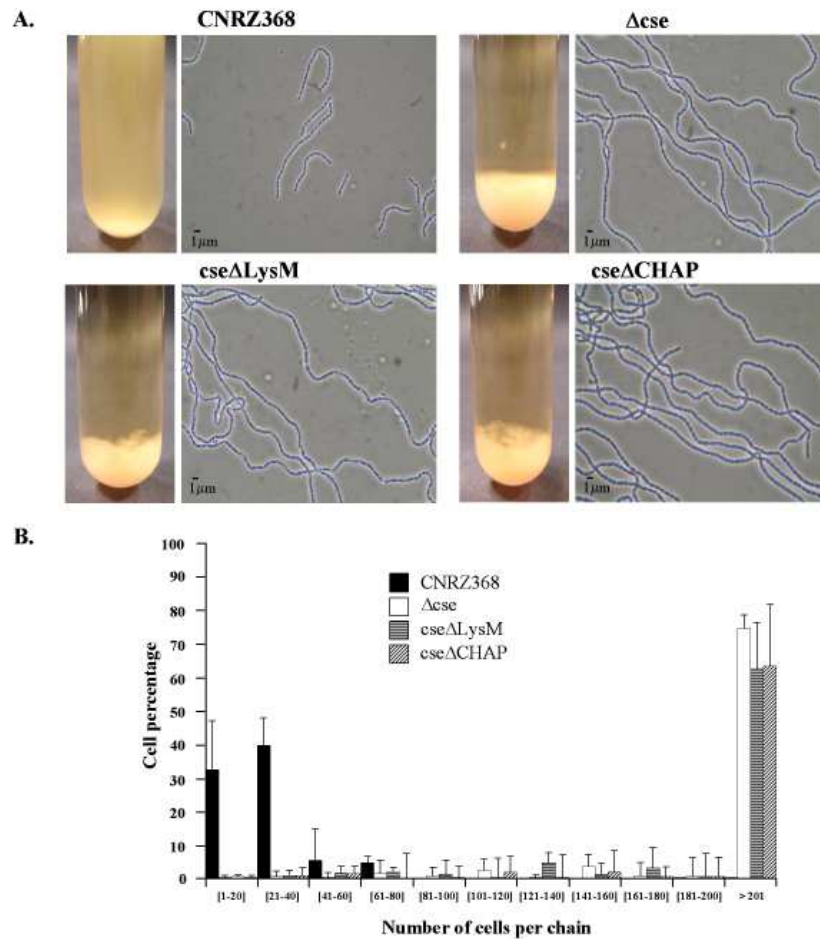


Fig. 1

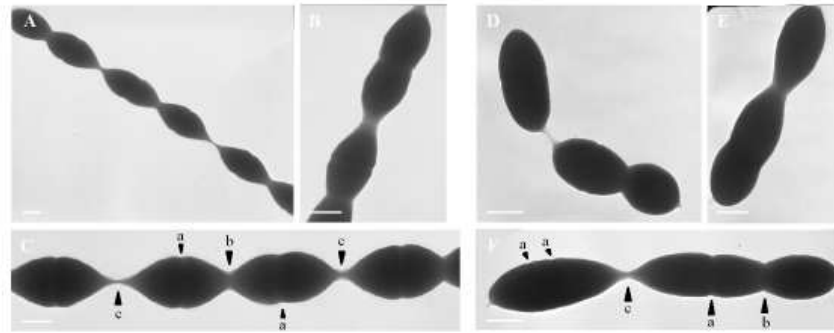
FIG. 1. RT-PCR detection of *cse* transcripts. A. *cse* modular structure. The positions in nucleotides delimit the signal peptide (SP), the LysM cell wall-binding module, the central variable region (Var) and the catalytic CHAP module of *S. thermophilus* CNRZ368 *cse* gene. Arrows and hairpin loops symbolize putative promoters and putative rho-independent transcriptional terminators, respectively. B. Semi-quantitative RT-PCR assays were carried out to compare the level of expression of the different *cse* alleles (*cse*,  $\Delta cse$ , *cse* $\Delta$ LysM, *cse* $\Delta$ Var and *cse* $\Delta$ Chap). Semi-quantitative RT-PCR reactions were performed with *cse* locus specific primers (surlyM5' and Del\_lysmI5') referred in Table S2, yielding a product of 110 bp in size. The internal housekeeping gene *gyrA* served as a reference point to detect relative difference in the integrity of individual RNA samples and was amplified using the *gyrA*5' and *gyrA*3' primers (Table S2), which yielded a product of 140 bp in size. As a negative control, all DNase RNA samples were subjected to PCR prior to RT analysis [- RT (*gyrA*)]. T(-), also corresponds to a negative control, using water as a PCR matrix. As positive control [T(+)], DNA samples extracted from the culture of each strains were subjected to PCR. For semi-quantitative analysis, the density ratios of the *cse* mutant allele versus the *cse* wild-type were calculated and used as an indication for the relative expression (*cse* =100%  $\Delta cse$  = 0%; *cse* $\Delta$ LysM = 99.3 $\pm$  2.9%; *cse* $\Delta$ Var = 94.7 $\pm$  6.2% and *cse* $\Delta$ Chap = 97.2 $\pm$  8.2%).

178x171mm (96 x 96 DPI)



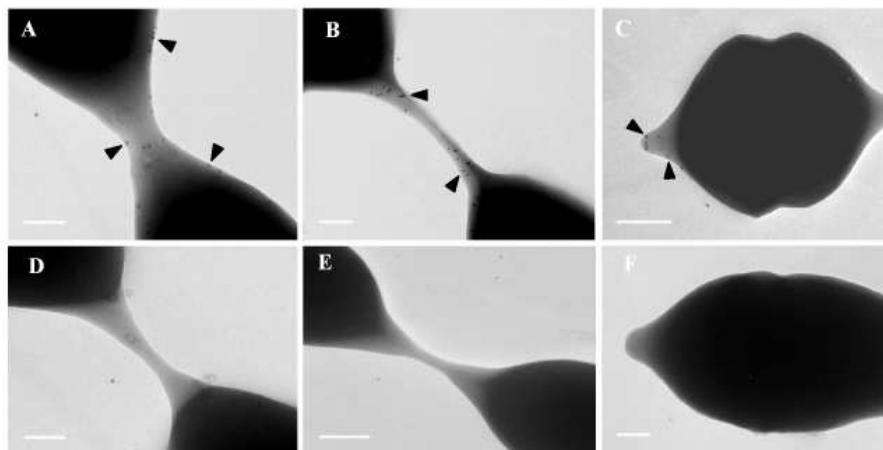
**Fig. 2**

FIG. 2. Mutation of *cse* alters *S. thermophilus* cell separation. A. Picture of standing HJL cultures and phase contrast microscopy of the strains. Photographs were taken after 20 h of growth at 42°C in HJL medium. Magnification, x1,000. B. Chain length analysis. Cells were counted in stationary phase after 20 h of growth at 42°C in HJL medium. The error bars represent standard deviations of three independent experiments. The chain length analysis of the *cse*Δ*Var* mutant was reported in the following reference (Borges et al., 2006).  
184x193mm (96 x 96 DPI)



**Fig. 3**

FIG. 3. *S. thermophilus* chaining phenotype observed by transmission electron microscopy (TEM). The deltase mutant chaining phenotype is shown in panels A to C, that of the wild-type in D to F. Cells were visualized after 20 h of growth at 42°C in HJL medium. Arrowheads in panels C and F pointed distinct septa. Diplococcal dividing cells are characterized by the in-growth of the septum (nascent septum, a) initiated by the constriction ring located equidistant from the cell poles. The progression of the septal peptidoglycan synthesis is materialized by the further constriction of the cell walls (intermediate septum, b). At the end of the division process, diplococcal cells are held together by a thin peptidoglycan filamentous corresponding to an extension of the septum (mature septum, c). Bars = 0.5  $\mu$ m.  
175x101mm (96 x 96 DPI)



**Fig. 4**

FIG. 4. Immunolocalization of Cse on *S. thermophilus* cell surface. The TEM pictures of the wild-type strain are shown in A to D and that of the deltacse mutant in E and F. Cells were successively probed with anti-LysMCse rabbit polyclonal antibodies (A, B, C, E and F) or with preimmun serum (D) and with anti-rabbit IgG conjugated with 10 nm colloidal gold secondary antibody. The localization of Cse protein is indicated by the arrowheads pointed on gold-conjugates secondary antibodies (A to C). No labelling was observed on the negative controls (D to F). Bars = 0.1  $\mu$ m.  
189x127mm (96 x 96 DPI)



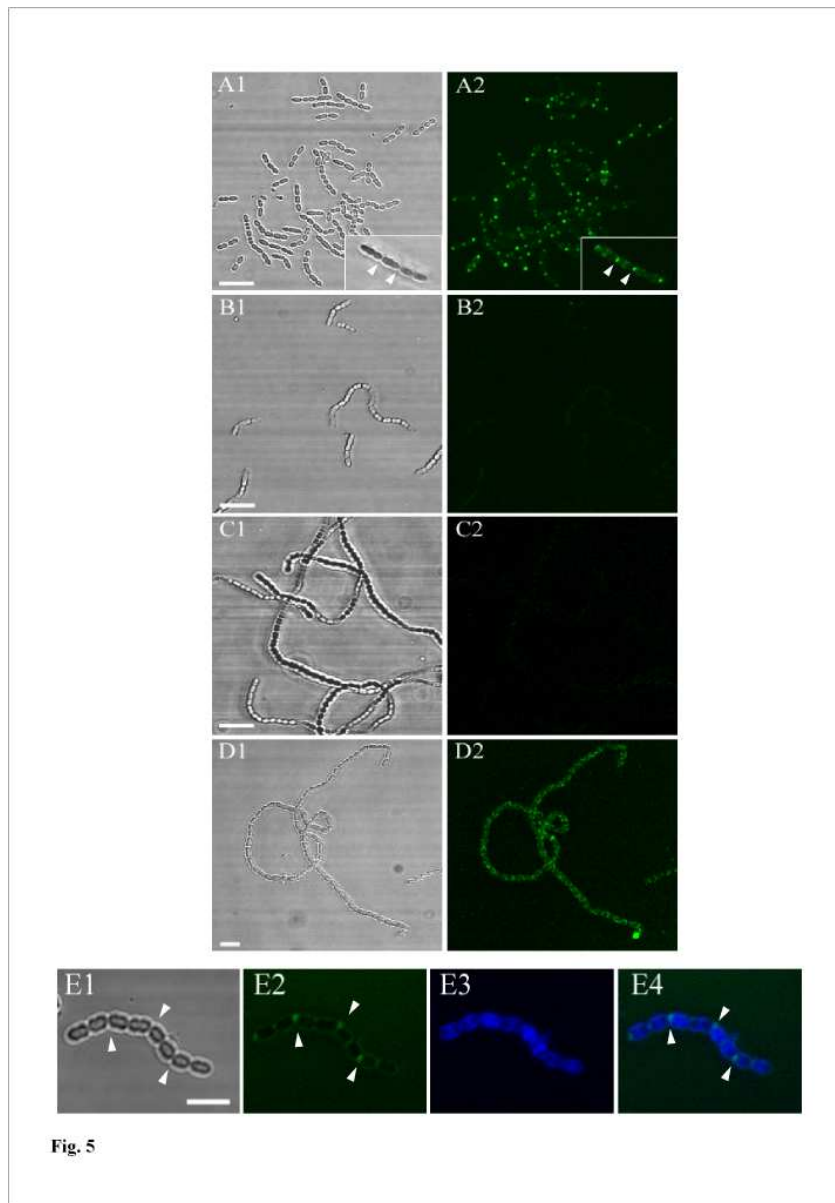


FIG. 5. Cse localizes on *S. thermophilus* CNRZ368 mature septa. CNRZ368 wild-type (A, B and E), *csedeltaLysM* (C) and *csedeltaCHAP* (D) cells are shown. Surface bound Cse and derivatives proteins were detected by immunofluorescence microscopy using anti-LysMCse antibodies. Phase-contrast images (A1 to E1) and fluorescence images (A2 to B2 and E2 to E4) of the bacterial cells in the same field are shown. The arrowheads pointed mature septa. No fluorescence staining on the wild-type cell surface was observed using the preimmun serum (B2), as well as on the *csedeltaLysM* mutant cells with the anti-LysMCse antibodies (C2), as negative controls, (Bars = 25  $\mu$ m). E2 shows a single-labeled with anti-LysMCse antibodies that indicates the localization of Cse exclusively on mature septa (Bars = 5  $\mu$ m). E3 shows the fluorochrome calcofluor having an affinity for peptidoglycan. E4 is the result double-labelled.

188x270mm (96 x 96 DPI)

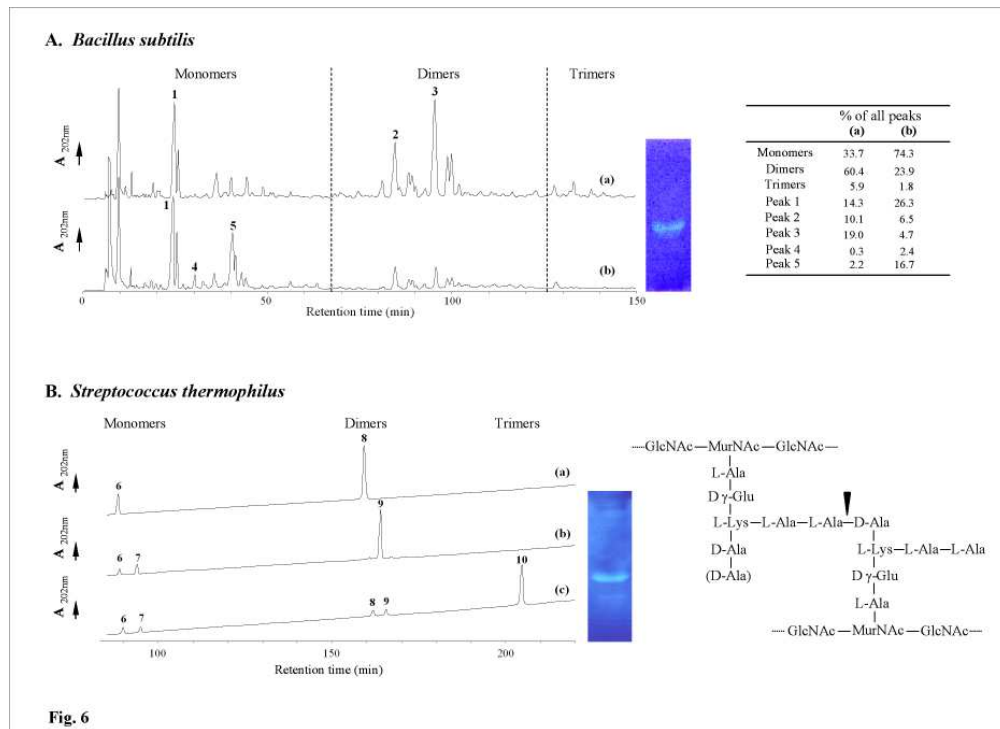


FIG. 6. Cse functions as an endopeptidase. A. RP-HPLC analysis of the mucopeptides released from *B. subtilis* cell wall after incubation with mutanolysin (a) or the CHAP-His6-tagged protein and mutanolysin (b). B. RP-HPLC analysis of three different purified mucopeptides from *S. thermophilus* (Table 1, Fig. S4) after digestion with the CHAP-His6-tagged protein. The numbers indicate the peaks analyzed by MALDI-TOF MS. The molecular ions  $m/z$  values are indicated in Table 1. The CHAP domain activity is visible as a clear hydrolysis band observed on a renaturing SDS-PAGE with 8  $\mu$ g of CHAP-His6-tagged protein in gel containing 0.08% [wt/vol] *B. subtilis* HR168 or *S. thermophilus* CNRZ368 cell-wall as substrate. The percentage of monomers corresponds to the sum of the area of the peaks corresponding to monomers over the sum of the areas of all peaks. The same was done for dimers and trimers. The percentage of each peak was calculated as the ratio of the peak area over the sum of areas of all the peaks identified by RP-HPLC. Schematic structure of *S. thermophilus* cell-wall is illustrated. Arrow indicates the cleavage site of the CHAP-His6-tagged protein. GlcNAc, N-acetylglucosamine; MurNAc, N-acetylmuramic acid.

246x178mm (96 x 96 DPI)