The ABC transporter DerAB of *Lactobacillus casei* mediates resistance against insect-derived defensins

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RUNNING TITLE: **Defensin resistance in *Lactobacillus casei***

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ABSTRACT

Bce-like systems mediate resistance against antimicrobial peptides in Firmicutes bacteria. *Lactobacillus casei* BL23 encodes an 'orphan' ABC transporter that, based on homology to BceAB-like systems, was proposed to contribute to antimicrobial peptide resistance. A mutant lacking the permease subunit was tested for sensitivity against a collection of peptides derived from bacteria, fungi, insects and humans. Our results show that the transporter specifically conferred resistance against insect-derived cysteine-stabilized αβ-defensins, and it was therefore renamed DerAB for *defensin resistance* ABC transporter. Surprisingly, cells lacking DerAB showed a marked increase in resistance against the lantibiotic nisin. This could be explained by significantly increased expression of the antimicrobial peptide resistance determinants regulated by the Bce-like systems PsdRSAB (formerly Module 09) and ApsRSAB (formerly Module 12). Bacterial two hybrid studies in *E. coli* showed that DerB could interact with proteins of the sensory complex in the Psd resistance system. We therefore propose that interaction of DerAB with this complex in the cell creates signaling interference and reduces the cell's potential to mount an effective nisin resistance response. In the absence of DerB, this negative interference is relieved, leading to the observed hyper-activation of the Psd-module and thus increased resistance to nisin. Our results unravel the function of a previously uncharacterized Bce-like orphan resistance transporter with pleiotropic biological effects on the cell.

IMPORTANCE

Antimicrobial peptides (AMPs) play an important role in suppressing the growth of microorganisms. They can be produced by bacteria themselves – to inhibit competitors – but are also widely distributed in higher eukaryotes, including insects and mammals, where they form an important component of innate immunity. In low GC Gram-positive bacteria, BceAB-like

transporters play a crucial role in AMP resistance but have so far been primarily associated with inter-bacterial competition. Here, we show that the orphan transporter DerAB from the lactic acid bacterium *Lactobacillus casei* is crucial for high-level resistance against insect-derived AMPs. It therefore represents an important mechanism for inter-kingdom defense. Furthermore, our results support a signaling interference from DerAB on PsdRSAB module that might prevent the activation of a full nisin response. The Bce modules from *L. casei* BL23 illustrate a biological paradox where the intrinsic nisin detoxification potential only arises in the absence of a defensin specific ABC transporter.

INTRODUCTION

Antimicrobial peptides (AMPs) are found in all domains of life and constitute an important aspect of the natural immune response of many organisms (1, 2). AMPs are considered as an alternative to classical antibiotics, since the development of resistance has occurred to a lesser extent (3, 4). One prominent mechanism of action of AMPs is binding to lipid II, leading to the inhibition of bacterial cell wall biosynthesis, often followed by pore formation with the concomitant release of cell metabolites and the loss of membrane potential (5-7). Most AMPs are structurally very diverse, amphipathic molecules composed of 5-60 amino acids with a net positive charge (http://aps.unmc.edu/AP/main.php (8)). Nisin and subtilin are elongated and flexible, positively charged type A lantibiotics, while mersacidin is a more globular and rigid type B lantibiotic with net negative charge (9). Insect AMPs such as cecropins have an α-helical structure, while defensins have a cysteine-stabilized structure consisting of an N-terminal loop followed by an α-helix and an antiparallel β-sheet (CSαβ), which are linked by disulfide bridges (10, 11).

Since AMPs represent common threats in microbial habitats, bacteria have developed a wide range of different AMP resistance mechanisms (3, 12). General or non-specific resistance is conferred by changing the bacterial surface properties. The *dlt* (D-alanyl-lipoteichoic acid) operon mediates the D-alanylation of lipoteichoic and wall teichoic acids (13, 14), while expression of *mprF* ("multiple peptide resistance factor") modifies anionic phospholipids of the membrane with L-lysine or L-alanine (15, 16). In both cases, the resulting decrease in the net negative charge of the bacterial envelope reduces the access of cationic AMPs to their surface targets, thereby conferring resistance. In contrast to this general AMP resistance, ABC transporters constitute compound-specific resistance determinants for AMP detoxification by actively removing the peptides from their site of action (17).

79 Bce-like systems, named after BceAB from *Bacillus subtilis*, represent a unique type of
80 AMP-detoxifying ABC transporters (18, 19). They most likely consist of two nucleotide-binding
81 domain (NBDs) subunits (ATPases) and a membrane spanning domain (MSD) subunit (permease)
82 (20) and are functionally and genetically associated with BceRS-like two-component systems (TCS)
83 (21, 22). The transporter confers resistance by a target-protection mechanism, where constant
84 removal of the AMP from its cellular target keeps sufficient amounts of lipid II cycle intermediates
85 available to ensure continued cell wall synthesis (23, 24). The transporter works in a sensory
86 complex with the histidine kinase (HK), BceS (20). Signaling within this complex is activated in
87 response to transport activity (25), which is achieved by the transporter directly controlling the
88 conformational state of the HK (26). Upon activation, BceS then phosphorylates BceR, its cognate
89 response regulator (RR), which in turn induces the expression of *bceAB* and sometimes additional
90 target genes, which ensures antibiotic resistance. Since this detoxification process also removes
91 the antibiotic from its site of detection (i.e., the transport activity of the resistance transporter
92 decreases), Bce-dependent signalling is gradually switched off again (25, 26).

93 So-called 'dual function' BceAB-like transporters are required both for sensing the presence
94 of the AMPs (input) and their detoxification (output). However, a division of labor between Bce-
95 like transporters can be found in some systems: here, a specialized 'sensing transporter' perceives
96 the signal and passes this information on to its cognate TCS, which in turn leads to the expression
97 of a second 'resistance transporter' that removes the AMP from the cell surface (12, 27).

98 So far, the specificity of BceAB-like transporters could not be correlated with any particular
99 characteristic feature of the AMPs, such as structure, origin, modification or mechanism of action
100 (17, 21, 28). Some transporters can confer resistance against structurally very different AMPs,
101 while at the same time being able to distinguish between very similar compounds. For example,
102 the Psd system of *B. subtilis* responds to actagardine and enduracidin but not to mersacidin or

ramoplanin (29). Intriguingly, BceAB-like transporters can even be induced by AMPs against which they do not mediate any resistance: e.g. PsdAB is induced by actagardine but does not confer resistance against it (29). This behaviour indicates that sensing and removal of AMPs are two separable functions of BceAB-like transporters, an assumption that has been genetically verified for BceAB of *B. subtilis* (30).

L. casei BL23 encodes 17 TCSs (31), two of which, TCS09 and TCS12, are homologous to BceRS from *B. subtilis.* Both systems are genomically and functionally associated with BceAB-like transporters, ABC09 and ABC12 respectively, and constitute functional Bce-like units that were initially referred to as Module 09 and Module 12 (32). Module 09 is a stand-alone detoxification system, in which ABC09 is a dual function transporter and *abc09* is the only known target operon of RR09. TCS09 responds to nisin via ABC09 and induces the expression of the transporter, which then confers nisin resistance (Fig. 1). Module 09 additionally confers resistance against bacitracin, plectasin and subtilin (32). Because its inducer/substrate spectrum and regulatory behaviour resembles that of PsdRSAB from *B. subtilis* (29), we renamed Module 09 to PsdRSAB, for *peptide antibiotic sensing and detoxification.* For Module 12, ABC12 is a sensing transporter that is not involved in the detoxification process. In response to nisin, the cognate RR12 instead induces the expression of a larger regulon that includes the *dlt* operon, the *mprF* gene and an operon encoding an orphan BceAB-like ABC transporter of unknown function (Fig. 1). Module 12 deletion mutants are sensitive to bacitracin, nisin, subtilin, mersacidin, plectasin and vancomycin, mainly due to the impaired functionality of the Dlt system, which also renders these mutants acid sensitive (33). This organisation and behaviour is similar to the Aps system of *Staphylococcus epidermidis*, which regulates the expression of the *dlt* operon, the *mprF* gene and the *vraFG* ABC transporter in response to AMPs (34). We therefore renamed Module 12 to ApsRSAB standing for *antimicrobial peptide sensor.*

In this report, we investigated the function of the ApsR-dependent orphan ABC transporter from *L. casei* BL23 in response to AMPs. A mutational study demonstrated that the orphan transporter is a *defensin*-specific *resistance* transporter, which we therefore renamed DerAB, with DerA (locus *LCABL_21680*) forming the NBD (ATPase) and DerB (locus *LCABL_21670*) the MSD (permease) subunits of the system. Absence of a functional DerAB transporter not only increased the sensitivity to defensins, but remarkably also resulted in a decreased sensitivity to nisin. This surprising finding could be explained by gene expression studies in *ΔderB* mutant showing hyper-activation of the Psd and Aps regulated systems in response to nisin. Moreover, bacterial two-hybrid assays showed that DerB can interact with PsdS and PsdA. Based on these results, we propose that non-productive protein-protein interactions of DerAB with the PsdRSAB sensory complex might result in regulatory interference within Psd-module signal transduction that modulates the induction of the nisin resistance response.

RESULTS

DerAB mediates resistance against insect-derived defensins but renders L. casei nisin sensitive

ApsRSAB from *L. casei* BL23 is involved in resistance against several bacteriocins and the fungal peptide plectasin, and it controls the expression of the BceAB-like orphan transporter DerAB (32), which has so far not been studied with respect to its physiological role. Since all known BceAB-like transporters mediate AMP resistance (17), we tested the sensitivity of a *ΔderB* strain against a wide range of different AMPs. No differences in MIC values were obtained for bacitracin, mersacidin and vancomycin when comparing the *ΔderB* strain with the parental strain BL23 (Table 1). While the absolute MIC values for plectasin (> 40 µg ml^{-1}) and subtilin (3% (v/v)) were also identical, the *derB* mutant showed slightly reduced growth in the presence of these peptides compared to the wild type (Fig. 2A and B, respectively). Surprisingly, the *ΔderB* strain was

ten-fold more resistant against nisin than the parental strain (Fig. 2C). Since nisin and subtilin are structurally similar type A lantibiotics, these results were puzzling. We had previously shown that PsdAB from BL23 is involved in nisin and subtilin resistance (32), therefore we reasoned that a contribution to resistance/sensitivity mediated by DerAB should be revealed in a double mutant *ΔderBΔpsdB.* For subtilin, we did not observe any significant contribution of DerAB to mediating resistance (the MIC of subtilin was 0.5% (v/v) for both *ΔpsdB* and *ΔderBΔpsdB*). In contrast, the MIC of nisin was 0.5 µg ml^{-1} for BL23, 0.3 µg ml^{-1} for the more sensitive *ΔpsdB* and 5 µg ml^{-1} for the highly resistant strain *ΔderB,* while the *ΔderBΔpsdB* mutant had an intermediate phenotype with an MIC of 1 µg ml^{-1}, being this double mutant more resistant to nisin than the wild type. These results demonstrate that a *derB* deletion could rescue the nisin sensitivity of a *psdB* mutant and corroborated the relevance of DerAB in the induction of a full nisin resistance response. A more detailed investigation of the nisin resistance phenotype of *ΔderB* strain is described below.

Since *L. casei* strains can be found in the human gastrointestinal tract (35), where it is exposed to AMPs of the innate immune defence (36), we next tested the sensitivity of the strains to human AMPs. LL37 is a human cathelicidin (37) that functions as a specific activator of the Bce-like ApeRSAB (formerly YxdJKLM) module of *B. subtilis* (38, 39), while hBD1 is a human defensin that is activated by reduction of its disulfide bridges (40, 41). We did not observe any differences in sensitivity to LL-37 or hBD1 between BL23 and *ΔderB* strains (Table 1). In contrast, strains carrying *ΔapsR, ΔapsB* and *ΔdltA* mutations were more sensitive to LL-37 than the BL23 wild type (Fig. S1), indicating a role of ApsRSAB in resistance against LL-37, likely by regulating the activity of the Dlt system.

Lactobacilli can also be found in the microbiota of insects (42, 43). Next, we tested the sensitivity of BL23 and *ΔderB* strains against a collection of 18 insect-derived AMPs. Both strains were resistant against even the highest concentrations of most insect AMPs tested (Table 1).

174 However, for three defensins we could observe significant differences in resistance. The *ΔderB*
175 mutant was slightly more sensitive to LSer-Def4 (BR090, Fig. 2D) and much more sensitive to
176 sapecin A (BR080; MIC > 160 µg ml^{-1} for BL23, 80 µg ml^{-1} for *ΔderB*) and Lser-Def3 (BR092; MIC >
177 320 µg ml^{-1} for BL23, 320 µg ml^{-1} for *ΔderB*) (Figs. 2E and F, respectively) than the parental strain,
178 indicating that DerAB mediates resistance against these compounds. To confirm that the
179 observed phenotype was specific to and directly caused by the loss of DerAB, we repeated the
180 sensitivity experiment for sapecin A on a strain carrying an ectopic copy of *derB* to complement
181 the *ΔderB* mutation. Indeed, complementation restored much of the original resistance (Fig. S2).
182 The slight remaining differences to the wild type are likely due to altered expression levels of *derB*
183 between the native and ectopic copy, as was observed for complementation of a *bceB* mutant of
184 *B. subtilis* (44). Taken together, the data indicate that DerAB specifically mediates resistance
185 against insect-derived AMPs.
186 Subsequent microscopic studies revealed significantly different morphological aberrations
187 in the *ΔderB* strain when challenged with different AMPs (Fig. 3 and Sup. Table 1). No
188 morphological differences were found between BL23 and *ΔderB* strains after exposure to BR005
189 (Fig. 3C and D), BR081, BR087, BR088, BR091 or subtilin 2% (v/v) (data not shown). In contrast, the
190 *ΔderB* strain was strongly affected after exposure to 400 µg ml^{-1} BR090, showing chaining (Fig. 3J
191 and K), aberrant morphologies and cells becoming phase transparent (Fig. 3F). Although minor
192 changes were also observed in the wild type treated with BR090, these were far less pronounced
193 (Fig. 3E). After incubation with BR080 (Fig. 3G and H) or BR092 (data not shown), the chaining
194 phenotype of *derB* deletion mutant was even more pronounced (Fig. 3J and K), whilst the parental
195 strain remained unaffected. These morphological changes of the *ΔderB* strain after exposition to
196 BR080, BR090 and BR092 are in good agreement with the sensitivity phenotypes observed for
197 these AMPs (Fig. 2).

198 *L. casei* mutants in *apsRSAB* are defective in D-alanylation of teichoic acids, resulting in a
199 more negative surface charge and a higher AMP sensitivity of *ΔapsR*, *ΔapsB* and *Δdlt* compared to
200 the parental strain (32). A possible explanation for the observed sensitivity of the *ΔderB* strain
201 could therefore be that DerAB somehow contributes to the regulation of the Dlt system through
202 ApsRS. However, measurements of the cell surface charge by cytochrome *c* binding assays (32, 45)
203 did not show any significant differences between BL23 and *ΔderB* strain (Fig. S3), thereby ruling
204 out this cause for the higher AMP sensitivity of the *derB* mutant.

205 Since the *ΔderB* strain showed the strongest sensitivity phenotypes when exposed to insect-
206 derived defensins (Fig. 2E and F), we additionally investigated the contribution of DerAB to
207 resistance against crude extracts derived from larvae of the dipteran species black soldier fly
208 *Hermetia illucens* (see Materials and Methods for their preparation), which are particularly prolific
209 sources of broad-spectrum antimicrobial substances (46). A recent transcriptome study identified
210 53 genes encoding putative AMPs from different families, half of which are putative defensins
211 (47). Amongst those, the defensin-like peptide 2 (DLP2;
212 ATCDLLSPFKVGHAACALHCIAMGRRGGWCDGRAVCNCRR) and the defensin-like peptide 4 (DLP4;
213 ATCDLLSPFKVGHAACAAHCIARGKRGGWCDKRAVCNCRK) have been characterized (48, 49). Both
214 defensins possess a CSαβ structure and are active against Gram-positive bacteria. If DerAB is a
215 defensin-specific resistance transporter, its absence should render *L. casei* also sensitive to
216 *H. illucens* extracts. Indeed, the *ΔderB* strain was over 100-fold more sensitive than the parental
217 strain (Fig. 2G; MIC is 5 % (v/v) for BL23 and 0.04 % (v/v) for *ΔderB*), thereby confirming its role in
218 conferring resistance against AMPs produced by *H. illucens*. Besides the strong effect on
219 resistance, we observed some morphological differences in the form of elongated and chaining
220 cells in the *ΔderB* strain after exposition to *Hermetia* larvae extracts (Fig. S4).

ApsRSAB regulates different layers of resistance against antibiotics produced by H. illucens larvae

The AMP resistance determinants of *L. casei* are controlled by the Psd and Aps modules: the PsdRSAB system regulates the target operon *psdAB*, and the ApsRSAB system regulates the expression of the *dlt* operon, *mprF* gene and *derAB* transporter (32) (Fig. 1). Because of the potency of the *H. illucens* larval extracts and the strong difference in sensitivity between the *derB* deletion mutant and the parental strain, we next aimed at analysing the hierarchy within the AMP resistance network orchestrated by the Psd and Aps modules and the individual contributions of their target genes to protecting *L. casei* against the combined challenge of *H. illucens* extracts. Towards this goal, we performed a comprehensive mutational study of the individual components of the AMP resistance network of *L. casei* (Fig. 4).

The MIC values for strains *ΔpsdR* and *ΔpsdB* were similar to that of the wild type strain BL23 (5% (v/v)), indicating that the stand-alone Psd module is not involved in mediating resistance against larval extracts (Fig. 4). In contrast, both mutants that rendered the Aps system dysfunctional, *ΔapsR* and *ΔapsB* strains, were highly sensitive to *H. illucens* extracts, with an MIC of 0.01% (v/v) (500-fold more sensitive than the wild type).

Next, we determined the MIC for all three Aps-dependent AMP resistance determinants deleted individually. While both the *ΔmprF* and *ΔdltA* mutants showed a slight increase in sensitivity compared to the wild type, the most marked effect was again observed in the *ΔderB* strain (Fig. 4). These data clearly show that the DerAB transporter, provides the primary resistance layer against the AMPs present in the larval extract, while D-alanylation of teichoic acids and – to a smaller extent – the L-lysinylation of phospholipids represent a secondary layer of resistance. In agreement with this hierarchy, the MIC of a *ΔderBΔdltA* double mutant (0.02% (v/v)) was further increased compared to the single mutants, that is, 16-fold more sensitive than *ΔdltA* strain and 2-

245 fold more sensitive than *ΔderB* strain. To rule out any minor contributions to resistance by the Psd
246 system, we also tested a *ΔderBΔpsdB* double mutant, but could not detect any changes relative to
247 the *ΔderB* single mutant. Taken together, our results demonstrate that a clear hierarchical
248 organization of multiple layers ensure protection of *L. casei* against insect-derived AMPs, and all
249 resistance determinants relevant for counteracting the AMPs contained in *H. illucens* extract are
250 under control of a single module: ApsRSAB.

251 ***Resistance determinant genes are transcriptionally over-expressed in ΔderB strain in response to***
252 ***nisin.***

253 As mentioned above, the *ΔderB* strain unexpectedly showed a ten-fold increase in
254 resistance against nisin (MIC 5 µg ml^{-1}; MIC for parental strain 0.5 µg ml^{-1}) (Table 1 and Fig. 2C).
255 PsdAB is involved in nisin resistance and partially contributes to the hyper-resistance of *ΔderB*
256 (MIC value for double mutant *ΔderBΔpsdB* of 1 µg ml^{-1}). However, the main nisin resistance
257 determinant of *L. casei* is the Dlt system, since the *ΔdltA* mutant was 12.5-fold more sensitive to
258 nisin than the wild type (MIC for *ΔdltA* strain is 0.04 µg ml^{-1}) (32). We have previously shown that
259 transcription of the *psdAB* and *dltA* genes is induced in a nisin-dependent manner in BL23, as are
260 the genes *derAB* and *mprF* (32). We therefore hypothesized that the increased resistance of *ΔderB*
261 strain might be due to a higher expression level of the nisin resistance determinants in this
262 mutant. Thus, we tested the response of these genes following nisin exposure in the *ΔderB* strain
263 background compared to the wild type, following the previously established procedure (32).

264 Expression of *psdR*, *apsB*, *apsA* and *apsR* was not induced by nisin in either strains (Fig. 5A),
265 in agreement with the role of PsdRS and ApsRSAB in signaling rather than resistance (32).
266 Strikingly, nisin exposure of the *ΔderB* strain led to a notable increase of induction of nisin
267 resistance genes compared to the BL23 wild type (Fig. 5A): the genes encoding the transporters
268 (*psdA*, *psdB* and *derA*) were up to ten-fold stronger induced in the *ΔderB* strain than in the wild

type. Likewise, *dltA* and *mprF* also responded more strongly (~ 2.5-fold and ~ 3.5-fold, respectively) in the mutant. Importantly, no significant differences in gene expression were found between *ΔderB* and the parental strain in reference conditions (Fig. S5), showing that the increased induction was due to a hyper-response to nisin exposure and not general changes in gene expression upon *derB* deletion. Moreover, since the systems involved in nisin resistance in *L. casei* BL23 also mediate subtilin resistance (32), we next tested the response of these genes following subtilin exposure in the *ΔderB* strain background compared to the wild type. Noticeably, no significant differences in gene expression were found between *ΔderB* and the parental strain in response to subtilin (Fig. 5B and Fig. S5). We therefore concluded that the increased nisin resistance of *ΔderB* strain was due to an over-expression, compared to the parental strain, of the nisin resistance determinants *psdAB*, *mprF* and the *dlt* operon, and that this response was specific for nisin.

DerAB may interfere with signaling through spurious protein-protein interactions.

We next investigated the molecular basis for the observed hyper-induction of nisin resistance genes in the *ΔderB* strain. For the BceRSAB system of *B. subtilis*, it is known that signaling depends on a sensory complex formed between the transport permease BceB and the histidine kinase BceS (20). Moreover, signaling requires a functional transporter that is capable of ATP hydrolysis (25, 44), i.e. correct interaction between the permease BceB and the ATPase (BceA) subunits. Since it could be possible that DerAB may somehow interfere with one or more of the nisin-responsive signaling pathways in the cell, we performed bacterial two-hybrid experiments of all involved protein partners to test if the permease DerB is able to interact with any of the components of the Psd or Aps resistance systems (Fig. 6 and Fig. S6). In addition to the expected interaction between DerB and DerA, we also obtained positive results for DerB paired with PsdA (Fig. 6). It is possible that such non-cognate binding of the ATPase PsdA by DerB may reduce the ability of the PsdAB

293 transporter to trigger signaling via PsdS. Moreover, we observed clear interactions between DerB
294 and PsdS (Fig. 6). It is likely that such non-cognate interactions between the permease DerB and
295 the Psd histidine kinase would interfere with native signaling. Relief of this interference in the
296 *ΔderB* strain could then explain the observed increase in the amplitude of the nisin response and
297 resulting nisin resistance.

298 Unfortunately, similar bacterial two-hybrid experiments with the Aps proteins were less conclusive
299 because several of the fusion constructs did not even give positive results with their known
300 interaction partners (Fig. S6); consequently, these assays were not informative for potential
301 interactions between DerAB and the Aps system.

302 **DISCUSSION**

303 ABC transporters acting as detoxification mechanisms are of major importance as AMP
304 resistance systems in Firmicutes (17). In this study, we unraveled the function of DerAB in *L. casei*
305 BL23, which belongs to the BceAB-like group of transporters.

306 Our results demonstrate that from the available panel of antimicrobial compounds, four
307 CSαβ defensins (plectasin, sapecin A, LSer-Def4 and LSer-Def3) are the most relevant substrates of
308 DerAB. Such defensins are ubiquitously produced in plants, insects, mussels and fungi and form an
309 important component of the innate immunity (10). In addition to defined compounds, we also
310 demonstrated the relevance of DerAB for the survival of *L. casei* when challenged with a potent
311 mix of insect AMPs from *H. illucens* larvae. Lactobacilli grow in a variety of nutrient-rich
312 carbohydrate-containing habitats. In addition to its well-known roles in fermentation and spoilage
313 of food, *L. casei* is also found in the oral cavity, gastrointestinal and genital tracts of humans and
314 other animals (50). Moreover, different *Lactobacillus* species have been found in the microbiota of
315 insects (42, 43). It is usually assumed that lactobacilli present in food come from the food

316 processing equipment, raw foodstuffs such as plant material or faecal contamination, but it may
317 appear that insects may play a role in the dissemination of *L. casei*. A recent study has provided
318 evidence suggesting that insects are the natural reservoir of *Lactobacillus sanfranciscensis*, an
319 organism involved in sourdough fermentation (51). Interestingly, in this study, Operational
320 Taxonomic Units (OTUs) belonging to *L. casei* group were the second most numerous after
321 *L. sanfranciscensis* within lactobacilli OTUs (51). Our results suggest that possession of DerAB may
322 protect *L. casei* in different AMP-enriched environments of eukaryotic origin, including insects,
323 and thereby enable it to colonise its hosts.
324 Furthermore, by testing the sensitivity of our collection of mutants to extracts from
325 *H. illucens* larvae, which contain a very potent mixture of AMPs (46, 47), we showed that BL23
326 possesses several layers of AMP resistance. In this network, DerAB is the defensin-specific primary
327 resistance mechanism, while the Dlt system and MprF protein constitute the secondary, more
328 general resistance layer by altering the bacterial surface charge (Fig. 1). Remarkably, in
329 *Bacillus subtilis,* the response to bacitracin also consists of a hierarchy of different layers of
330 resistance: the BceAB transporter constitutes the primary (drug-sensing and highly efficient)
331 resistance determinant, and the LiaIH system together with the BcrC phosphatase constitute the
332 secondary (damage-sensing and less efficient) layer of resistance (52). Thus, a clear hierarchical
333 organization of multiple layers ensure protection of both *L. casei* and *B. subtilis* against AMPs.
334 Interestingly, not only the individual components of the resistance networks are different between
335 *L. casei* (DerAB transporter, Dlt operon and MprF protein) and *B. subtilis* (BceAB transporter, LiaIH
336 system and BcrC phosphatase) (52), also, the resistance layers are controlled by separate cell
337 envelope stress systems in *B. subtilis* (52), whereas all resistance determinants relevant for
338 counteracting the AMPs contained in *H. illucens* extract are under control of a single module,
339 ApsRSAB, in *L. casei*.

So far, the substrate specificity of BceAB-like transporters could not be related with any particular feature of the respective AMPs (17, 21, 28). Our results for DerAB indicated a preference for CSαβ defensins, e.g. plectasin, sapecin A (BR080), LSer-Def4 (BR090) and LSer-Def3 (BR092). Surprisingly, DerAB does not confer resistance against the structurally closely related defensins lucifensin (BR088), BR081, BR087, LSer-Def7 (BR089) and LSer-Def6 (BR091) (Table 1). This indicates that DerAB can distinguish between very similar CSαβ defensin substrates, a situation reminiscent of the results obtained for the Psd module of *B. subtilis* (29). We performed a structural analysis of all tested candidates mentioned above to further investigate this apparent specificity of DerAB for some defensins (Fig. S7). The investigated defensins show a moderate sequence conservation with an average sequence identity of 50 % (Fig. S8). The overall structure of the defensins is well conserved with all available structures harboring a cysteine-stabilized α-helix β-sheet (CSαβ) motif. The main structural deviations are in the N-terminal loop region, which is also least well conserved, both with respect to its size and amino acid sequence (Fig. S7). No obvious pattern of structural determinants distinguishing substrates from non-substrates could be extracted, in line with previous studies on the substrate specificity of BceAB-like transporters (21).

The most puzzling result that we obtained during our initial sensitivity screen was the hyper-resistance of the *derB* deletion mutant against the lantibiotic nisin. Transcriptional studies in the *ΔderB* strain in response to nisin demonstrated that the absence of this transporter resulted in an over-induction of *mprF*, the *dlt* operon and *psdAB*. Both the Dlt system and the PsdAB transporter are crucial for nisin resistance in *L. casei* (32). Our results strongly suggest that their over-expression accounts for the hyper-resistance of the *ΔderB* strain to nisin. This hypothesis is supported by independent studies in other Firmicutes bacteria that demonstrated the role of *dlt* expression levels for AMP resistance. Acquisition of nisin resistance in *Lactococcus lactis* IL1403 was partly due to higher expression levels of the *dlt* operon (53). Similarly, strains of

364 *Staphylococcus aureus* Sa113 bearing additional copies of the *dlt* operon showed an increased
365 level of D-alanine in LTA and WTA, which led to an increased nisin resistance (45).

366 In the case of the *ΔderB* strain investigated here, increased nisin resistance could, however,
367 not be explained by acquisition of additional copies of resistance genes. Instead, we could show
368 that DerB has the ability to interact with components of the Psd resistance system. We propose
369 that such spurious interactions with non-cognate protein partners likely have a negative impact on
370 signal transduction. That is, in the presence of nisin, not all PsdS histidine kinases receive a signal
371 from their cognate transporter PsdAB, because a proportion is in a non-productive complex with
372 DerB. This interference is removed upon *derB* deletion, allowing the full potential activation of
373 *psdAB* expression and thus a greater level of resistance against the AMP. Of note, whereas the
374 strain C-*derB,* carrying an ectopic copy of *derB* in the *derB* deletion mutant background,
375 complemented sensitivity to the defensin sapecin A, the restoration of nisin sensitivity was only
376 very weak (Fig. S2). Likely the ectopic copy of *derB* did not result in the same protein levels of DerB
377 in the cell and therefore the interference with normal Psd signaling was not observed. However,
378 indirect evidence supporting this interference model is available. Results of gene expression
379 previously reported (32) for mutants defective in the ApsRSAB system, and results reported here
380 for *ΔderB* (Fig. 5A and Fig. S5), showed an increase in expression of *psdAB* in the presence of nisin,
381 suggesting that a decrease in the ratio of DerAB over PsdAB results in increased PsdRSAB signal
382 transduction. Furthermore, results obtained with subtilin (Fig. 5B and Fig. S5) show that this is a
383 nisin-specific effect. To our knowledge, such a negative effect of one Bce-like resistance system on
384 the function of another has not been previously reported. Also, why this phenotype is observed
385 with nisin and not with a closely related lantibiotic such as subtilin, is still unclear.

386 We previously showed that Bce-like systems are wide-spread among Firmicutes bacteria,
387 and that many species contain multiple copies with different substrate specificities (21). Often, the

closest homolog to a given system is found in a different species, while the paralogs within a single species can be quite distantly related (21). For the Bce-like systems characterized to date, signaling between transporter and two-component system appears to be highly specific and no accidental cross-talk has been reported. The example of DerAB reported here may constitute an interesting evolutionary intermediate where the interaction specificity is not yet completely insulated, allowing non-productive interference with the Psd system. In this scenario, in the presence of nisin, the interference by DerAB should pose a significant fitness burden on the cell. However, we did not observe any effects of a *derB* deletion on gene expression when cells were grown in un-challenged reference conditions or after subtilin exposure (Fig. 5B and S5), suggesting that DerAB has no negative effect in most situations. An alternative scenario could then be that the interference by DerAB is in fact beneficial to prevent an over-reaction to nisin that could also pose a fitness burden to the cell. Interestingly, a similar hidden potential in the response to nisin mediated by Bce-like systems was also previously reported in *S. aureus* (54). While beyond the scope of the present study, it would be interesting to investigate if, under suitable experimental pressure, *L. casei* BL23 could evolve increased signaling specificity and circumvent the interference from DerAB.

In summary, in this work we demonstrated that DerAB is a defensin-specific resistance transporter that constitutes a primary layer of the *L. casei* cell envelope stress response. Its expression is controlled by the Aps module that also regulates the secondary, more general, layers of resistance, the Dlt system and MprF. Given the high degree of protection against insect-derived AMPs, it appears likely that the physiological role of DerAB is in host-microbe interactions and may allow *L. casei* to avoid innate immune defenses to colonise its eukaryotic hosts.

EXPERIMENTAL PROCEDURES:

411 ***Bacterial strains, plasmids and grown conditions***

412 Table 2 and 3 list the strains and plasmids, respectively, used in this study. *Escherichia coli*
413 DH10β and *Lactococcus lactis* MG1363 were used as intermediate hosts for cloning purposes.
414 *E. coli* strains were grown in LB medium at 37°C with aeration. *L. lactis* strains were grown in M17
415 medium supplemented with 0.5 % (w/v) glucose at 30°C under static conditions. *L. casei* strains
416 were grown in MRS broth (Oxoid) at 37°C under static conditions. 1.5 % (w/v) agar was added to
417 prepare the corresponding solid media. Strains were stored at -80°C in their corresponding growth
418 media containing 20 % (v/v) glycerol. Ampicillin 100 µg ml^{-1} was added to *E. coli*, and erythromycin
419 5 µg ml^{-1} was added to *L. lactis* and *L. casei*, when required.

420 ***Construction of mutants***

421 Oligonucleotides used in this study are listed in Supplemental Table 2. Cloning in *E. coli* was
422 performed following standard methods (55). *E. coli* strains were transformed by electroporation
423 with a Gene Pulser apparatus (Bio-Rad), as recommended by the manufacturer; *L. lactis* strains
424 were transformed by electroporation (56) and *L. casei* strains were transformed as described
425 previously (57).

426 For a complete deletion of gene LCABL_21670 (*ΔderB*) from *L. casei* BL23, two DNA
427 fragments of approximately 700 bp upstream and downstream of the target gene were amplified
428 from genomic DNA using primers pairs RG062-063 and RG064-065 (see Sup. Table 2). All
429 subsequent steps of mutant construction were performed as previously described (32). Strain C-
430 *derB* with the complementation of the *derB* deletion was achieved by cloning the corresponding
431 gene and potential ribosome binding site (12 pb intergenic region between *derA*-*derB*), with
432 primer pair RG220-221 (*SpeI* and *BglII* restriction sites; Sup. Table 2), under the constitutive P1
433 promoter in the expression vector pT1NX (58). The resulting plasmid *pT1-*RBS_{derB}*derB* (Table 3) was
434 used to transform *L. lactis* MG1363, and transformants were checked by sequencing of the

435 inserted fragment. Subsequently, plasmid *pT1-RBS$_{derB}$derB* was used to transform *L. casei ΔderB*,
436 resulting in strain *L. casei C-ΔderB* (Table 2) which was maintained with erythromycin selection.
437 Double mutant strains *ΔderBΔdltA* and *ΔderBΔpsdB* were obtained by insertional
438 inactivation of genes LCABL_08550 (*dltA*) and LCABL_16400 (*psdB*), respectively, in *L. casei ΔderB*
439 mutant background. A procedure similar to the previously described to obtain insertionally
440 inactivated single mutants of genes LCABL_08550 and LCABL_16400 was followed (32).

441 ***Bacterial two-hybrid assays***

442 We constructed C-terminal and N-terminal translational fusions of the T18 and T25
443 domains of the adenylate cyclase CyaA of *Bordetella pertussis* for each protein individually (40
444 constructs; Table 3), to test protein-protein interactions between DerAB and PsdRSAB module,
445 and between DerAB and ApsRSAB module. Fusions were tested in pairwise combinations in *E. coli*
446 BTH101 (59). For each co-transformation mixture, 3 times 10 µl were spotted onto LB agar plates
447 containing 1 mM isopropyl-β-D-1-thio-galactopyranoside (IPTG) and 100 µg ml^{-1} 5-bromo-4-chloro-
448 3-indolyl-β-D-galactopyranoside (X-Gal) with selection for ampicillin and kanamycin resistance.
449 Plates were incubated at 30 °C for 48 h. Positive interaction results were identified by the
450 formation of blue colonies.

451 ***Source or preparation of eukaryotic AMPs and subtilin***

452 HBD-1 and LL-37 were purchased from Sigma-Aldrich™ (SRP3011 and 94261, respectively)
453 and were reconstituted according to manufacturer instructions. The insect AMPs shown in Table 1
454 were selected according to their reported structural and functional properties, synthesized and
455 purified to >95%. Cecropin 1 (from *Eristalis*) was synthesized by PepMic (Pepmic Suzhou, Jiangsu,
456 China). Cecropin A (from *Hyalophora* and *Aedes*), Stomoxyn (from *Stomoxys*) and Sarcotoxin IA
457 were synthesized by JPT (JPT Peptide Technologies GmbH, Berlin, Germany). The rest of the
458 peptides were synthesized by Covalab (Covalab S.A.S., Villeurbanne, France), based on the

sequence of the mature peptides. All peptides were lyophilized for storage and were resuspended and diluted in double-distilled water. Excluding *Aedes* and *Eristalis* cecropins, all other cecropins and *Stomoxys* stomoxyn were modified by the C-terminal amidation.

Larvae of the black soldier fly (*Hermetia illucens*) were obtained from a pilot rearing plant in Grimma, Saxony, Germany, and grown at 24°C in the laboratory. *H. illucens* larvae were induced as previously described (39, 46) by injecting a fungal spore suspension (spores of *Verticillium lecanii* and *Metarhizium anisopliae*) into the haemolymph and by feeding a bacterial mix (*E. coli*, *Micrococcus luteus*, *Pseudomonas fluorescens*, *B. subtilis*) to simulate an infection and boost AMP production. The larvae were pricked as previously described (46). Aqueous larval extract from *H. illucens* was prepared as previously described (46) and was considered to be at a concentration of 100% (v/v) for the MIC assays.

B. subtilis ATCC 6633 was grown in medium A to induce subtilin production as in (60). Culture supernatant was collected and was considered to be at a concentration of 100% (v/v) for MIC assays.

Antibiotic sensitivity testing

MIC assays were performed in 96-well microtiter plates as previously described (32). Overnight cultures of the strains under study were prepared with antibiotic selection when required but, no antibiotic was added for the MIC assays. The 96-well plates were incubated at 37°C under static conditions in a Synergy™ NEOALPHAB multi-mode microplate reader (BioTek®, Winooski, VT, USA). Growth was monitored by changes in OD_{595}. For each strain, the MIC at 15 h was defined as the lowest antibiotic concentration where the final OD was at or below the starting OD. All experiments were performed at least in duplicate.

Microscopy

Stationary phase cell cultures assessed in MIC assays were photographed. Morphology of cultures grown for 24 h in MRS was taken as reference. Possible morphological changes on bacteria were checked after exposition for 24 h to BR005, BR080, BR081, BR087, BR088, BR090, BR091, BR092, subtilin and *H. illucens* larval extracts. The cells were observed in an Olympus AX70 microscope with phase contrast at 40x magnification. Pictures were taken with an Olympus U-TV1XC camera. Pictures were analysed using the tools implemented in the Olympus Cells Sens Dimensions 1.14 software and Corel Photo Paint X5.

The average cell length of the bacteria (n = 200), the average cell-chains length (n = 40 cell-chains) and the average number of cells per chain (n = 40 cell-chains) of the stationary phase cell cultures photographed were determined using the tools implemented in the ImageJ 1.52i software (61). Unpaired t-tests (two-tailed P value, 95% confidence intervals) comparing the values of BL23 and *ΔderB* under the reference condition indicated means significantly different ($P<0.05$) for the cell-chains length (P value= 0.023) and the number of cells per chain (P value= 0.002). To determine whether the morphological phenotypes of the mutant strain upon exposition to each insect derived AMP assayed were significantly different from that of the wild type, pairwise two-way ANOVA analyses were run with GraphPad Prism 5 software, testing the values of both strains under the reference condition and after each AMP exposition. A significant difference was considered when the analysis estimated P values were below of 0.01.

Cytochrome c binding assay

Comparison of the whole-cell surface charge of the wild-type strain and mutant *ΔderB* was performed by a cytochrome *c* binding assay as in (32). Briefly, cells in stationary phase at 10^{10} CFU ml^{-1} were incubated with 150 µg ml^{-1} cytochrome *c* (Sigma) in 20 mM MOPS (morpholinepropanesulfonic acid), pH 7, for 10 min at room temperature. The mixture was centrifuged twice, and the absorbance of the supernatant (containing unbound cytochrome *c*) was

506 determined at 530 nm. The binding ratio was calculated by comparing the absorbance of each
507 supernatant after incubation with the cells relative to the absorbance of the cytochrome *c* solution
508 without bacterial cells.

509 ***Antimicrobial peptide information and structure predictions***

510 The Antimicrobial Peptide Database (APD) (http://aps.unmc.edu/AP/main.php) (8) was
511 used as a reference for the information listed in Table 1. For structural information the Protein
512 Data Bank (www.rcsb.org) (62) or UniProt (http://www.uniprot.org/) (63) were used. The
513 structures of Plectasin (PDB ID 1ZFU (64)), BR080 (sapecin A; PDB ID 1L4V (65)) and BR088
514 (lucifensin, PDB ID 2LLD (66)) were used. If no structure was available, the Swiss-Model webpage
515 was used to generate structural predictions (https://swissmodel.expasy.org/) (67-70). The
516 structures of BR081, BR087, BR089, BR090, BR091 and BR092 were modelled applying the
517 Sapecin A structure (PDB: 1L4V) as template. Structural comparison was performed with YASARA
518 View (www.yasara.org) program. Multiple sequence alignment of the defensins was performed
519 with the CLC Main Workbench 7.7.3 program.

520 ***Reverse-transcription and quantitative real-time PCR (qRT-PCR)***

521 Samples for RNA isolation were collected as previously described (32). Nisin 22.5 ng ml^{-1}
522 and subtilin 1 % were used for the induction assays. Isolation of total RNA from *L. casei* strains,
523 synthesis of cDNA, primer design and qRT-PCR were carried out as described previously (71).
524 Primers used are listed in Sup. Table 2. *lepA*, *ileS*, *pyrG* and *pcrA* were used as constitutive
525 reference genes (71). Linearity and amplification efficiency for each primer pair were previously
526 determined (32). The relative expression based on the expression ratio between the target genes
527 and reference genes was calculated using the software tool REST (72). Every real-time PCR
528 determination was performed at least six times.

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The authors declare no conflict of interest.

AUTHORS CONTRIBUTIONS:

A.R.-G., M.Z. and T.M. conceived the study and planned the experiments. A.R-G analyzed the data and wrote the manuscript under the supervision of T.M.; M.Z. and S.G. contributed to discussing the results and the final manuscript. A.R.-G. carried out most of the experiments with *L. casei* and designed the B2H constructs; C.A. contributed to the construction of the mutant strains and the qRT-PCR experiments; Q.Z. performed the B2H cloning and experiments. C.L. performed the structural analysis of defensins and contributed to writing of the manuscript. A.M. prepared *H. illucens* larvae extracts. M.R and A. V. prepared insect derived AMPs. All authors read the paper and commented on the final manuscript.

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TABLES

Table 1: Antimicrobial peptides used in this study and MIC values against *L. casei* BL23 and *ΔderB*.

AMP		Class	AP Database ID[a]	Sequence	3D structure[b]	MIC[c] (15h)	
						BL23	*ΔderB*
Bacteriocins							
Bacitracin		cyclic peptide	n. r.	ICLEIKOrnIFHDN [d] (bond between Lys_6 and Asn_{12})	cyclic	10	10
Nisin A		type A lantibiotic	AP00205	ITSISLCTPGCKTGALMGCNMKTATCHCSIHVSK	non-αβ	**0.5**	**5**
Mersacidin		type B lantibiotic	AP01206	CTFTLPGGGGVCTLTSECIC	non-αβ	10	10
Subtilin		type A lantibiotic	AP00206	WKSESLCTPGCVTGALQTCFLQTLTCNCKISK	unknown	3[c]	3[c] **(¶)**
Vancomycin		glycopeptide	n. r.	n.f.	branched tricyclic	1.7[c]	1.7[c]
Fungi AMPs							
Plectasin		defensin	AP00549	GFGCNGPWDEDDMQCHNHCKSIKGYKGGYCAKGGFVCKCY	combine-αβ	**>40**	**>40 (¶)**
Insect AMPs							
BR001	Cecropin A	cecropin	AP00139	KWKLFKKIEKVGQNIRDGIIKAGPAVAVVGQATQIAK*-NH2	α	>320	>320
BR002	Sarcotoxin IA	cecropin A2	AP00230	GWLKKIGKKIERVGQHTRDATIQGLGIAQQAANVAATAR*-NH2	α	>320	>320
BR003	Cecropin A (insect: *Aedes aegypti*)	cecropin	n.r.	GGLKKLGKKLEGAGKRVFNAAEKALPVVAGAKALRK	(α)	>320	>320
BR005	Stomoxyn	stomoxyn	AP00484	RGFRKHFNKLVKKVKHTISETAHVAKDTAVIAGSGAAVVAAT	α	>320	>320
BR044	LSerStomox2	stomoxyn	AP02513	GFRKRFNKLVKKVKHTIKETANVSKDVAIVAGSGVAVGAAMG	(α)	>320	>320
BR080	Sapecin A	defensin	AP00227	ATCDLLSGTGINHSACAAHCLLRGNRGGYCNGKAVCVCRN	combine-αβ	**>160**	**80**
BR081	(insect: *Aeschna cyanea*)	defensin	AP00182	GFGCPLDQMQCHRHCQTITGRSGGYCSGPLKLTCTCYR	bridge	>320	>320
BR087	(insect: *Lucilia sericata*)	defensin	n. r.	ATCDLLSATGFSGTACAAHCLLIGHRGGYCNTKSVCVCRD	(combine-αβ)	>400	>400
BR088	Lucifensin	defensin	AP01532	ATCDLLSGTGVKHSACAAHCLLRGNRGGYCNGRAICVCRN	combine-αβ	>400	>400
BR089	LSer-Def7	defensin	AP02507	FTCNSYACKAHCILQGHKSGSCARINLCKCQR	bridge	>320	>320
BR090	LSer-Def4	defensin	AP02505	LTCNIDRSFCLAHCLLRGYKRGFCTVKKICVCRH	bridge	**>400**	**>400 (¶)**
BR091	LSer-Def6	defensin	AP02506	GTCSFSSALCVVHCRVRGYPDGYCSRKGICTCRR	bridge	>400	>400
BR092	LSer-Def3	defensin	AP02504	ATCDLLSGTGANHSACAAHCLLRGNRGGYCNSKAVCVCRN	bridge	**>320**	**320**
BR097	Cecropin A (*Galleria mellonella*)	cecropin	AP03067	KWKIFKKIEKAGRNIRDGIIKAGPAVSVVGEAATIYKTG*-NH2	(α)	>320	>320
BR098	Cecropin B (*G. mellonella*)	cecropin	AP03068	KWKFFKKIERVGQNIRDGIIKAGPAVQVVGQAATIYKGK*-NH2	(α)	>320	>320
BR099	Cecropin C (*G. mellonella*)	cecropin	AP03069	RWKVFKKIERMGQHIRDGIIKAGPAVAVVGQASTIISG*-NH2	(α)	>320	>320

BR100	Gm cecropin D-like pept	cecropin D	AP00755	ENFFKEIERAGQRIRDAIISAAPAVETLAQAQKIIKGGD*-NH2	(α)	>320	>320
BR101	Et-Cec1 (*Eristalis tenax*)	cecropin	n. r.	GFLKKIGKKLEGAVQRTRDATIQTIAVAQAAANVAATAKQG	(α)	>320	>320
Human AMPs							
LL37		cathelicidin	AP00310	LLGDFFRKSKEKIGKEFKRIVQRIKDFLRNLVPRTES	α-helix	>27	>27
hBD-1		defensin	AP00451	DHYNCVSSGGQCLYSACPIFTKIQGTCYRGKAKCCK	combine-αβ	>20	>20

741 [a] Antimicrobial Peptide Database (APD3) (8) identification number. n.r., not registered in APD3; n.f., not found. [b]3D structure as annotated in

742 APD3 based in (73): **α**, AMPs with helical structures; **combine-αβ**, AMPs with α-helical and β-strands in the 3D structure; **non-αβ**, contains neither

743 α-helical nor β-strands; **bridge**, AMPs without 3D structure determined, disulfide-linked, usually β-structure. When no structural data was

744 available, structure prediction was made using the Swiss-Model webpage (https://swissmodel.expasy.org/) (67) and is indicated in parenthesis.

745 [c]MIC in µg ml^{-1} except for: subtilin (% (v/v)) and vancomycin (mg/ml). **(¶)** indicates that the mutant is more sensitive when assays for final cell

746 densities (see Fig. 2). [d] Sequence of linear peptide precursor.

747 **TABLE 2. Bacterial strains used in this study**

Strains	Description[a]	Source or reference
E. coli DH10β	F$^-$ *mcrA* Δ(*mrr-hsdRMS-mcrBC*) Φ80d*lacZ*Δ*M15* Δ*lacX74 endA1 recA1 deoR* Δ(*ara,leu*)7697 *araD139 galU galK nupG rpsL* λ$^-$	Stratagene
E. coli BTH101	F-, *cya-99, araD139, galE15, galK16, rpsL1 (Str^r), hsdR2, mcrA1, mcrB1.*	Lab collection
L. lactis MG1363	Plasmid-free derivative of NCDO712	(74)
L. casei BL23	Wild type	B. Chassy, U. Illinois
L. casei ΔpsdR	BL23 *ΔLCABL_16430*	(32)
L. casei ΔapsR	BL23 Δ*rrp1* (*LCABL_19600*)	(31)
L. casei ΔderB	BL23 *ΔLCABL_21670*	This study
L. casei C-ΔderB	BL23 *ΔLCABL_21670* harbouring plasmid *pT1*-RBS$_{derB}$*derB Ery^r*	This study
L. casei ΔpsdB	*LCABL_16400* mutant; *pRV16400 Ery^r*	(32)
L. casei ΔapsB	*LCABL_19580* mutant; *pRV19580 Ery^r*	(32)
L. casei ΔdltA	*LCABL_08550 (dltA)* mutant*; pRV08550 Ery^r*	(32)
L. casei ΔmprF	*LCABL_24490* mutant; *pRV24490 Ery^r*	(32)
L. casei ΔderBΔpsdB	BL23 *ΔLCABL_21670*; *LCABL_16400* mutant, *pRV16400 Ery^r*	This study
L. casei ΔderBΔdltA	BL23 *ΔLCABL_21670*; *LCABL_08550 (dltA)* mutant, *pRV08550 Ery^r*	This study

748 [a] *Amp^r*, ampicillin resistance; *Ery^r*, erythromycin resistance; *Str^r*, streptomycin resistance.

749

TABLE 3. Vectors and plasmids used in this study

Vector or plasmid	Description[a]	Source or reference
pRV300	Insertional vector for *Lactobacillus*, *Amp*^{r}, *Ery*^{r}	(75)
pT1NX	Expression vector for Gram-positive bacteria harboring the constitutive P1 promoter; *Ery*^{r}	(58)
pRVOrPe-del	*pRV300* containing fused flanking fragments upstream and downstream of *LCABL_21670*	This study
pRV08550	*pRV300* containing a 679-pb internal fragment of *LCABL_08550* (*dltA*)	(32)
pRV16400	*pRV300* containing a 975-pb internal fragment of *LCABL_16400* (*psdB*)	(32)
pT1-RBS$_{derB}$*derB*	*pT1NX* with cloned *LCABL_21670* (*derB*) and its ribosome binding site (*derA-derB* 12 pb intergenic region)	This study
pUT18	Vector for B2H, *Amp*^{r}	Euromedex, BACTH System Kit Manual
pUT18C	Vector for B2H, *Amp*^{r}	
pUT18C zip	Control plasmid for B2H, *Amp*^{r}	
pKT25	Vector for B2H, *Kan*^{r}	
pKNT25	Vector for B2H, *Kan*^{r}	
pKT25 zip	Control plasmid for B2H, *Kan*^{r}	
pUT18C-HK9	*pUT18C* containing histidine kinase *psdS LCABL_16420*	This study
pKT25-HK9	*pKT25* containing histidine kinase *psdS LCABL_16420*	This study
pU-HK9-T18	*pUT18* containing histidine kinase *psdS LCABL_16420*	This study
pKN-HK9-T25	*pKNT25* containing histidine kinase *psdS LCABL_16420*	This study
pUT18C-RR9	*pUT18C* containing response regulator *psdR LCABL_16430*	This study
pKT25-RR9	*pKT25* containing response regulator *psdR LCABL_16430*	This study
pU-RR9-T18	*pUT18* containing response regulator *psdR LCABL_16430*	This study
pKN-RR9-T25	*pKNT25* containing response regulator *psdR LCABL_16430*	This study
pUT18C-Per9	*pUT18C* containing permease *psdB LCABL_16400*	This study
pKT25-Per9	*pKT25* containing permease *psdB LCABL_16400*	This study
pU-Per9-T18	*pUT18* containing permease *psdB LCABL_16400*	This study
pKN-Per9-T25	*pKNT25* containing permease *psdB LCABL_16400*	This study
pUT18C-ATP9	*pUT18C* containing ATPase *psdA LCABL_16410*	This study
pKT25-ATP9	*pKT25* containing ATPase *psdA LCABL_16410*	This study

pU-ATP9-T18	*pUT18* containing ATPase *psdA LCABL_16410*	This study
pKN-ATP9-T25	*pKNT25* containing ATPase *psdA LCABL_16410*	This study
pUT18C-HK12	*pUT18C* containing histidine kinase *apsS LCABL_19610*	This study
pKT25-HK12	*pKT25* containing histidine kinase *apsS LCABL_19610*	This study
pU-HK12-T18	*pUT18* containing histidine kinase *apsS LCABL_19610*	This study
pKN-HK12-T25	*pKNT25* containing histidine kinase *apsS LCABL_19610*	This study
pUT18C-RR12	*pUT18C* containing response regulator *apsS LCABL_19600*	This study
pKT25-RR12	*pKT25* containing response regulator *apsS LCABL_19600*	This study
pU-RR12-T18	*pUT18* containing response regulator *apsS LCABL_19600*	This study
pKN-RR12-T25	*pKNT25* containing response regulator *apsS LCABL_19600*	This study
pUT18C-Per12	*pUT18C* containing permease *apsB LCABL_19580*	This study
pKT25-Per12	*pKT25* containing permease *apsB LCABL_19580*	This study
pU-Per12-T18	*pUT18* containing permease *apsB LCABL_19580*	This study
pKN-Per12-T25	*pKNT25* containing permease *apsB LCABL_19580*	This study
pUT18C-ATP12	*pUT18C* containing ATPase *apsA LCABL_19590*	This study
pKT25-ATP12	*pKT25* containing ATPase *apsA LCABL_19590*	This study
pU-ATP12-T18	*pUT18* containing ATPase *apsA LCABL_19590*	This study
pKN-ATP12-T25	*pKNT25* containing ATPase *apsA LCABL_19590*	This study
pUT18C-OrPe	*pUT18C* containing permease *derB LCABL_21670*	This study
pKT25-OrPe	*pKT25* containing permease *derB LCABL_21670*	This study
pU-OrPe-T18	*pUT18* containing permease *derB LCABL_21670*	This study
pKN-OrPe-T25	*pKNT25* containing permease *derB LCABL_21670*	This study
pUT18C-OrATP	*pUT18C* containing ATPase *derB LCABL_21680*	This study
pKT25-OrATP	*pKT25* containing ATPase *derB LCABL_21680*	This study
pU-OrATP-T18	*pUT18* containing ATPase *derB LCABL_21680*	This study
pKN-OrATP-T25	*pKNT25* containing ATPase *derB LCABL_21680*	This study

[a] Amp^r, ampicillin resistance; Ery^r, erythromycin resistance; Kan^r, kanamycin resistance.

Supplemental Table 1. Quantification of the different sensitivity phenotypes of *L. casei* BL23 and *ΔderB* strains after exposition to insect derived AMPs. Stationary phase cell cultures of BL23 and *ΔderB* grown for 24 hours under reference conditions or in the presence of insect derived AMPs were photographed (see Figure 3 in the main text). The bacterial length, cell-chain length and number of cells per chain values were measured for each strain under the reference and stress conditions. Pairwise two-way ANOVA statistical analysis were applied to determine the contribution of the treatment and the strain to the morphological phenotypes (see Materials and methods in the main text for further details).

		Strain		ANOVA[d]		
Condition	Phenotype	BL23	*ΔderB*	Cond.	Strain	Int.
Reference conditions	Bacterial length (µm) [a, b]	3,22 ± 1,00	3,30 ± 0,83			
	Cell-chain length (µm) [a, c]	7,43 ± 2,74	9,92 ± 6,19			
	Number of cells/chain [a, c]	2,25 ± 0,54	3,03 ± 1,39			
BR005 320 µg/ml	Bacterial length (µm) [a, b]	2,80 ± 0,68	2,69 ± 0,64	**< 0,0001**	0,8318	0,0929
	Cell-chain length (µm) [a, c]	6,82 ± 2,65	7,59 ± 3,12	0,0200	0,0100	0,1711
	Number of cells/chain [a, c]	2,45 ± 1,01	2,9 ± 1,15	0,8362	**0,0004**	0,3304
BR090 400 µg/ml	Bacterial length (µm) [a, b]	2,85 ± 0,87	2,90 ± 1,10	**< 0,0001**	0,3104	0,8299
	Cell-chain length (µm) [a, c]	8,37 ± 4,22	21,1 ± 10,2	**< 0,0001**	**< 0,0001**	**< 0,0001**
	Number of cells/chain [a, c]	2,93 ±1,25	7,30 ± 3,55	**< 0,0001**	**< 0,0001**	**< 0,0001**
BR080 80 µg/ml	Bacterial length (µm) [a, b]	3,07 ± 0,83	2,57 ± 0,86	**< 0,0001**	**0,0008**	**< 0,0001**
	Cell-chain length (µm) [a, c]	7,82 ± 3,13	30,6 ± 21,7	**< 0,0001**	**< 0,0001**	**< 0,0001**
	Number of cells/chain [a, c]	2,55 ± 0,90	11,4 ± 7,46	**< 0,0001**	**< 0,0001**	**< 0,0001**

[a] The values represent means and standard deviations. [b] For bacterial length determination, n = 200 cells per condition; [c] for the determination of the cell-chain length and the number of cells per chain, n = 40 cell-chains per condition. [d] P values from pairwise two-way ANOVA analyses testing the growth of BL23 and *derB* mutant strain under the reference condition and in the presence of each of the three AMPs (BR005, BR090 and BR080) characterized microscopically in Figure 3. Significant differences (P value <0.01) are indicated in bold characters. Cond., condition; Int., interaction.

772 **Sup. Table 2. Primers used in this study**

Primer	Gene	Sequence (5´- 3´) [a]
Cloning		
RG037	LCABL_08550	AGTCAAGCTTGTTCAGATTATTCGCGCACC
RG038	LCABL_08550	GACTACTAGTCTGACACTTGATTGCCTTGC
RG047	LCABL_16400	**CTATAGGGCGAATTG**GGTACCGCAAGCCTTCAGTATCGCCG
RG048	LCABL_16400	**CTCGAGGGGGGGCCC**GGTACCTCAGCCGCGTTTTGATAGCG
RG062	LCABL_21680	TTTTCTCGAGTCAGGTTCAGGGAAAACGAC
RG063	LCABL_21680	GTGCGACCTAAAGGATCTTTTCTAGACGACGCCCCTTACTTTTG
RG064	Intergenic region LCABL_21670 and LCABL_21660	CAAAAGTAAGGGGCGTCGTCTAGAAAAGATCCTTTAGGTCGCAC
RG065	LCABL_21660	AAAAGAATTCCGCCTCAAAAGACTTCATGC
RG220	LCABL_21670	AAAAACTAGTTTAGGCTTTTTCCGCTAAGTTCTTATTG
RG221	LCABL_21670	AAAAAGATCTGGGGCGTCGTCTATGTTAACG
Cloning checking		
pRV300.fw	pRV300 vector	GTTTTCCCAGTCACGAC
pRV300.rv	pRV300 vector	CAGGAAACAGCTATGAC
pT1NX.fwd	pT1NX vector	TGGATTGGATTAGTTCTTGTGG
pT1NX.rev	pT1NX vector	CTTCTCTGTCGCTATCTGTTG
RG068	LCABL_21660	TATGAAGTCGGCTTCCCGCATG
RG069	LCABL_21680	GTGAATTCGTCGGCATCATG
RG076	LCABL_21680	AACACCCGCATTGAAAGGTG
RG077	LCABL_21660	TCAGCAAAAACGTCACTGGC
LSEI1418R	LCABL_16410	GTCAACATTACTTAAATTAAAAA
qRT-PCR		
lepA-F	lepA	CACATTGATCACGGGAAGTC
lepA-R	lepA	GTAATGCCACGTTCACGTTC
ileS-F	ileS	ACCATTCCGGCTAACTATGG
ileS-R	ileS	TCAGGATCTTCGGATTTTCC
pcrA-F	pcrA	CGGCCAATAATGTGATTCAG
pcrA-R	pcrA	TCATCAGTTTCGCTTTGAGC
pyrG-F	pyrG	AATTGCGCTTTTCACTGATG
pyrG-R	pyrG	CGAAATGATCGACCACAATC
RG006	LCABL_19580	GGGAACGCGCATTCATTGTG
RG007	LCABL_19580	TCTCGCGCTGAACAAGATCC
RG008	LCABL_21670	TTGCCGGTATTTTGGTCGGG
RG009	LCABL_21670	ATGTCCACAATACGGCTGGC
RG019	LCABL_08550	TGGTCGAGGTTTTCTTGGGC
RG020	LCABL_08550	CCGGTGTATGGGCAACATCC
RG021	LCABL_24490	GCCGGATCAGCCAAGACTTG
RG022	LCABL_24490	TTAGCATCGGTGTAACGGCG
RG027	LCABL_19590	TAGCTTTCAGGTCAACGCGG
RG028	LCABL_19590	CTTGGCGTCTCAATCGTTGC
RG029	LCABL_19600	GGCAATGAATATGGGCGCTG
RG030	LCABL_19600	TAGGTTCGTCGAAGCAAGGC
RG031	LCABL_21680	CACCCGCATTGAAAGGTGTC
RG032	LCABL_21680	GCAAGGTCGTTTTCCCTGAAC
RG033	LCABL_16410	GGACAGGATCTGAGCAACGTC
RG034	LCABL_16410	ATTGAAGGTGTCAAGCAAGTCG

	RG054	LCABL_16400	GTACCGTCCTTTCCCGCATC
	RG055	LCABL_16400	CCGATGGTAATGATCCCGGC
	RG056	LCABL_16430	AGCGAGTTACGCAAACACAG
	RG057	LCABL_16430	CGGCTCCTAAGTTCATCGCC
B2H			
	TM1220	pUT18 fwd	AGCTCACTCATTAGGCACCC
	TM1221	pUT18 rev	CCGTCGTAGCGGAACTGGCG
	TM1222	pUT18C fwd	TCGACGATGGGCTGGGAGCC
	TM1223	pUT18C rev	AGCAGACAAGCCCGTCAGGG
	TM1224	pKT25 fwd	GGCGGATATCGACATGTTCG
	TM1225	pKT25 rev	ATCGGTGCGGGCCTCTTCGC
	TM1226	pKT25N fwd	GCTCACTCATTAGGCACCCC
	TM1227	pKT25N rev	GGCGGAACATCAATGTGGCG
	TM5702	HK9-B2H-XbaI.fw1	AAAATCTAGAGATGATGAAAGCTTATTGCCGCTCG
	TM5703	HK9- B2H-SmaI.rv1	AAAACCCGGGTTACTCCACTTGCCACCGCG
	TM5704	HK9-B2H-SmaI.rv2	AAAACCCGGGGCTCCACTTGCCACCGCGTTTG
	TM5705	RR9-B2H-XbaI.fw1	AAAATCTAGAGATGGCACAGAAAATTTTTATTGTCGAAG
	TM5706	RR9-B2H-SmaI.rv1	AAAACCCGGGTCATGGCTTTGGTCCCTCAC
	TM5707	RR9-B2H-SmaI.rv2	AAAACCCGGGGTGGCTTTGGTCCCTCACTTGC
	TM5708	ATP9-B2H-XbaI.fw1	AAAATCTAGAGATGTCAACATTACTTAAATTAAAAAATATCGA AAAAAC
	TM5709	ATP9-B2H-BamHI.rv1	AAAAGGATCCTCTCATTGTCCATCGCCTGCCTTTG
	TM5710	ATP9-B2H-BamHI.rv2	AAAAGGATCCTCTTGTCCATCGCCTGCCTTTG
	TM5711	Per9-B2H-XbaI.fw1	AAAATCTAGAGATGAAATTCTACTTTAAGCTCGCTGC
	TM5712	Per9-B2H-SmaI.rv1	AAAACCCGGGTTAGCTGCGACTGGTAGCTTGG
	TM5713	Per9-B2H-SmaI.rv2	AAAACCCGGGGGCTGCGACTGGTAGCTTGGC
	TM6396	HK12-B2H-XbaI.fw1	AAAATCTAGAGATGCGGTTTCGTGATTATTTAAAGG
	TM6397	HK12-B2H-SmaI.rv1	AAAACCCGGGTCAGCTGTCTGGATGTGACCTAG
	TM6398	RR12-B2H-XbaI.fw1	AAAATCTAGAGGTGTTTAAAATCATGATCGTAGAGG
	TM6399	RR12-B2H-SmaI.rv1	AAAACCCGGGCTAAGGAACGATGTAACCTTGTC
	TM6400	P12-B2H-XbaI.fw1	AAAATCTAGAGGTGGAGGAGGCCATACCCGTG
	TM6401	P12-B2H-SmaI.rv1	AAAACCCGGGCTAATCAATCGCCCAACGGGAAAC
	TM6402	A12-B2H-XbaI.fw1	AAAATCTAGAGATGGCAATTCTTGAAGTATCTAACTTGAG
	TM6403	A12-B2H-SmaI.rv1	AAAACCCGGGTTAATCAGATGCCACACGGG
	TM6404	OrPe-B2H-XbaI.fw1	AAAATCTAGAGATGTTAACGAAACTTGCACTCGG
	TM6405	OrPe-B2H-BamHI.rv1	AAAAGGATCCTTAGGCTTTTTCCGCTAAGTTCTTATTG
	TM6406	OrA-B2H-XbaI.fw1	AAAATCTAGAGATGGACAAGCAACCTGTCGTAAC
	TM6407	OrA-B2H-BamHI.rv1	AAAAGGATCCTTACTTTTGAAATGTGCCGAGTGTG
	TM6408	HK12-B2H-SmaI.rv2	AAAACCCGGGGGCTGTCTGGATGTGACCTAGTCTG
	TM6409	RR12-B2H-SmaI.rv2	AAAACCCGGGGAGGAACGATGTAACCTTGTCC
	TM6410	P12-B2H-SmaI.rv2	AAAACCCGGGGATCAATCGCCCAACGGGAAACAG
	TM6411	A12-B2H-SmaI.rv2	AAAACCCGGGGATCAGATGCCACACGGGTATG
	TM6412	OrPe-B2H-BamHI.rv2	AAAAGGATCCTCGGCTTTTTCCGCTAAGTTCTTATTG
	TM6413	OrA-B2H-BamHI.rv2	AAAAGGATCCTCCTTTTGAAATGTGCCGAGTGTG

[a] Restriction sites are underlined. Sequences highlighted in boldface type are the sequences for the CloneEZ PCR reaction as in reference (32)

FIGURES

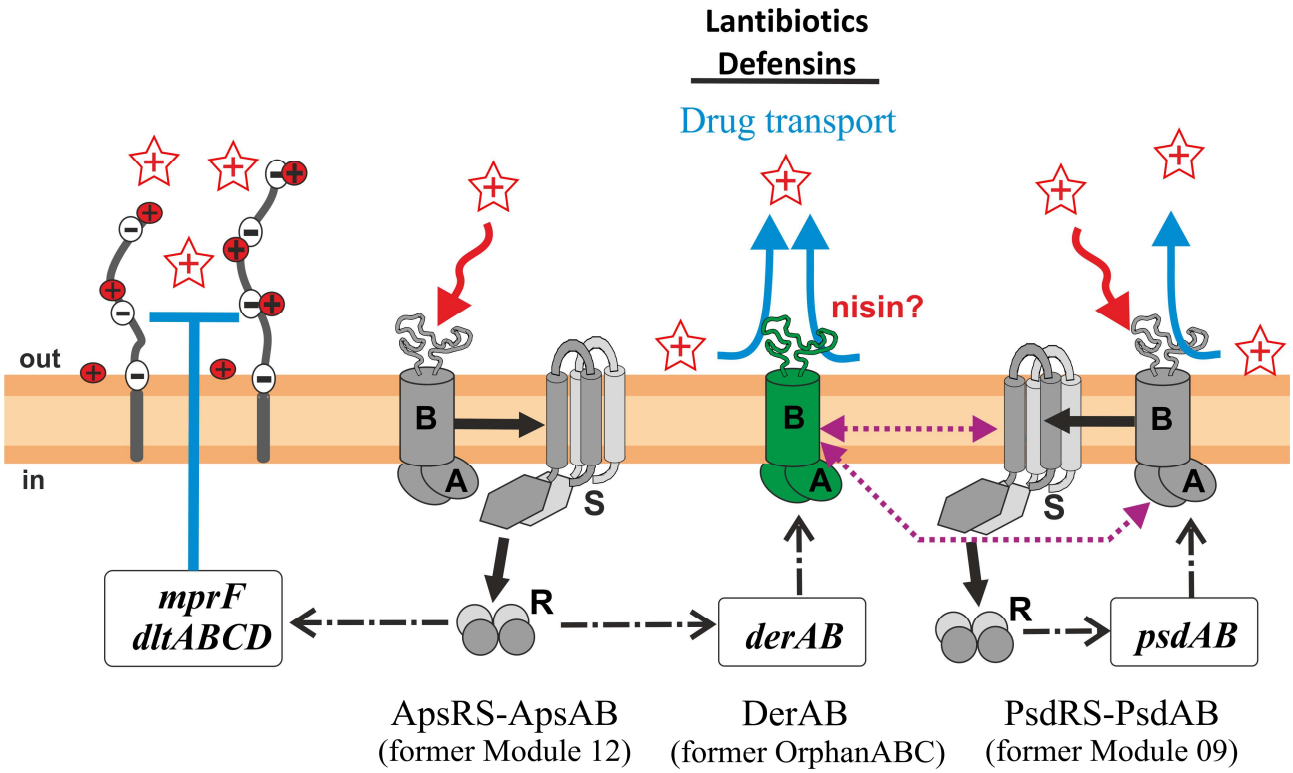
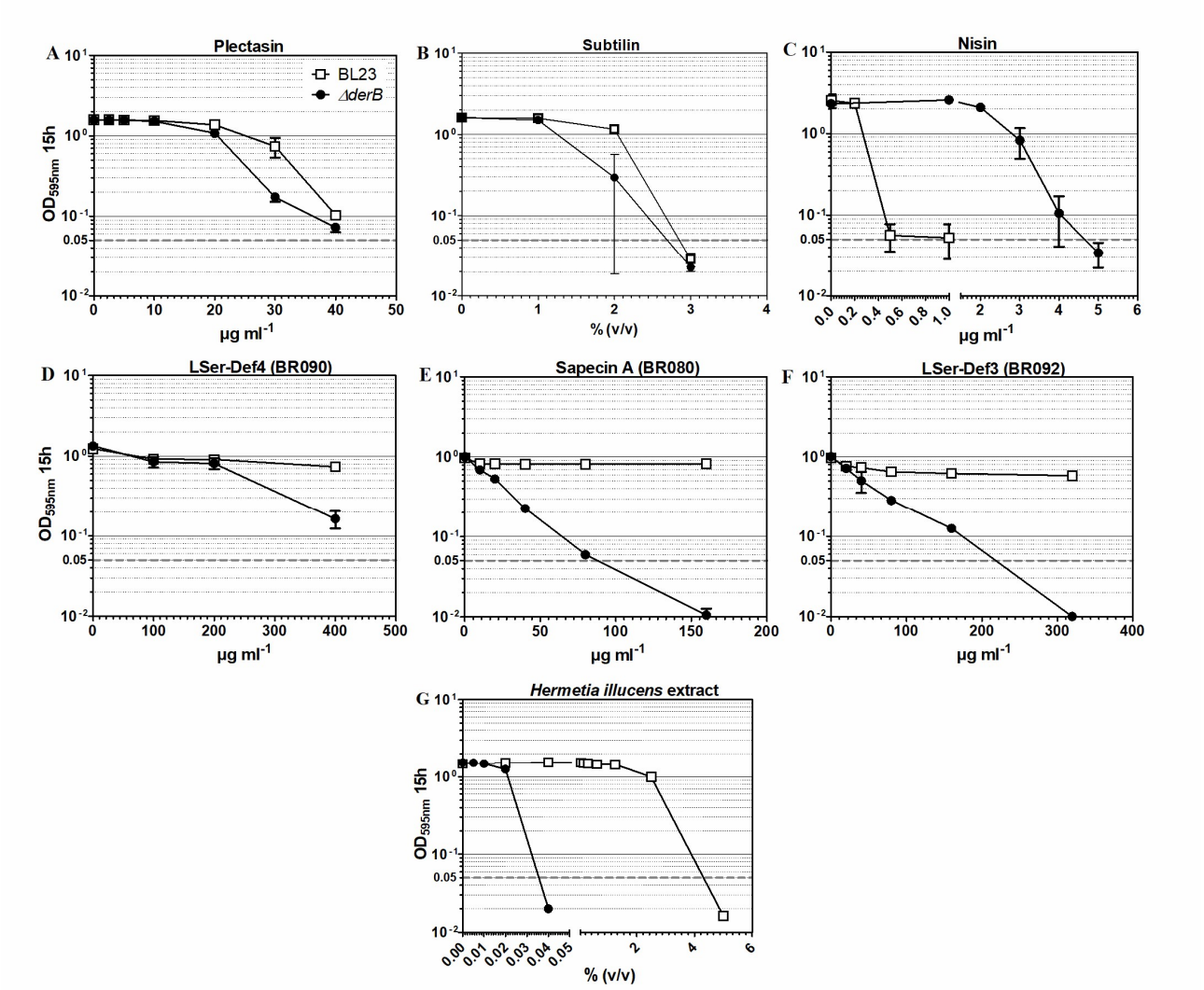


Figure 1: Different layers of resistance against AMPs in *L. casei* BL23.

ApsRSAB is a sensory module that regulates different layers of resistance against numerous AMPs. The primary layer of AMP resistance is mediated by DerAB (drug transport) and the secondary layer of resistance is mediated by the Dlt-system and MprF protein (drug repulsion). Resistance mediated by DerAB is specific for defensins and – to a lesser degree - lantibiotics (see text for details). PsdRSAB is a dual-function module involved in sensing and transport of various AMPs.

AMPs are depicted as red positively charged starts. S, histidine kinase; R, response regulator; B, permease; A, ATPase. Homodimers of HKs and RRs are indicated. ABC transporters are composed of a permease subunit and two ATPase domains (20). Signaling between the permeases and the HKs and between the HKs and the RRs is indicated by black solid arrows. Gene activation and the increased production of the transporters is indicated by black dash-dot arrows. Wave-shaped, downward red arrows indicate sensing of AMPs; blue up-facing arrows indicate transport and detoxification. B2H protein-protein interactions of DerB with PsdRSAB are indicated with purple dotted lines. Lipoteichoic acids are indicated with grey negatively charged lines; D-alanylation of teichoic acids and L-lysinilation of membrane phospholipids is indicated with positive red-filled spheres; AMP charge-repulsion is indicated with a bar-headed up-facing blue line.



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796 **Figure 2: MIC of different AMPs for *L. casei* BL23 (white squares) and *ΔderB* strains (black**
797 **circles). (A)** Plectasin. **(B)** Subtilin. **(C**) Nisin. **(D)** LSer-Def4 (BR090). **(E)** Sapecin A (BR080). **(F)** LSer-
798 Def3 (BR092). **(G)** Extract from *H. illucens* larvae. Strains were inoculated to an OD_{595} of 0.05
799 (dashed line) in MRS with different concentrations of antibiotics. Final OD_{595} readings were taken
800 after 15h incubation at 37°C (OD_{595} 15h). MIC (see Table 1) was defined at the lowest antibiotic
801 concentration where the final OD was at or below the starting OD. Mean and standard deviation
802 are presented of at least duplicates. A representative result of *H. illucens* extract is presented
803 because due to the preparation procedure, the absolute potency of each extract (as expressed in
804 %) varies significantly between individual preparations, but the relative sensitivities were very well
805 reproduced in independent assays.

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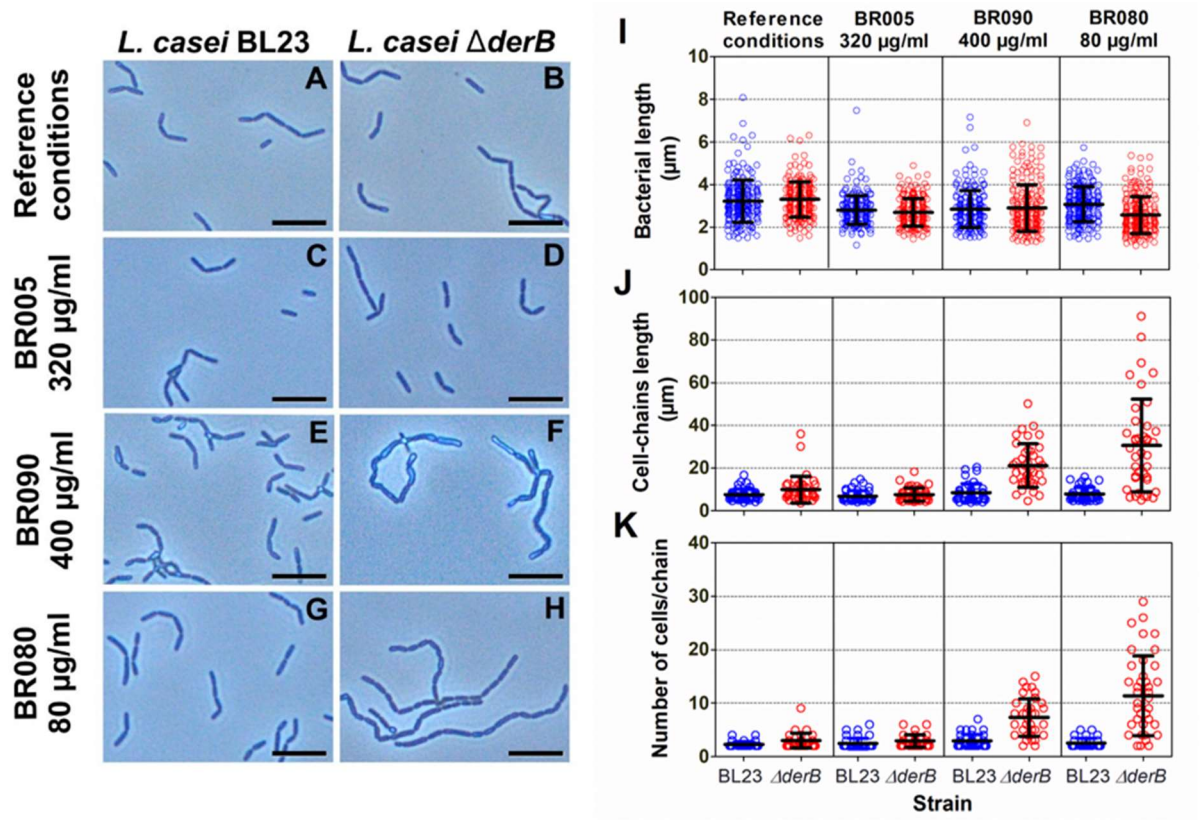

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808 **Figure 3: Sensitivity phenotypes of *ΔderB* strain are associated to morphological changes.**
809 **(A - H) Microscopic characterization after AMP exposition:** stationary phase cell cultures of BL23
810 (left column pictures) and *ΔderB* (right column pictures) grown for 24 hours under reference
811 conditions **(A and B)** or in the presence of insect derived AMPs were photographed (phase
812 contrast, 40x magnification). Selected AMPs were chosen as representative of different
813 sensitivities of the *ΔderB* strain relative to the wild type (see Table 1). Similar sensitivity
814 phenotype: BR005 at 320 µg ml^{-1} **(C and D)**. *ΔderB* slightly more sensitive than BL23: BR090 at 400
815 µg ml^{-1} **(E and F)**. Mutant much more sensitive than wild type: BR080 at 80 µg ml^{-1} **(G and H)**. Scale
816 bar 10 µm.
817 **(I - K) Quantification of the morphological changes associated to the sensitivity phenotypes.**
818 **(I)**The average bacterial length (µm; n = 200), **(J)** the average cell-chains length (µm; n = 40 cell-
819 chains) and **(K)** the average number of cells per chain (n = 40 cell-chains) of the stationary phase
820 cell cultures photographed in **(A - H)** were determined. Means and standard deviations are
821 indicated with the horizontal and the bar-headed vertical black lines, respectively. For a detailed
822 statistical analysis of the results see Supplemental Table 1.

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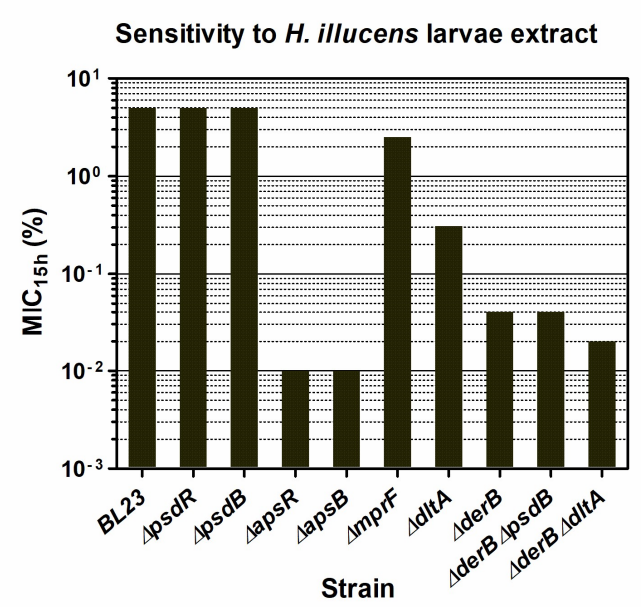

825

826 **Figure 4: Different layers of resistance against AMPs from *H. illucens*.** MIC at 15h (expressed as
827 % (v/v) of initial extract) of *H. illucens* larvae extract against *L. casei* BL23 and derivative strains. A
828 representative dataset is shown. Due to the preparation procedure, the absolute potency of each
829 extract (as expressed in %) vary significantly between individual preparations, but the overall
830 relative sensitivities were very well reproduced in independent assays.

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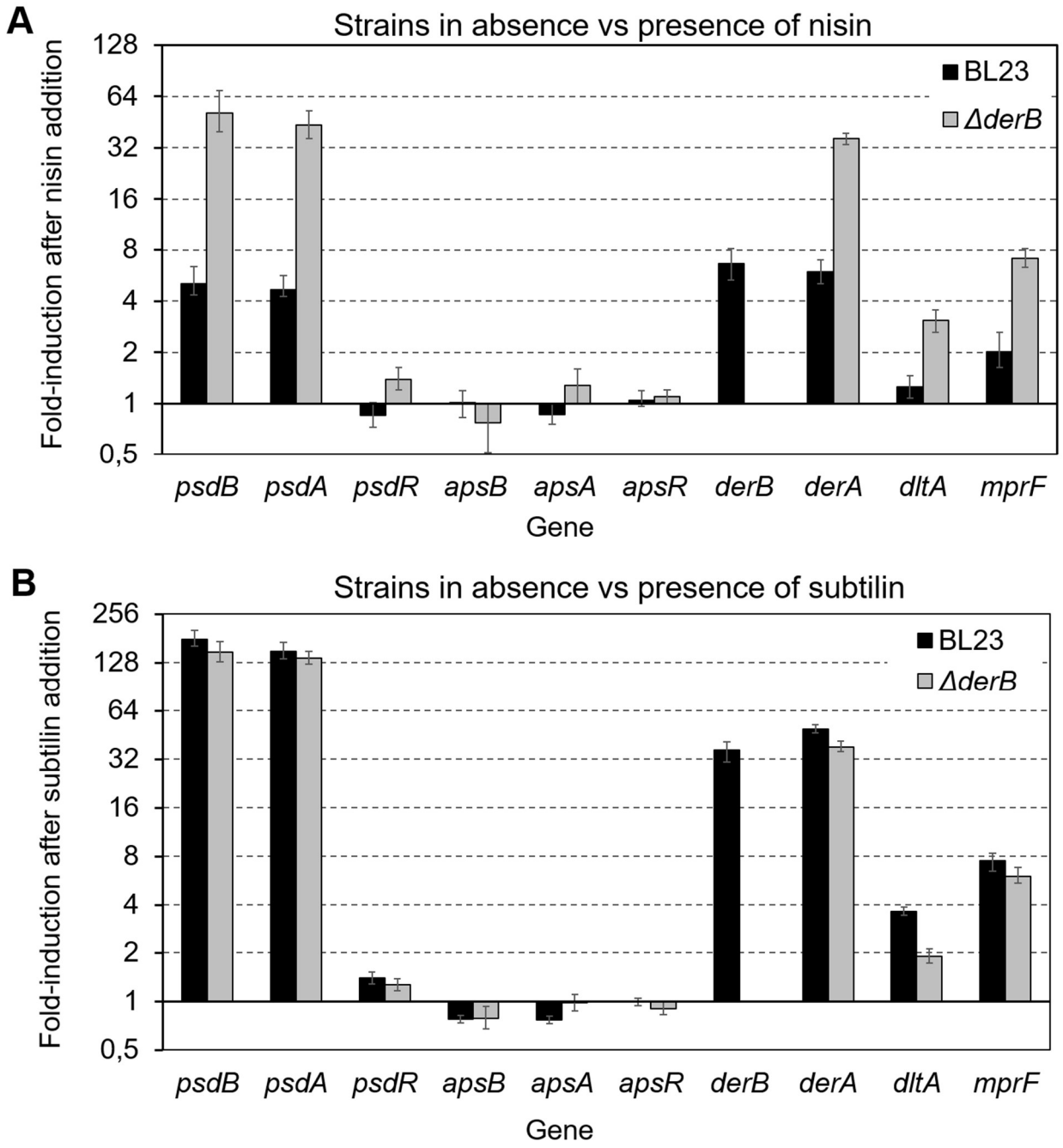

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839 **Figure 5: Expression of known AMP resistance determinants in *L. casei* BL23 and *ΔderB* mutant**
840 **after nisin (A) and subtilin (B) addition.** Transcript levels were determined by real-time RT-PCR
841 10 min after addition of 22.5 ng ml^{-1} nisin **(A)** and 1% subtilin **(B)**. X-fold induction was calculated
842 relative to transcript levels in the same strain under reference conditions. Data are shown as mean
843 ± standard error of at least six replicates.

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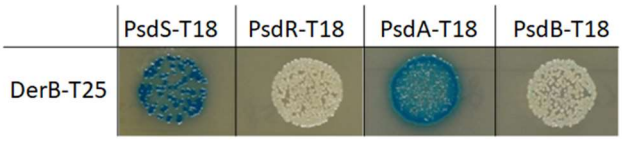

Figure 6: Bacterial two-hybrid analysis of the interactions of DerB with the PsdRSAB module. C-terminal and N-terminal translational fusions of the T18 and T25 domains of the adenylate cyclase CyaA of *B. pertussis* were created for each protein individually. Different hybrid fusions were tested in pairwise combinations in *E. coli* BTH101. The cells were spotted onto LB plates containing X-Gal (100 µg ml^{-1}), IPTG (1 mM), and antibiotics for selection. Pictures were taken after 48 h of incubation at 30 °C. The blue colonies indicate positive interaction results. For clarity, only a single representative pair is shown in the figure. See Figure S6 for the complete set of combinations.