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Genetics of Lactococci

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ABSTRACT *Lactococcus lactis* is the best characterized species among the lactococci, and among the most consumed food-fermenting bacteria worldwide. Thanks to their importance in industrialized food production, lactococci are among the lead bacteria understood for fundamental metabolic pathways that dictate growth and survival properties. Interestingly, lactococci belong to the Streptococcaceae family, which includes food, commensal and virulent species. As basic metabolic pathways (e.g., respiration, metal homeostasis, nucleotide metabolism) are now understood to underlie virulence, processes elucidated in lactococci could be important for understanding pathogen fitness and synergy between bacteria. This chapter highlights major findings in lactococci and related bacteria, and covers five themes: distinguishing features of lactococci, metabolic capacities including the less known respiration metabolism in Streptococcaceae, factors and pathways modulating stress response and fitness, interbacterial dialogue via metabolites, and novel applications in health and biotechnology.

INTRODUCTION

Lactococci have been used for centuries in dairy fermentation. These Gram-positive, generally nonpathogenic, nonmotile, and nonsporulating bacteria are members of the Streptococcaceae family, which includes food, commensal, and virulent species (Fig. 1). *Lactococcus lactis* is a relatively simple bacterium, with a 2.4-Mbp genome. Many of its functions of interest are nonredundant, which facilitates functional genetic studies of nonessential genes. Lactococci are presumed to be devoid of virulence factors (although isolated cases of *L. lactis* as the infectious agent in human and bovine infections have been reported [1, 2]). The goal of this article is to confront previous and current information in different areas of lactococcal genetics, keeping in mind the relevance of findings to related

bacteria, especially pathogens. Work on pathogens has long focused on surface and secreted virulence factors, while work on lactococci has gone deeper in characterizing basic metabolic properties, nutrient uptake, and survival. Genes in basic metabolic pathways (e.g., respiration, metal homeostasis, amino acid metabolism) are now known to be essential not only for fitness but also for virulence. Numerous *Lactococcus* researchers who shifted their focus to pathogens have contributed to this understanding. The overall nonvirulence of lactococci has also been useful in determining how metabolic and virulence factors participate in bacterial “everyday life” outside the animal host. Our deep knowledge of *L. lactis* physiology has led to new concepts and general findings, for example by (i) establishing the bases for dialog between Firmicutes, (ii) providing concrete *in vivo* data on

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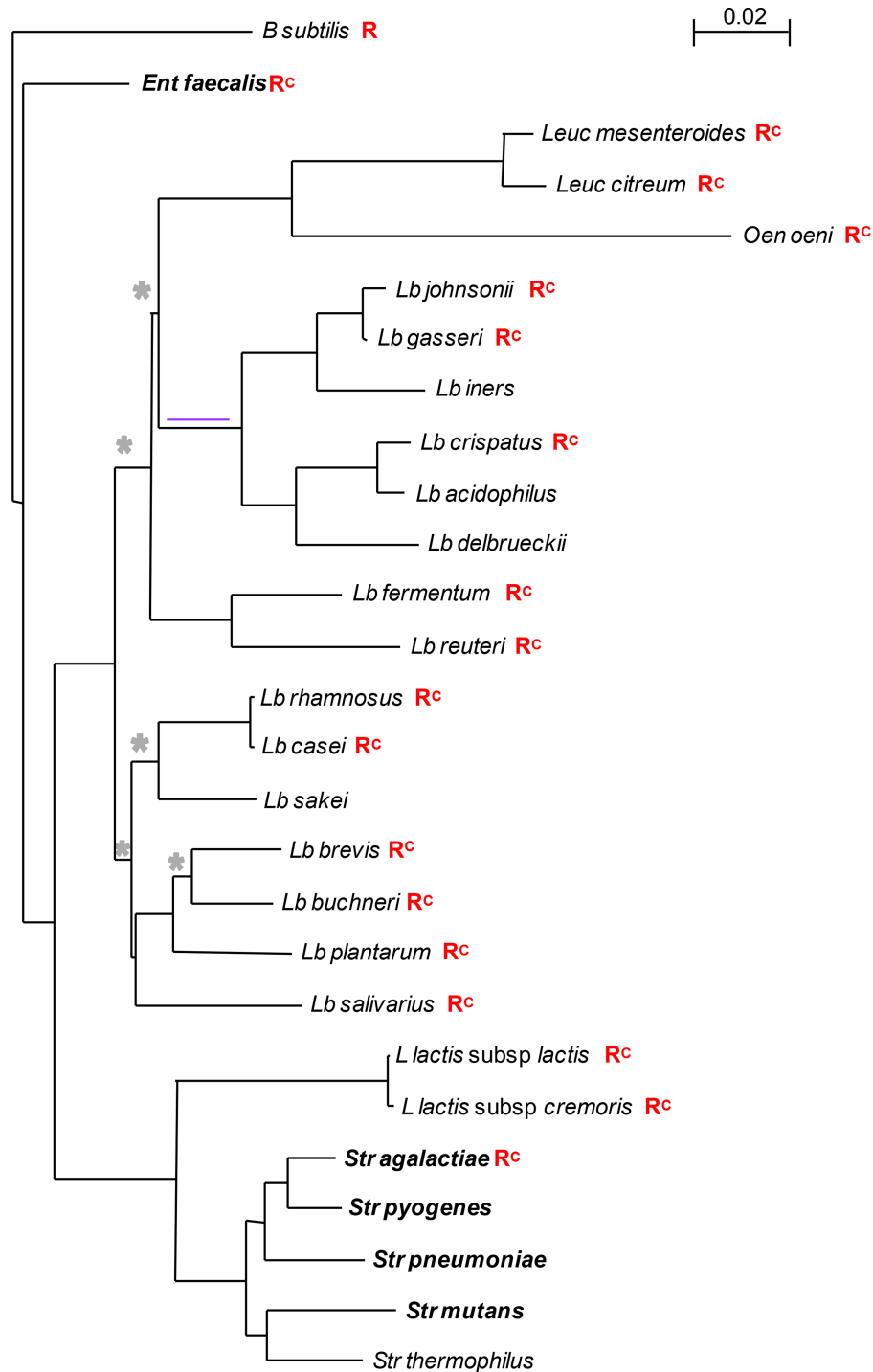


FIGURE 1 The phylogenetic tree reveals similarities between lactococci and streptococcal pathogens. A phylogenetic tree built on 16S sequences was constructed directly on the Ribosomal Database interface (210). Branches with a bootstrap value below 60% are indicated with an asterisk. Respiration capacity (see text) is indicated by a red R. R^c indicates conditional respiration: for *L. lactis*, *E. faecalis*, and *Leuconostoc* spp., aerobic respiration is activated by exogenous heme. For all *Lactobacillus* spp. and *S. agalactiae*, respiration is activated by exogenous heme and menaquinone. Opportunist pathogens are indicated in bold. *B. subtilis*, *Bacillus subtilis*; *Ent.*, *Enterococcus*; *Leuc.*, *Leuconostoc*; *Oen.*, *Oenococcus*; *Lb.*, *Lactobacillus*; *Str.*, *Streptococcus*. This figure is based on reference 155.

the biomedical or probiotic potential of recombinant and wild-type lactic acid bacteria (LAB) (3, 4), and (iii) establishing the existence of an inverse correlation between bacterial mRNA concentration and stability (5).

This article, organized in five sections, highlights major work in lactococci, including metabolic capacities, physiology, stress response, interbacterial effects, and studies leading to novel uses of lactococci for protein delivery or as probiotics. Prophages have a primordial role in fermentation processes, genetic diversity, expression, and cell lysis; this important area of research, including abortive infection mechanisms, is not a focus of this review (see 6–12). Comparative *L. lactis* genome organization analyses are considered in references 13 and 14 and references therein.

The first section, “Basic Features of Lactococci,” presents a primary description of *L. lactis* and its relationship to other *Streptococcaceae*. The next section is “Metabolic Options for Lactococci.” Because lactococci are industrial bacteria, the study of them has focused on optimizing growth and flavor production during fermentation. Lactococci shift to a respiration metabolism when provided with an exogenous heme source. Metabolic flexibility provides a valuable prototype for the lifestyle of other LAB and certain streptococcal pathogens, which respire when supplied with heme and menaquinones. Nitrogen metabolism is extensively studied in *L. lactis*, because it determines the capacity to grow in dairy medium for food fermentation. Remarkably, nucleotide metabolism coordinates intracellular pools with the envelope state. The third section is “Lactococcal Stress Responses.” Lactococci, though largely consumed through fermented foods, have been considered noncolonizers of the animal host. Lactococci express numerous and diverse factors that allow bacteria to respond and survive in a crowded or hostile environment and were identified by simple selective systems. Unique structures discovered on the lactococcal envelope (pellicles and pili) may extend survival in harsh environments, notably the gut, and narrow the divide between food bacteria and pathogens. The fourth section, “*L. lactis* and Interbacterial Dialogue” discusses how lactococci impact expression and/or development of other bacteria in their biotopes, including pathogens. Several findings may prove valuable when considering the roles of cognate functions in pathogens. The last section is “Applications and Tools of Lactococci.” Lactococci are useful bacterial vectors for biomolecule delivery. Protein expression systems were developed in lactococci for applications in biotechnology and have been used for expression in related low-GC-content Gram-positive bacteria, including pathogens; remarkably, some of them

have stayed in use for over 25 years. As a simple non-pathogen, *L. lactis* is a useful host for separating potential virulence factors from pathogenic bacteria and analyzing their roles. While medical applications have not been marketed, numerous proof of concept studies show the feasibility of using *L. lactis* or other LAB as biomolecule delivery vectors (see 15 and 16 for reviews).

BASIC FEATURES OF LACTOCOCCI

What Is *L. lactis*?

LAB are named for their ability to produce lactic acid via fermentation metabolism. *L. lactis* is a mesophilic LAB with an optimal growth temperature of ~30°C. It is the most extensively characterized of the LAB, which comprise a highly diverse group (Table 1, Fig. 1), including various cocci and bacilli. However, the term “LAB” is misleading, because although “LAB” generally refers to bacteria used in food fermentation, lactic acid producers also include opportunists and pathogens, including streptococci and enterococci; of note, *Enterococcus faecalis*, despite its reported beneficial effects for fermentation, has now clearly emerged as an important clinical antibiotic-resistant opportunist pathogen that may lead to intestinal dysbiosis after antibiotic treatments (17–19). Among sequenced relatives, *L. lactis* is related to *Streptococcus mutans* (Fig. 1). The 2.4-Mb genome of *L. lactis* strain IL1403 is intermediate in size between streptococcal pathogens such as *Streptococcus pneumoniae* and *Streptococcus pyogenes* (reported as 2.1 and 1.9 Mb, respec-

TABLE 1 Characteristics of *L. lactis*

Characteristic	Description
Classification	Gram-positive 38% GC content 2.4 Mb Nonpathogenic food microorganism (referred to as a lactic acid bacterium)
Close neighbors	Streptococci (food, commensal, pathogen)
Optimal growth temperature	30°C
Growth media	Plants, milk, food silage, farm animals, and human gut constituents
Environmental contacts	Plants (environmental niche) Farm animals Milk and other foods (environmental niche may rely on plasmid-encoded factors) Gastrointestinal tract
Metabolism	Fermentation Respiration in aerobic, heme-containing medium
Survival	Usually poor after fermentation growth Good long-term survival after growth by respiration

tively) and *E. faecalis* (3.4 Mb). Although described as “cocci,” *L. lactis* subpopulations may differentiate to a rod shape, possibly reflecting a change in the proportions of wall and division enzymes (20).

L. lactis is classified within the *Streptococcaceae* family, and it appears that *L. lactis* and the pathogenic streptococci may have a common origin. In addition to high genetic relatedness, DNA motifs called Chi, which are required for chromosomal integrity and are over-represented in *L. lactis*, are identical to Chi sites present in both pathogenic and food-derived *Streptococcaceae*, providing evidence that a common core genome organization preceded divergence of streptococcal pathogens and food bacteria (21). Relatedness between *L. lactis* and streptococci surpasses by far that with many other LAB (including *Lactobacillus* species; Fig. 1). Streptococci also produce lactic acid and thus may be considered a branch of LAB. The *Streptococcaceae* family diverged as the result of unknown selective pressures to generate groups of pathogens, colonizers, and food bacteria, which seem to have diversified to adapt to their preferred biotopes.

Varied Lifestyle of LAB

L. lactis and LAB in general seem to have a varied lifestyle. Lactococci are isolated from plants and are likely to be ingested by grazing animals, together with milk in the case of calves. Coingestion could explain how lactococci ended up in milk. The need for several plasmid- or transposon-encoded characteristics for growth in milk (e.g., enzymes for sugar and protein metabolism, DNA restriction and abortive phage infection functions, and bacteriocins) supports the hypothesis that milk is not the original habitat of LAB.

Genome Plasticity

Studies of lactococci have focused on two organisms, IL1403, an *L. lactis* subsp. *lactis* strain, and MG1363, an *L. lactis* subsp. *cremoris* strain. Despite ~80% sequence identity between these genomes, they differ by a large chromosomal inversion (22). Even closely related isolates of MG1363 show considerable polymorphism, corresponding to large rearrangements (23) that might be mediated by mobile elements. Studies of artificial chromosomal rearrangements suggest that lactococci tolerate certain large genomic inversions if the origin and terminus regions are not disturbed (24).

Genome transfer and rearrangements may occur in lactococci via conjugation, transposition or insertion sequences, and phage transduction, as suggested by the identification of the required elements in different species, or by experimental systems in which natural DNA

transfer occurs (see 25–28 for examples). DNA transfer occurs in streptococci by natural competence, as first discovered and then characterized in *S. pneumoniae* (29). Since then, competence among LABs was shown for *Leuconostoc mesenteroides* and *Streptococcus thermophilus* (30–33). *L. lactis* strains encode homologs of all late competence genes that are regulated by ComX; *comX* overexpression led to the induction of several genes linked to late competence (e.g., *comGA*, *GB*, *GC*, *GD*, *EA*, *EC*, *FA*, *FC*, *C*, *dprA*, and *coiA*), but these bacteria seemed to be defective for competence (34). Nevertheless, overexpression of ComX did lead to competence in a subgroup of lactococci (35, 36) but not in *L. lactis* model strains IL1403 and MG1363. In *L. lactis* strains KW2 and KF147, *comX* overexpression led to a transformation rate of 10^{-5} to 10^{-7} transformants/total cell number/ μ g of plasmid. These rates are similar to those obtained by electroporation in glycine-treated cells (37).

L. lactis IL1403 contains 40 putative insertion elements, 14 of which correspond to an insertion sequence element similar to IS1070 from *Leuconostoc lactis*, and at least 4 prophage elements (38, 39). *L. lactis* and *S. thermophilus* share common integrative conjugative elements, as well as highly conserved regions coding, for example, exopolysaccharide synthesis enzymes (26). The existence of functional genes that have been transferred to *L. lactis* is suggested by the presence of atypical regions, i.e., those containing DNA that differs structurally from its context, or unexpected open reading frames (Orfs), e.g., a hemolysin-like protein. Similarly, an *S. thermophilus* isolate was shown to encode a pigment that was suspected to be transferred from pathogens and usually lost in milk bacteria (40).

Close interactions between microorganisms, e.g., in the gastrointestinal or vaginal mucosa of animals, or in industrial milk fermentation processes, could lead to horizontal genetic exchange. Contact between these bacteria is also suggested by the existence of nearly identical genes, e.g., in lactococci and *S. thermophilus* (26). Close physical contact, visualized microscopically between *S. thermophilus* and *Lactobacillus bulgaricus*, may facilitate genetic exchange (41).

METABOLIC OPTIONS FOR LACTOCOCCI

Lactococcal metabolism has been intensively studied because of its industrial importance in fermentation processes, with a focus on metabolic pathways and their engineering (42). Importantly, basic metabolic functions may have far-reaching effects, and as described below,

metabolic shifts can result in dramatic changes in *L. lactis* growth characteristics and survival.

A remarkable metabolic process in lactococci, respiration, was essentially overlooked with the focus on dairy fermentation (43). Researchers confirmed and developed a 1970 study showing that lactococci not only ferment sugars but are also capable of forming an active electron transport chain to generate respiration metabolism (44–47). *L. lactis* respiration requires an external heme source due to an incomplete biosynthetic pathway (48). The respiration process and relevance for certain pathogenic streptococci and numerous lactobacilli is discussed below.

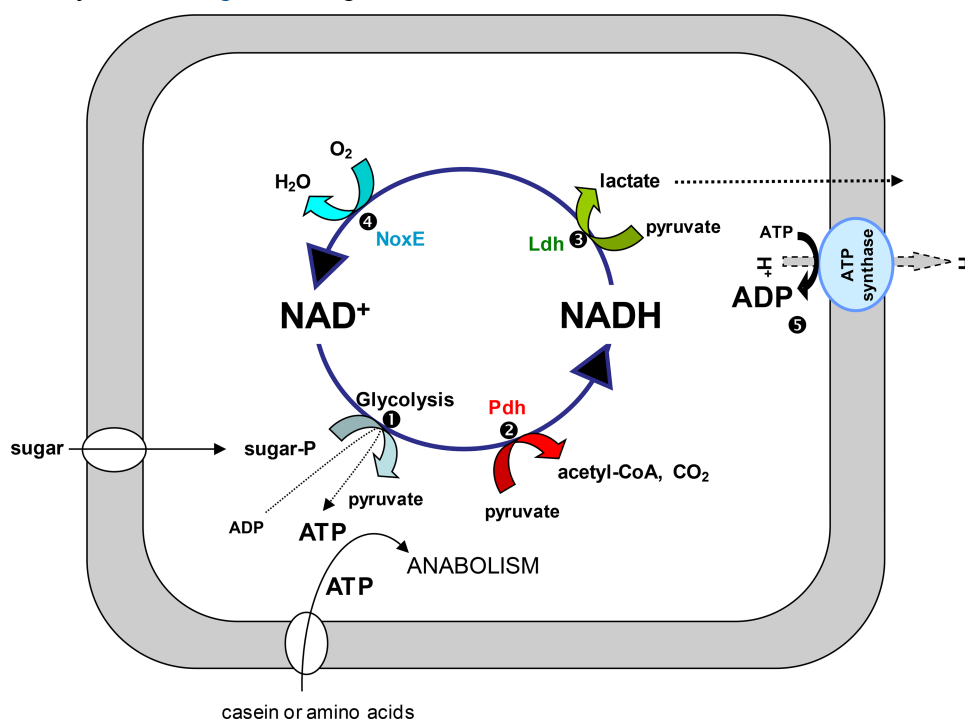
The two energy metabolism options, fermentation and aerobic/anaerobic respiration, are presented in the fol-

lowing sections. Pathways for nucleotide metabolism are also described, including a link established between nucleotide homeostasis and cell wall regulation.

Energy Option 1: Fermentation in *L. lactis*

Simplistically, lactococci use sugars to provide energy and amino acids to synthesize proteins (Fig. 2). Dairy lactococci have multiple nutritional requirements for amino acids and vitamins, probably resulting from their adaptation to a life in milk. Lactose is the major sugar source in milk, and through its uptake and degradation, lactococci generate energy in glycolysis. Casein, the major protein component in milk, is degraded to provide the major carbon source for anabolism. The flow of carbon

FIGURE 2 Basics of *L. lactis* fermentation. The NADH/NAD⁺ ratio is placed as a central determinant of carbon metabolic choice in *L. lactis* (56). **(1)** Sugar fermentation generates ATP, which is used for amino acid anabolism. In anaerobic conditions and rapid sugar flux, essentially all sugar is converted to lactate (homolactic fermentation) from pyruvate (glycolysis). When sugar flux is slower, in the presence of sugars other than glucose or lactose or in aerobic growth, mixed acid fermentation may occur. The latter conditions are characterized by lower NADH/NAD⁺ ratios than those found during homolactic fermentations. Besides NADH, glycolysis generates ATP and pyruvate from sugar degradation. **(2)** Pyruvate dehydrogenase (Pdh) provides extra NADH from pyruvate when oxygen is present. **(3)** Lactate dehydrogenase (Ldh) oxidizes NADH into NAD⁺ by conversion of pyruvate into lactate, thus maintaining glycolytic activity during fermentation. **(4)** When oxygen is present, NADH can be oxidized by the cytoplasmic H₂O-forming NADH oxidase (NoxE), generating NAD⁺. **(5)** The ATPase expulses H⁺ at the expense of ATP to avoid acidification due to glycolysis. Pyruvate build-up leads to synthesis of acetate or the neutral acetoin and diacetyl (also see Fig. 4). This figure is modified from reference 155.



for energy production is therefore almost separable from the flow of carbon for anabolism in these bacteria, making them ideally suited for metabolic studies.

All species belonging to the genus *Lactococcus* produce acid from glucose, fructose, mannose, and N-acetylglucosamine. *L. lactis* species used for dairy fermentation undergo mainly homolactic fermentation of lactose and other sugars. *L. lactis* subsp. *lactis* strains are more versatile than *L. lactis* subsp. *cremoris* in their use of diverse sugar sources, including maltose, ribose, and trehalose (reviewed in 49). Sugars may be transported by a plasmid-encoded phosphotransferase system in dairy strains or at a slower rate by a permease in nondairy strains (50).

Carbohydrate fermentation may be shifted from homolactic (lactate production) to mixed acid fermentation (acetic acid, formic acid, CO₂, acetoin, and ethanol produced in addition to lactate; Fig. 2). Two sets of conditions accompany this change, namely, (i) an altered redox state created by increased aeration during growth or (ii) reduced entry of sugar that is used for energy production.

Under the first set of conditions, oxygen appears to be involved in maintaining the NADH/NAD ratio, which itself seems to regulate the switch between homolactic and mixed acid fermentation (50); aerobic conditions result in oxidation of NADH to NAD⁺ (catalyzed by NADH oxidases), thereby reducing the NADH/NAD⁺ ratio in the cell. Lactate dehydrogenase (Ldh) is active at high NADH/NAD⁺ ratios (i.e., low oxygen), while glyceraldehyde-3-phosphate dehydrogenase (GAPDH) is inhibited. Increasing the amounts of water-forming NADH oxidase from a nisin-inducible promoter was shown to decrease the NADH/NAD ratio and to decrease *in vivo* activity of Ldh. The increased pyruvate pool was directed to acetoin and the flavor compound diacetyl. Other types of engineering (e.g., through mutations which block specific pathways) can also result in altered flavor properties in lactococcal fermentation (reviewed in 42, with descriptions of applications in 51–54). Note that Ldh is essential in *S. mutans* but not in *L. lactis*, possibly because *S. mutans* lacks alternative pathways for reoxidation of NADH that are present in *L. lactis*. Among the three Ldh-like Orfs potentially present on the *L. lactis* IL1403 genome, studies suggest that at least two genes encoding functional Ldh are potentially expressed (55).

Under the first set of conditions, sugar entry may be decreased if galactose is used as an energy source or when lactose is transported by a permease (56). All sugar-carbon utilization produces pyruvate regardless of the growth conditions and the pathway; the activity of en-

zymes using pyruvate as a substrate determines if fermentation is homolactic or mixed acid. Decreased sugar flow thus favors the activity of enzymes giving rise to mixed fermentation products. One hypothesis is that when carbon fluxes are high, GAPDH is a bottleneck in glycolysis, resulting in high pools of upstream intermediates. These pools would then inhibit pyruvate formate-lyase in one of the fermentation pathways from pyruvate, resulting in homolactic fermentation under anaerobic conditions. The extent to which GAPDH is a bottleneck in lactococci was examined by constructing strains with GAPDH activities ranging from 13 to 210% of the normal activity and measuring metabolic fluxes (57, 58). Surprisingly, GAPDH was in large excess even when carbon fluxes were high; in terms of flux control, GAPDH would thus not be the controlling factor. Moreover, the fermentation pattern remains homolactic even after 4-fold reduction of GAPDH activity, which shows that GAPDH has no control over mixed acid flux either. Similar studies were carried out to determine the importance of other glycolytic enzymes on the fermentation pattern. Phosphofructokinase had no control over glycolytic flux or on mixed acid flux (59), despite the presence of this enzyme in excess (60). Ldh had no control over glycolytic flux either but did exert a strong negative control over mixed acid flux (61). An intriguing possibility is that the excess glycolytic enzymes are somehow shuttled to the surface, where they could play other roles in bacterial dissemination; glycolytic enzymes, like GAPDH, have been reported to be present on the surface of numerous *Streptococcaceae* (62–64).

The genetic organization of enzymes involved in sugar utilization may reveal regulation at the transcriptional level. *L. lactis* appears to coordinate the expression of three genes, each involved in key but distinct steps in fermentation, *pfk*, *pyk* (encoding phosphofructokinase and pyruvate kinase, respectively) and *ldh* genes, by having them present in one operon (called *las*). The operon organization may prevent unwanted accumulation of glycolytic intermediates. In *S. pyogenes* and *S. pneumoniae*, the *ldh* gene is not within this operon, suggesting that a common regulation of the three genes may be unique to lactococci. The *las* operon is induced in the presence of glucose via the catabolite control protein CcpA (65). Expression of the entire *las* operon was modulated to determine its importance for metabolic flux; flux was highest when expression was at its normal level and decreased rapidly when expression was reduced or increased (59).

In *Escherichia coli*, glycolytic metabolic flux is controlled almost exclusively by the demand for ATP.

In *L. lactis*, the ATP demand also controls flux in slow- or nongrowing cells but not in fast-growing cells (59, 66–68).

The importance of individual enzymes for system properties such as fluxes, metabolite concentrations, frequencies of infection, survival rates, etc., can be accessed by modulating the activities of the respective components. Using synthetic promoters has proven useful for obtaining accurate tuning of gene expression and optimizing metabolic fluxes (57, 58). Moreover, this technique allows numerous genes to be modulated simultaneously and at differential levels in a cell; in one example an *L. lactis* strain was constructed in which all 10 genes encoding the enzymes of the glycolytic pathways were upregulated using synthetic promoter libraries (69).

Energy Option 2: Respiration in *L. lactis*

Components of the electron transport chain

An active respiration chain comprises three elements: (i) an electron donor, supplied by NADH dehydrogenases, (ii) menaquinones (including demethylmenaquinones or DMK), which are non-protein components of the respiration chain that deliver electrons to the terminal oxidoreductases, and (iii) terminal oxidoreductases, which contain heme as an essential cofactor and use oxygen as the final electron acceptor (70, 71). Although *L. lactis* undergoes fermentation in a rich medium, addition of a heme source to an aerated medium activated respiration metabolism in *L. lactis* (44, 46). Demonstration of the existence of an electron transport chain and heme-dependent membrane NADH oxidase activity, and identification of factors implicated in respiration, all point to the major impact of this metabolic mode on bacterial growth and survival (Fig. 3) (45–47, 72–75). Heme-stimulated growth leads to an approximate doubling of cell biomass (in keeping with greater energy production by respiration activity), increased pH, and massive production of acetoin rather than lactic acid (46, 76). In combination with sugar-limiting conditions, as occurs during growth on maltose, the biomass yield increased further and indicated a reversal of the function of the H⁺-ATPase toward the direction of ATP synthesis (77). An important feature of respiration metabolism is decreased oxidation in the cell, due to respiration-dependent oxygen elimination. This leads to a more reduced intracellular environment and consequently less oxygen-induced damage. This feature, together with increased pH, may explain the extraordinary increase in bacterial survival during respiration growth (46, 72).

Like other Gram-positive bacteria that grow via respiratory metabolism, *L. lactis* utilizes only menaquinones

as electron carriers to the terminal oxidoreductase. Inactivation of *menB*, which encodes a menaquinone biosynthesis enzyme (dihydroxy naphthonic acid synthase), totally abolished both quinone production and respiration in *L. lactis* (78). However, while other respiring bacteria have several oxidoreductases that ensure respiration under different conditions, *L. lactis* uses a single enzyme, the cytochrome *bd* quinol oxidase (encoded by *cydAB*) (45, 46). This kind of oxidase has a high affinity for oxygen (79). Moreover, as shown for *Streptococcus agalactiae*, cytochrome *bd* quinol oxidase contributes to both virulence and colonization (80, 81; Y. Yamamoto, A. Gruss, and P. Gaudu, unpublished data).

Respiration in *L. lactis* requires uptake of heme (iron is insufficient), possibly suggesting the presence of a heme transporter. Genetic studies suggested that the *fhu* operon mediates heme uptake (75). However, more recent studies suggest that heme might diffuse into *L. lactis* membranes and then be recovered by cytoplasmic heme-binding factors. Heme reduction by menaquinones appears to favor membrane incorporation (82). Other factors that facilitate heme entry via diffusion are being investigated.

Based on the dramatic differences in growth, survival, and metabolite production, we had anticipated that respiration growth would induce massive changes in gene expression compared to fermentation. Surprisingly, the expression of very few genes was specifically altered by respiration as evaluated by proteomic (21 proteins) and transcriptomic (11 transcripts) analyses of late exponential phase cells (73, 83). These studies led to the hypothesis that NADH/NAD balance, which is shifted toward NAD by respiration chain activity, is responsible for modulating enzyme activities that accompany respiration growth (Fig. 3). Significant changes in expression were observed for a single operon, as discussed below (see section on heme homeostasis) (73).

Role of CcpA in respiration

The regulator CcpA, which controls catabolite carbon repression, imposes a hierarchical use of carbohydrates (84). CcpA controls carbohydrate catabolism (glycolysis) and positively controls production of Ldh (65), which converts pyruvate to lactate. CcpA also seems to coordinate respiration metabolism at different levels. The first control concerns sugar uptake, because *L. lactis* does not use amino acids or glycerol as a carbon source (85). CcpA also controls the transporter *fhu*, which appears to contribute to heme uptake (75). Third, CcpA regulates expression of genes encoding protein components of the respiratory chain.

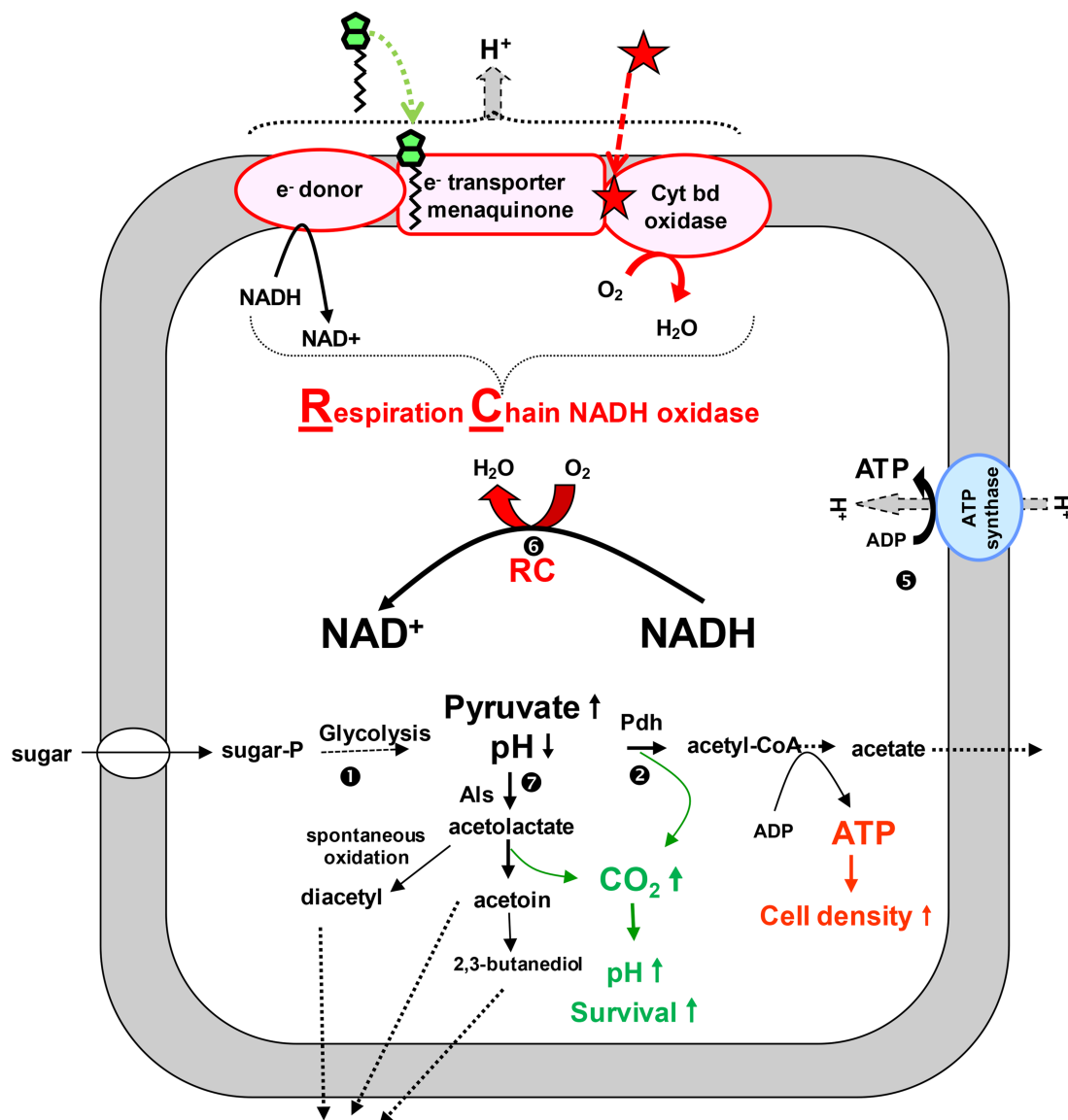


FIGURE 3 Basics of *L. lactis* respiration. Refer to Fig. 2 for reactions 1, 2, and 5, which are common to fermentation and respiration (numbering is the same). **(6)** The membrane respiration chain (RC) comprises an electron donor (putatively encoded by *noxAnoxB* [45, 89]), menaquinones (encoded by *men* operon genes or provided exogenously [80]), and a terminal electron acceptor (the cytochrome oxidase encoded by *cydAcydB* [46, 211]). Heme (red star) must be added exogenously (red arrow) to activate cytochrome oxidase. *S. agalactiae* and lactobacilli with respiration capacity (see Fig. 1 legend) require menaquinones (schematic molecule with green center) and heme to activate respiration. Respiration chain activity results in H^+ expulsion. **(5)** The ATPase might import H^+ , which generates ATP but with low efficiency [47, 77]. *L. lactis* lacks a complete Krebs cycle. Thus, NADH, which is needed for the respiratory chain, is produced by carbon catabolism. **(1)** Once phosphorylated, sugar is catabolized to pyruvate via glycolysis with production of ATP and NADH. As the respiration chain consumes NADH, Ldh activity decreases and pyruvic acid accumulates. Pyruvic acid dissociates to pyruvate and a proton, decreasing the internal pH. **(7)** To avoid acidification, pyruvate/pyruvic acid is converted to acetolactate via acetolactate synthase (Als) and then to the neutral compound acetoin with production of CO_2 . Diacetyl is produced by spontaneous oxidation of acetolactate. This pathway raises the pH and improves cell survival. Some LAB convert acetoin to 2,3-butanediol. **(2)** Pyruvate may also be converted to acetyl-CoA via pyruvate dehydrogenase (Pdh), providing extra NADH and CO_2 . Acetyl-CoA is further converted to acetate with production of ATP, promoting higher cell density. Acetate, acetoin, diacetyl, and 2,3-butanediol diffuse or are secreted into the medium. This figure is modified from reference 155.

In *L. lactis*, *ndh* (encoding NADH dehydrogenase [Ndh]) and *cydAB* are present on distinct operons (85, 86), while in other LAB they appear to be organized in a single operon (80, 87). The latter organization suggests coordinated expression of *ndh* and *cydAB* and may indicate that the respiratory chain is fueled by just one NADH dehydrogenase. In *L. lactis*, two putative NADH dehydrogenase genes (*noxA* *llmg_1735* and *noxB*, *llmg_1734*) are present in the genome, and both enzymes could drive electrons to menaquinones. Though *noxA* is adjacent to *noxB*, transcriptome analyses indicated that they are not in an operon (86). In the case of *noxB*, direct control by CcpA is suggested by the presence of a CcpA binding motif *cre* (catabolite response element) in the promoter region. Altogether, *noxB* seems to be repressed by CcpA, while *noxA* and *cydAB* are induced (88). Deletion of *noxA* abolished respiration activity on glucose growth, while the role of *noxB* is unknown (89). Because *noxB* is likely induced late in growth (when CcpA is less active), it may drive electrons to menaquinone, as does NoxA, but in late growth.

Interestingly, CcpA does not control respiration-induced acetoin production, because gene expression of this pathway was not affected by *ccpA* deletion (88). A challenging question concerns regulation of the pyruvate-acetoin pathway, which is functional late in respiration growth, as evidenced by acetoin accumulation in stationary phase cells; ~70% of the pyruvate pool is converted to acetoin (46, 73, 76) (Fig. 3). Interestingly, this pathway produces not only acetoin, but also carbon dioxide, which may contribute to lowering medium acidification in respiration growth (pH 6, compared to pH 4.5 in fermentation; both media contain 1% glucose as an energy source) (212). The search for regulators and/or cofactors of the pyruvate-acetoin pathway and for regulatory checkpoints of *L. lactis* respiration is ongoing.

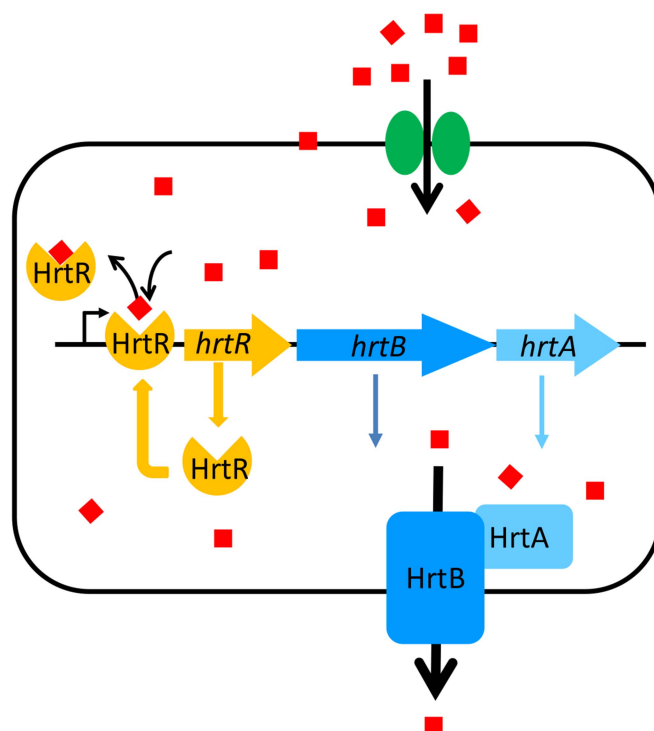
Although *L. lactis* is only equipped for aerobic respiration, other LAB can also perform anaerobic respiration. In *Lactobacillus plantarum*, nitrate can be used as an electron acceptor instead of oxygen. Reduction of nitrate into nitrite is performed by a quinone-nitrate reductase (NarG). Nitrate respiration is repressed by glucose, suggesting potential participation of CcpA in anaerobic metabolism in this organism (89).

Heme homeostasis is a key to *L. lactis* respiration

Transcriptome studies of *L. lactis* in respiration versus fermentation conditions during exponential growth revealed strong upregulation of components of a single operon, *ygfCBA*, encoding a putative transcriptional regulator (YgfC; also detected by proteomics [83]), a

predicted permease (YgfB), and an ATPase (YgfA) (73). YgfB and YgfA are HrtB and HrtA orthologs (*hrtBA* for heme-regulated transporter”) encoding HrtBA, an ABC transporter that was found in parallel in *Staphylococcus aureus* (90). Its function was subsequently clarified as a dedicated heme-efflux pump, which was necessary and sufficient to maintain intracellular heme concentrations at subtoxic levels while allowing sufficient intracellular amounts for functional respiration (Fig. 4). The predicted TetR family repressor YgfC, renamed HrtR, regulates expression of *hrtBA* in *L. lactis*. HrtR shows high affinity for heme through a noncovalent hexacoordinated interaction with heme iron (74). HrtR binds a 15-nucleotide palindromic sequence in the *hrtRBA* promoter region, which is needed for repression (74). Heme binding to HrtR modifies its conformation, releasing it from its target promoter and alleviating transcriptional repression of *hrtRBA* (74, 91).

FIGURE 4 Schematic representation of *L. lactis* heme-sensing and HrtBA-mediated efflux, which regulate heme homeostasis. In *L. lactis* and numerous commensal bacteria, heme is suggested to be taken up by *fhuDBA* gene products (green ovals) and/or by diffusion through membranes (75, 82). Internalized heme binds to the HrtR repressor, which releases binding to the *hrtRBA* operon. Consequent activation of *hrtBA* results in heme efflux (74). Red squares, heme.



The use of HrtR as an intracellular heme sensor and *hrtBA* regulator appears to be conserved among commensal bacteria. In contrast, numerous Gram-positive pathogens use an extracellular two-component system, *hssRS*, to regulate *hrtBA* (92). These findings point to an essential role of efflux for heme homeostasis in *L. lactis*. In contrast, heme import mechanisms remain elusive, despite a partial role for *fhu* (75). Membrane-associated menaquinones were shown to favor the accumulation of reduced heme in membranes (82). An oxidative environment, provided by oxygen, prevents and reverses hemin reduction by menaquinone and thus limits heme accumulation in membranes (82). HrtBA counteracts menaquinone-dependent membrane retention of excess heme in membrane, suggesting direct efflux from this compartment. Moreover, both HrtBA and menaquinone-mediated reduction have a strong impact on heme intracellular pools, detected as induction of an HrtR heme sensor. This indicates that intracellular heme acquisition is controlled at the membrane level without the need for dedicated import systems, at least at high heme concentrations (82). While pathogens may have access to blood heme during infection, the existence of heme-responsive genes in lactococci and other commensal bacteria raises questions concerning the nature of heme sources in their natural ecosystems (48).

Roles of respiratory chain components in nonrespiration processes

Milk, one of the main industrial media for food fermentation, lacks heme and thus cannot support *L. lactis* respiration metabolism. However, respiration chain activity does affect fermentation by decreasing the milk redox potential of *L. lactis*, which is one of most reducing LAB, providing a very negative redox potential value in milk. To establish a low redox potential, oxygen must be removed and oxidized compounds should be reduced. During fermentation, water-forming NADH oxidase (NoxE) eliminates oxygen, and respiration chain components (NoxAB and MenC) provide a lower redox potential by reducing oxidants in milk. The redox potential of milk is known to affect the microbiota and sensorial quality of fermented dairy products. Thus, although the *L. lactis* respiration chain is incomplete in milk due to the absence of a heme source, its reducing ability plays a significant role during fermentation (93).

L. lactis is a respiration prototype

Lactococci, unlike *E. coli* and *Bacillus subtilis*, respire using a restricted electron transport chain, and only if heme is provided. Comparative studies revealed that certain, but

not all, *Streptococcaceae* and certain other *Firmicutes* have the capacity to respire when provided with heme, or heme plus a menaquinone source (45) (Fig. 1). They include *S. agalactiae* (80, 94), *E. faecalis* (95, 96), and *Lc. plantarum* (89). Since the first characterization of *L. lactis*, a far wider group of LAB have been revealed to adopt respiration metabolism when provided with heme, or heme plus a menaquinone source, is added (see 48 for review).

Nitrogen Metabolism

In a milk medium, lactococci derive amino acids from casein via hydrolysis by the extracellular protease PrtP, transport of the generated peptides, and further degradation by a multitude of intracellular and envelope proteases and peptidases (97, 98). Amino acids readily available in milk are used both directly as amino acid building blocks and as a general carbon supply for other forms of anabolism in lactococci. Extracellular proteases plus at least 14 intracellular peptidases are of key importance for amino acid utilization. Lactococci grow poorly or die in milk fermentation conditions in mutants that are devoid of different combinations of these peptidases (99).

Dairy lactococci differ from plant lactococci in that they require several amino acids for growth. Surprisingly, strains of both origins appear to have the necessary genes for biosynthesis. Nevertheless, dairy lactococci require Ile, Leu, Val, and His, and sometimes Arg, Met, Pro, and/or Glu (100). These amino acid requirements in dairy strains appear to result from multiple mutations rather than deletions in the structural genes (39). This may suggest that mutations accumulated as an economic measure in strains maintained in a dairy environment. Similar results have been reported for *S. thermophilus*, a dairy bacterium related to *S. pyogenes*.

Nucleotide Metabolism

Nucleotides are not only substrates for DNA and RNA polymerases but are also substrates or allosteric effectors for many enzymes, and furthermore they constitute parts of different coenzymes. Thus, mutants in nucleotide metabolism may display numerous phenotypes. Cell nucleotide pools are also influenced by the presence of exogenous nucleobases or nucleosides in the medium. Pathways of uptake and utilization of these compounds (the so-called salvage pathways, which vary among organisms) are key contributors to bacterial responses to changes in the medium and to increased intracellular degradation of nucleic acids as illustrated below.

As seen above for operons involved in carbon metabolism, gene organization has unique characteristics in lactococci, which may impact regulation. For example,

genes encoding the pyrimidine (thymine, cytosine, and uracil) biosynthesis pathway leading to the formation of UMP are organized in five different operons in *L. lactis* and in a single operon in most investigated Gram-positive bacteria. Similarly, purine (adenosine, guanine, and xanthine) biosynthesis genes involved in the first 10 steps leading to IMP production are located in 5 separate operons in *L. lactis* and in a single operon in *B. subtilis*.

Pyrimidine biosynthesis is regulated by attenuation and antitermination by PyrR. The PyrR protein binds to PyrR “boxes” (5'-UCCAGAGAGGCUNGCAAG-3') present on the 5' ends of the untranslated mRNAs on four of the identified pyrimidine biosynthetic operons (101, 102). Mutation of the *pyrR* gene results in constitutively increased levels of the pyrimidine biosynthetic enzymes (101). The active RNA binding form of PyrR in *Bacillus* is a dimer which is formed when UMP, UTP, or PRPP (5-phosphoribosyl-1-pyrophosphate) is bound to PyrR; GTP counteracts UTP binding and thus promotes transcriptional read-through (103). The regulatory mechanisms seem to be the same in *L. lactis* (104). Interestingly, several *pyr* operons in *Mycobacterium smegmatis* have been found to be regulated by PyrR by translational repression (105).

Purine biosynthesis in *L. lactis* is positively controlled by PurR, and *purR* mutants are purine auxotrophs. PurR binds to a Pur box consensus sequence (5'-ANNNCCG AACAAT-3') (106–108) to activate transcription of the *purC* and *purD* operons. Data show that the PurR activating effector is PRPP. Because PRPP synthetase is inhibited by ADP and the addition of purine leads to increased purine pools (104), the addition of purine may indirectly decrease gene expression (108, 109). Interestingly, riboswitch control of the PurR-regulated *xpt* operon is modulated by purine pools (104). In operons activated by PurR, the distance between the Pur box and the –10 region was 57 to 58 bp. Mutational studies of pur boxes supported the importance of the central CCGAAC sequence. Interestingly, while *L. lactis* PurR often acts as an activator, the homologous PurR in *B. subtilis* usually works as a repressor. In addition to the importance of PurR binding sites, the two PurR proteins also differ in their PRPP binding properties. The two types of PurR proteins are related, and the *Bacillus* type seems to have evolved early from the activator type of PurR (109).

The PurR regulon includes purine biosynthetic genes but also genes involved in purine uptake and conversion into purine monophosphates. Genes involved in C1 carbon metabolism, guanosine tetraphosphate (ppGpp) metabolism, phosphonate transport, and pyrophosphatase activity were also identified. Interestingly, a Pur box was

also identified upstream of two ribosomal RNA operons, which could imply an interconnection between the purine pathway and translation, but this link needs to be confirmed (104, 106).

L. lactis can utilize the exogenous nucleobases or nucleosides present in the medium or formed from intracellular degradation of nucleic acids via the salvage pathways. The nucleobases uracil, guanine, and adenine, as well as hypoxanthine and xanthine, are taken up and converted to nucleotide monophosphates, while cytosine is not utilized by lactococci (110). Orotate may be incorporated in plasmid-bearing *L. lactis* strains that express an orotate transporter and may be used for UMP biosynthesis, since orotidine-5'-monophosphate (OMP) is a normal intermediate (111, 112). Thymine may be incorporated via pyrimidine phosphorylase to thymidine and further phosphorylated by thymidine kinase (*tdk*) to the corresponding monophosphate (110). Thus, all common nucleobases except cytosine can be transported and incorporated into nucleotides. The ability of *L. lactis* to scavenge nucleobases or nucleosides can confer a survival advantage in stress conditions.

In *L. lactis*, all nucleosides except cytidine can be degraded to the corresponding nucleobase. However, cytidine may first be deaminated to uridine and then further to uracil. Pyrimidine nucleosides may also be directly converted to nucleotides since the corresponding nucleoside kinases (*udk* and *tdk*) are functional in lactococci. Two high-affinity nucleoside transport systems were identified: UriP is specific for uridine and deoxyuridine, while BmpA-NupABC takes up cytidine and purine nucleosides and the corresponding deoxyribonucleosides (113).

LACTOCOCCAL STRESS RESPONSES

Stress response is the adaptation to homeostatic changes due to the environment and is generally modulated by sensors and regulators that sense the state and respond to signals. Major signals for *L. lactis* include metabolites such as nucleotides, acid (self-induced), oxygen, salt, metals such as heme (natural or industrially provoked), and toxic products (e.g., disinfectants). We refer readers to recent reviews on LAB stress responses (114) and on regulatory signals in *L. lactis* (115). Here, we focus on specific effectors and responses that were not previously considered, i.e., nucleotides, Spx, cyclic-di-AMP, and heme and respiration stress responses.

Regulation by Nucleotide Pools

Low nucleotide pool sizes may serve as internal stress signals that provoke expression of stress response genes

in *L. lactis* (116, 117). An important link between nucleotide pools and cell wall synthesis was uncovered: as part of the uridine synthesis pathway, PyrB converts L-aspartate (L-Asp) to N-carbamoyl-L-Asp. PyrB competes with cell wall enzymes for L-Asp; thus, L-Asp consumption during rapid growth favors cell wall flexibility, while its accumulation in the stationary phase may lead to a more rigid cell envelope (118). Additionally, high UTP pools in the human pathogen *S. pneumoniae* correlated with more capsule formation and lower biomass yield (119). These examples suggest that nucleotide pools connect nucleotide metabolism to the cell envelope structure.

The Spx Family of Regulators

A hot spot for *L. lactis* mutants that compensated for the stress sensitivity of a *recA* mutant, thermosensitivity of a *clpP* mutant, metal toxicity, and oxidative stress mapped to the *spx* gene (117, 120, 121). Spx is conserved in numerous *Firmicutes* and was shown in *B. subtilis* to be involved in oxidative stress regulation via thioredoxin gene expression (122). Seven *spx* homologues exist in *L. lactis* MG1363, five of which contain redox-reactive CXXC regions (121). Exploration of other Spx proteins revealed that SpxB, a non-redox-sensitive Spx, is a key regulator of cell wall resistance to lysozyme by activating O-acetylation of peptidoglycan (PG) (123). The Spx family is intrinsic to cell responses to oxidative stress and cell wall damage conditions.

Cyclic-di-AMP as a Second Messenger in Bacterial Adaptation and Its Potential Role in Heme Sensitivity

Nucleotide pools are required for DNA synthesis but are also involved in numerous stress responses, including amino acid starvation and acid stress (e.g., via ppGpp) (124). More recently, cyclic-di-AMP was identified as a second messenger in stress adaptation (125). In *L. lactis*, cyclic-di-AMP homeostasis is a balance between synthesis via the adenylate cyclase enzyme CdaA (Lmg_0448) and degradation by the cyclic-di-AMP phosphodiesterase enzyme (GdpP, Lmg_1816). Increasing the cyclic-di-AMP pool by deletion of *gdpP* increased heat resistance and salt hypersensitivity in *L. lactis* (126). These phenotypes might be due to a change in PG synthesis (127), because (i) salt sensitivity in the *gdpP* mutant is suppressed by deletion of *cdaA* or *glmM* encoding a phosphoglutaminase enzyme involved in PG integrity, (ii) *cdaA* is in an operon with *glmM*, (iii) GlmM interacts with CdaA to modulate its activity, and (iv) *L. lactis* cells spontaneously lyse when cyclic-di-AMP pools are decreased. The exact role of cyclic-di-AMP in PG syn-

thesis in *L. lactis*, though unknown, may be to modulate enzymatic activity to control cell wall plasticity. In contrast to CdaA, small molecules might interact with GdpP to modulate its activity. In *B. subtilis*, the GdpP homolog (YybT) harbors a PAS domain, which contains a heme binding site (128). Interestingly, *L. lactis* GdpP also harbors this domain, and deletion of the *L. lactis gdpP* gene increased the sensitivity of cells to heme (128). These observations suggest a dialogue/link between heme homeostasis and the cyclic-di-AMP pool enabling bacteria to adapt their physiology in response to exogenous heme.

In addition to its involvement in PG synthesis, cyclic-di-AMP changed pyruvate carboxylase (*pycA*) activity in *L. lactis* (129). PycA is required for aspartate synthesis. Milk acidification is delayed in a *pycA* mutant compared to the wild-type strain, indicating that cyclic-di-AMP might modulate the fermentation process in some conditions.

Strategies for Survival in Stress Conditions

L. lactis is equipped to deal with several stress conditions confronted in nature or in industrial settings, as summarized below. Salt and acid induce expression of GadB and GadC, which are putatively involved in glutamate transport by an antiporter; glutamate transport presumably involves efflux of H⁺, thereby maintaining intracellular pH (130, 131).

Toxic products such as bile, quaternary compounds, and antibiotics may be actively pumped out of the cell by specialized transport functions. Among the numerous transport systems that shuttle metabolites in and out of the cell, some mediate drug expulsion and, consequentially, can confer drug tolerance (132). In *L. lactis*, LmrA is a multidrug pump that effluxes a wide range of amphiphilic, cationic drugs (including potentially toxic antibiotics, quaternary ammonium compounds, aromatic dyes, and phosphonium ions) in exchange for H⁺ influx. LmrA (590 amino acids) is similar to the human multidrug resistance P-glycoprotein, thus raising questions about the origins of the pump. Judging from sequence analyses, an LmrA dimer would be the functional equivalent of the P-glycoprotein (LmrA is 32% identical to half of the P-glycoprotein, particularly within known functional domains). Remarkably, LmrA is functional in eukaryotic cells and is able to replace P-glycoprotein defects, thus making *L. lactis* an excellent model to study drug extrusion (132). Note that sequence comparisons predict an LmrA homologue in *S. pneumoniae* (an Orf with ~30% identity over 539 amino acids is present). The CmbT transporter (Lmg_1104), described initially as a cysteine and methionine biosynthesis transporter,

was subsequently identified as a multidrug efflux pump that effluxes a wide range of antibiotics and toxic drugs (133).

Other efflux systems protect *L. lactis* from toxic metabolites: the dedicated heme-specific HrtBA efflux pump (see above) protects cells from heme toxicity. *L. lactis* homologs of heme and protoporphyrin IX efflux pumps identified in *S. agalactiae* may suggest that backup systems are available (134).

A series of exciting reports reveal that there is more to the envelope than was previously thought: first, pili discovered in *L. lactis* led to the idea that these bacteria might persist in the gut upon ingestion of fermented food products (135, 136). Second, a pellicle-like carbohydrate structure was visualized on the *L. lactis* MG1363 surface and characterized biochemically (137). A third structure, described as trapped within the PG, corresponds to another pellicle-like carbohydrate thin outer layer surrounding *L. lactis* strain MG1363 (138).

Finally, basic cell metabolism can determine how well the bacterium copes with oxidative conditions. Respiration metabolism presents a clear advantage to lactococci in an aerobic environment for both growth and long-term survival (Fig. 5) (46, 72).

Selections Leading to Improved Adaptation to Environmental Stress Situations

Oxygen is a ubiquitous stress. If not eliminated, reactive oxygen derivatives provoke cell damage that can be lethal. One means of reducing oxygen-related damage is by removing oxygen. In fermenting cells, H₂O-forming NADH oxidases do eliminate oxygen during growth (139),

although cells are sensitive to oxygen-related damage in the stationary phase (140). Overproduction of H₂O-forming NADH oxidase could not only change metabolic end products (139) but also might improve survival in an oxidizing environment due to oxygen removal. An alternative means of creating a more reducing environment is by adding glutathione, a redox peptide (141), or dithiothreitol, a reducing agent (75), to the medium. Lactococci lack catalase, which eliminates hydrogen peroxide in many aerobic bacteria. Hydrogen peroxide has been effectively removed by cloning catalase in *L. lactis* (142). Respiration metabolism in lactococci is a “natural” and efficient means of eliminating oxygen compared to fermentation, leading to good survival in the stationary phase (46, 72).

L. lactis generates an acidic environment during fermentation growth, which might compromise its survival (143). Significantly, acidification may be more severe if cells are immobilized, because acid diffusion may be slower. This situation may provide a natural selection for strains to escape from a constrained environment, and it was shown experimentally to generate multistress-resistant mutants (116). Interestingly, acid-resistant mutants evoked changes linking nucleotide pools (ppGpp) and cell wall alterations (116, 118). Studies using a semiliquid medium have been used to impose a natural selection for mutants that can more readily escape a constraining environment (144). In one case, bacteria that make chains diffused more slowly than single cells (Fig. 6). “Dechaining” mutants, affected in penicillin binding protein and cell wall-synthesis enzyme PBP1A were isolated; the mutants no longer formed chains and were able to disperse more readily in the semiliquid medium; these

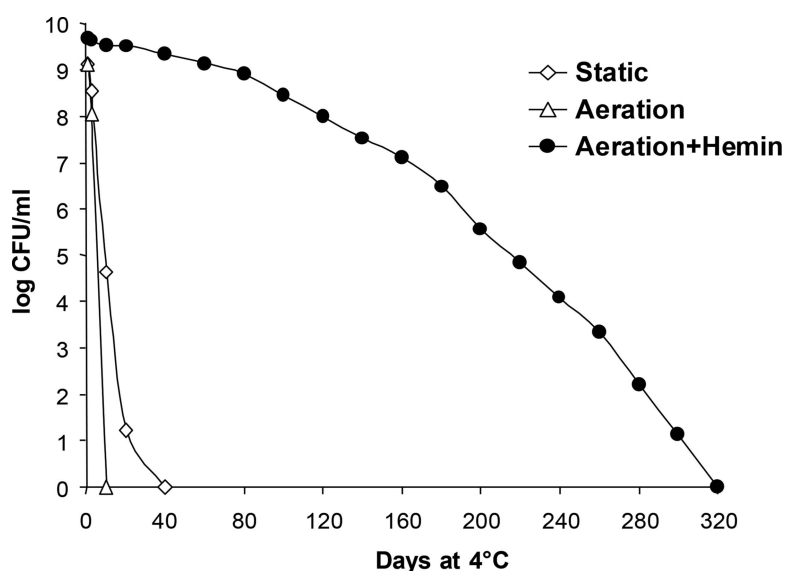


FIGURE 5 Respiration metabolism increases the survival capacity of lactococci. When supplemented with hemin, aerobically grown lactococci can undergo respiration metabolism. As a result, cells stored at 4°C show markedly better survival compared to cells grown aerobically in the absence of heme or in static conditions. Improved survival was also observed when cells were maintained at 30°C. The experiment shown was performed by Karin Vido in the authors' laboratory.

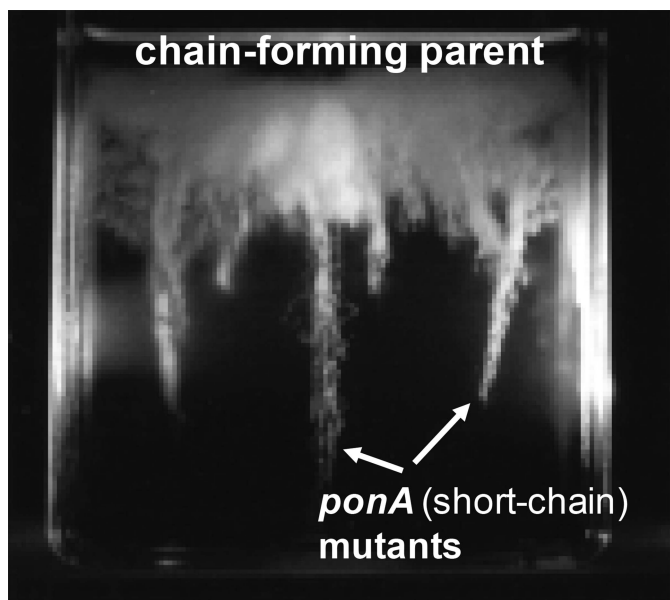


FIGURE 6 Bacterial root formation in semiliquid medium. Bacterial chains (here, an *acmA* mutant of *L. lactis*; parental strain) diffuse slowly in a semiliquid (0.035% agar) medium. Bacterial dechained mutants diffuse more quickly to form roots. In this experiment, all the roots corresponded to independent mutants in the same gene, *ponA*, encoding PBP1A (reproduced from Kulakauskas and coworkers [144]). Note that a similar strategy of semiliquid medium selection was used to uncover the existence of a cell-surface carbohydrate pellicle in *L. lactis*; the system is readily applied to other bacteria [137].

mutants display greater permeability, probably due to increased cell wall breaks [144]. In *S. agalactiae*, interruption of *ponA* results in reduced virulence that was linked to host antimicrobial peptide susceptibility [145, 146]. In view of the identified role of PBP1A in lactococci, it is tempting to speculate that the *ponA* *S. agalactiae* mutant may also be defective in cell wall permeability and its chain-forming ability, thus impacting its *in vivo* localization. Use of semiliquid medium for selections might prove effective in examining factors that are at work when bacteria are immobilized in their host and has also proven useful in other types of selections in which surface properties are altered [137].

Transposon insertional mutagenesis was also used to select for stress-resistant strains of lactococci. Three examples are given. (i) A combination of stress conditions is lethal for lactococci (and possibly for other organisms), although each condition alone may be nonlethal. Simultaneous high temperature (37°C), oxygen, and either low pH (i.e., similar to conditions in the stomach) or a *recA* background give rise to mutants, many of which seem to affect intracellular metabolic pools of guanosine-phosphate and phosphate in stress response [116, 117].

Low intracellular levels of these metabolite pools in the mutants may constitute a starvation signal to induce a stress response. These mutant strains show better long-term survival than their nonmutated parents. It thus appears that a general stress response is induced in *L. lactis* when intracellular guanosine-phosphate and phosphate pools are low. In accordance with this, *L. lactis* showed resistance to acid and heat stress when grown in milk or a synthetic medium without purines [147]. (ii) Hydrogen peroxide is toxic to lactococci. An H_2O_2 -resistant mutant was isolated at high temperature (37°C), and although its resistance was 1,000-fold greater than the parental strain, it displayed no other stress resistance phenotypes [148]. H_2O_2 -resistant mutants might have a survival advantage in coculture with strains producing mM amounts of H_2O_2 , e.g., some lactobacilli [149] and streptococci [150]. In the former case, use of H_2O_2 -resistant lactococci could lead to development of new fermented products; in the latter, more efficient growth of lactococci could improve the hygiene of food products. (iii) Mutants were selected for increased resistance to dithiothreitol (DTT), a reducing agent, at elevated temperature. By preventing the formation of disulfide bonds, DTT disables a part of the oxidative stress response pathway (numerous lactococcal stress-response proteins contain one or more CXXC motifs). All 18 DTT-resistant mutants mapped within a single operon, *pst*, involved in phosphate transport. Greater oxidative stress tolerance of *pst* was linked to its effects on copper and zinc homeostasis [151].

Stress-resistant lactococci have several potential uses. First, such strains are potentially valuable in dairy fermentation. Their greater resistance to stress may overcome survival variability as seen in conventional strains. The specifically acid-resistant strains may provide resistance to extreme acid pH conditions or may be better at maintaining a neutral internal pH. Stress-resistant strains may survive longer in fermentation and may also be more resistant to harsh storage conditions (such as freezing and lyophilization). Second, because such strains may survive the harsh environments in the gut better, they may be attractive for probiotic uses. A proof of concept mouse inflammatory gut model provided evidence that antioxidant superoxide dismutase produced by wild-type *L. lactis* may improve gut integrity [4, 152, 153]. Third, LAB are potentially valuable candidates for the production of molecules with medical or biotechnological uses; Lactococci are nontoxic and have documented potential for expressing and exporting proteins or other molecules of interest, either for industrial production or in the gut.

L. LACTIS AND INTERBACTERIAL DIALOGUE

Lactococci have long been known to inhibit the growth of coexisting bacteria, including pathogens, via acid production and are an important feature of fermented foods. This property has led to broader potential applications in the probiotic field, e.g., with respect to cholera infections (154). Recent studies also uncovered novel *in trans* effects of *L. lactis* and led to the identification of similar “public contributions” by other bacteria. Some examples are described in the following subsections.

Interbacterial Cross-Feeding

Via menaquinones

Other than *Lactococcus*, *Leuconostoc*, and *Enterococcus* species, most known LAB (pathogenic or not) lack a complete menaquinone biosynthesis pathway and require exogenous menaquinone or a precursor, in addition to heme, for respiration growth (48, 89, 155, 156). Unexpectedly, menaquinone-deficient strains can overcome this deficiency via contacts with menaquinone producer species. For example, respiration of *S. agalactiae*, an opportunistic pathogen, is activated in the presence of *L. lactis* via menaquinone donation and a heme source (78) (Fig. 7). Remarkably, *E. coli* expulses dihydroxy-naphthoate acid (DHNA), which is used by *S. agalactiae* to synthesize its own menaquinone (in this case a DMK) (156). DHNA is coupled to an isoprenyl chain by menaquinone prenyltransferase, encoded by *menA*. In *Lb. plantarum*, a *menA* ortholog is adjacent to the *cydAB* locus, suggesting that this organism can also use DHNA to synthesize menaquinones. Free menaquinones and DHNA are likely present in host ecosystems and can be used to activate metabolic pathways in commensal and pathogenic bacteria as well. Thus, environmental non-pathogens might contribute to the fitness, and potentially virulence, of neighboring pathogens.

Via respiration

Respiration growth leads to higher pH and efficient oxygen consumption. The presence of a respiration-positive *L. lactis* strain (grown aerobically with heme) rescued growth and survival of a respiration-negative mutant strain (tested with *cydA*) (Fig. 8).

Interbacterial Cross-Inhibition

Via secreted products

Lactococci, like other *Streptococcaceae*, produce toxic hydrogen peroxide under aerobic fermentation conditions, which may inhibit growth of peroxide-sensitive bacteria (72). Numerous LAB produce bacteriocins, which have widely different host spectra (see 157 for review); lysis of heterologous bacteria by bacteriocins may provide needed nutrients for the producer cells. Production of lysins may act to regulate bacterial cell wall properties *in trans* (158).

Via regulation of expression *in trans*

Studies of mixed cultures provide evidence for inhibitory effects of *L. lactis* on *S. aureus* growth and/or virulence gene expression. Tests conducted in either food or mammary gland cell lines indicate that (i) *L. lactis* reducing activity contributes to inhibition of a major virulence gene regulator (*agr*) and (ii) *L. lactis* at high bacterial concentrations inhibits *S. aureus* internalization in a mammary epithelial cell line (159, 160). These findings open prospects for antibiotic alternatives for prevention of infection, although their applicability to food industry and *in vivo* situations remains to be confirmed.

APPLICATIONS AND TOOLS OF LACTOCOCCI

The use of lactococci in “bioprotein” delivery, i.e., for antigen or enzyme delivery *in vivo*, is based on the idea

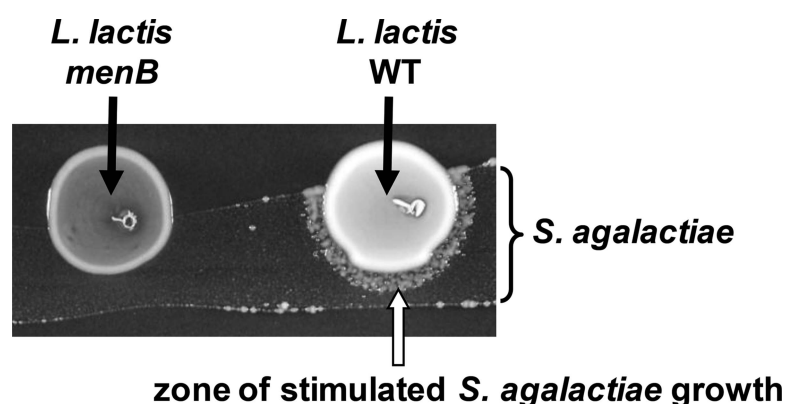


FIGURE 7 *L. lactis* produces menaquinones that cross-feed the opportunist pathogen *S. agalactiae*. Heme is present in the solid medium. A broad horizontal streak of an *S. agalactiae* strain (NEM316) is shown. Spots of cultures of *L. lactis* wild type (left) or *menB* that is defective for menaquinone synthesis (right) are deposited directly over the streaks. A stimulated growth zone is observed directly surrounding the wild-type *L. lactis* strain but not the *menB* mutant. From *Molecular Microbiology* (78).

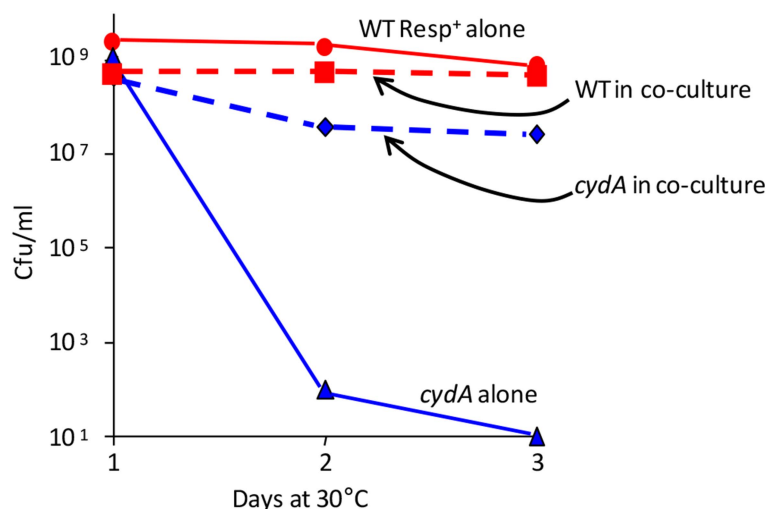


FIGURE 8 Respiring *L. lactis* can improve survival of nonrespiring bacteria in coculture. Differentially marked wild-type and *cydA* (nonrespiring mutant) *L. lactis* strains were grown separately or together in coculture. Non-respiring *cydA* grew less well and showed poor survival when maintained in an aerobic medium with heme over a 3-day period. However, the respiring wild-type strain thrived. In contrast, the *cydA* strain fared much better when grown in coculture with the wild-type strain, as determined by cell count determinations. From *Molecular Microbiology* (72).

that *L. lactis* can act as an effective nonpathogenic carrier, which can be administered orally or nasally without provoking a reaction other than that induced by the bioprotein of interest. Prior to this update, numerous reports described encouraging results of using lactococci for (i) prophylaxis to prevent bacterial infection (161), (ii) treatment of inflammatory bowel disease (3), (iii) prophylaxis and/or treatment of virally induced tumors (162), and (iv) allergy prevention (163, 164). Other properties of lactococci, including the expression of pili that might mediate bacterial adhesion *in situ* (135, 136), and novel applications have since been reported (165) which support their uses in biomolecule delivery. Despite a strong start, pharmaceutical drug development using *L. lactis* has not been reported, possibly due to the cost of development and the existence of industrially backed alternatives. Reported success with bioactive molecules might change this picture in the future.

Numerous applications using lactococci resulted from the development of genetic tools. Interestingly, a thermosensitive plasmid developed in *L. lactis* over 20 years ago, pG⁺host, is still the gene replacement and transposition tool of choice in numerous *Firmicutes*, including pathogenic bacteria (166, 167). pG⁺host is a derivative of the broad-host-range plasmid pWV01 and is nonreplicative in *L. lactis*, streptococci, staphylococci, and some lactobacilli at temperatures of 37.5°C or above. The thermosensitive replication protein has been retooled to produce numerous derivatives. Furthermore, pG⁺host is replicative in *E. coli*. The existence of an *E. coli* strain bearing a chromosomal copy of the non-temperature-sensitive *rep* gene (168) facilitates gene cloning, as well as characterization of pG⁺host insertions.

Another tool that has withstood time is the nisin-inducible expression system. Nisin is a bacteriocin encoded by a conjugative transposon (169–171). The promoter for the nisin biosynthesis gene, *nisA*, is regulated by *nisR* and *nisK* gene products. In the absence of nisin, or of *nisR* and *nisK* genes, promoter activity is very low. Addition of sublethal amounts of nisin results in strong induction of promoter activity, as demonstrated in innumerable applications of this system. This system has been shown to be functional in other *Firmicutes* (see 172 for review). Expression systems have also been developed for wider use among *Firmicutes* and in some cases may be advantageous over the nisin system. Controlled expression systems have arisen from studies of pH, salt, metal, heme, chloride, and sugar-regulated promoters (see 115 for review); some systems may overcome two potentially important limitations of the nisin system: (i) the requirement for either a specific host strain or a second plasmid (to provide *nisR* and *nisK* genes) and (ii) effects of nisin on the membrane, which may be particularly undesirable in studies of membrane proteins.

Highly regulated promoters can also be turned around for use as specific sensors. An interesting example concerns the HrtR repressor, which regulates heme efflux (Fig. 4). This and other heme-responsive promoters have been developed as sensitive heme sensors, with proof of activity *in vivo* (81; D. Lechardeur, unpublished data).

Constitutive expression of promoters at fixed levels can be valuable for quantitative physiological studies or for fine-tuning of gene expression in biotechnology. The *L. lactis* promoters P45 and P32 are commonly used, and strong constitutive promoters have been described (173). A set of synthetic promoters that differ by the sequence

and length of spacers between the consensus sequences allows a broad range of constitutive activities (57, 174). A high-expression promoter based on the phosphotransferase system is further enhanced by cellobiose and was shown to be active in *B. subtilis* (175).

Site-Specific Single-Copy Integration

Lactococcal bacteriophages were initially studied with the goal of controlling starter culture lysis during fermentation. These phage studies led to the characterization of numerous bacterial strategies to abort phage activity. Phage studies have also been exploited to develop a site-specific integration system. Integration of temperate phages uses a phage-specified integrase that catalyzes insertion of the phage at a specific bacterial target, which is often localized at or near a tRNA gene. Using elements of lactococcal bacteriophage TP901-1, a site-specific integrative vector was designed to obtain chromosomal single-copy integration (176). This system should allow stable insertion and expression of foreign genes and can also be used to study the expression of genes in single copies under different growth conditions. The TP901-1 integration system has also been used in human cells (177). Another integration system based on a lactococcal intron led to efficient and stable insertion of genes without the need for selection (178).

Immune System against Phages: the CRISPR-Cas System

Chromosomal manipulation was upstaged by a mechanistic breakthrough made in *S. thermophilus* on phage resistance via the clustered regularly interspaced short palindromic repeat (CRISPR)-CRISPR-associated (Cas) system, which makes up a natural immune system against phage infections (179). During phage DNA infection, a bacteriophage DNA fragment is integrated in a specific chromosomal CRISPR locus. During a second attack with the same bacteriophage, small RNA expressed from the CRISPR system directs adjacently expressed Cas nuclease to cleave phage DNA, which prevents new infection. CRISPR-Cas is present in various LAB, including *S. thermophilus* and lactobacilli, but is uncommon in lactococci (180), although applications of the system are seen as ubiquitous (181).

Protein Export and Display Systems

Protein export reporters were developed to probe the membrane protein structure and identify export signals (182–184). One such reporter, the nuclease of *S. aureus*, is a stable, well-characterized protein which is active when present as an amino- or carboxy-terminal fusion to

other peptides and is faithful in reporting export events and in determining membrane protein topology. It is used in *L. lactis* and other *Firmicutes* to follow expression of exported proteins under different environmental conditions. The major advantages of using the nuclease over previously described export reporters are that it rapidly assumes its conformation and thus avoids degradation, and as few as ~300 nuclease molecules per cell can be detected in colony assays (183–186).

The use of *L. lactis* as a bacterial factory has been developed to deliver proteins of interest in the extracellular medium or on the bacterial surface. The export signal of Usp45, a secreted *L. lactis* protein, or signals from identified secreted native or heterologous proteins, is routinely used. Secretion efficiency can be improved by introducing (if necessary) an overall negative charge at the N-terminal end of the mature, translocated secreted protein (185). Advantages of using LAB other than *L. lactis* concern transit time in the intestinal tract; systems are thus being transposed to lactobacilli, such as *L. plantarum*, to improve efficacy (see 165 for review).

Anchoring of exported proteins via C-terminal LPXTG motifs is widely documented, particularly with respect to virulence factors such as *S. pyogenes* M-protein (187–189). *L. lactis* encodes several anchored proteins and at least two sortase-like proteins (190). Expression of the anchoring motif of the *S. pyogenes* M6 protein has been adopted to express recombinant proteins on the lactococcal surface (191). The AcmA autolysin is also cell wall associated, due to the presence of a three-times-repeated LysM motif (192). Anchoring via the AcmA binding motif was found to effectively present antigens at the lactococcal surface; a spacer between the anchoring domain and the protein of interest (a fimbrial protein) facilitates its access to target epithelial cells (193).

Expression Strains

Lactococci are remarkable for their simple genomes compared to complex bacterial models such as *B. subtilis* or *E. coli*. An interesting example is HtrA, which is the only surface protease in *L. lactis*. In contrast, *B. subtilis* and *E. coli* both encode numerous exported proteases (194). An *htrA* mutation leads to temperature sensitivity; at 30°C, exported proteins showed increased stability, although activity was not necessarily improved (194).

Cell Lysis Systems

Controlled cell lysis is a potentially powerful means of arresting cellular and metabolic activity; in fermentation, it may additionally result in a coordinated release of enzymes which could accelerate product maturation. The

host autolysin, AcmA (195), or bacteriophage-encoded lysins and holins (which allow lysin release) are good candidates for this purpose. This application is potentially useful in controlling cell growth in fermented dairy products, as well as for enzyme release (196, 197). Expression of lysin and holin by a nisin-induced promoter does appear to accelerate cheese ripening (198). Lysins, derived from bacteriophage specific to several pathogens, effectively prevented or treated infections by streptococci, bacilli, and staphylococci in mice (199–201).

The cell envelope is an important barrier protecting the cell from stress situations. Cell wall damage via autolytic enzymes can render cells more sensitive to environmental conditions. Bacteria that have undergone even partial cell wall damage are permeable to small labeled probes used in standard *in situ* hybridization methods, while undamaged cells are not (202). As mentioned above, the SpxB protein mediates regulation of cell wall integrity (123). Rather than affect autolysin activity, SpxB is induced by lysozyme and/or PG digestion products, leading to PG O-acetylation, which renders it lysozyme resistant. Such changes could have profound effects on bacterial state, fitness, and resistance to autolysins, with applications for probiotic uses.

Containment and Food-Grade Strains

Inactivation of the *L. lactis* thymidylate synthase *thyA* gene results in a requirement for thymine or thymidine (66, 203). In *L. lactis*, a *thyA* mutant was exploited as a means of strain containment; i.e., strains can grow in a thymine-containing environment, such as the gut, but not in more limiting environments (203).

Nonsense suppressor strains are used in *E. coli* genetics to analyze phenotypes of point mutations. Plasmids carrying the suppressor genes could suppress an otherwise lethal nonsense mutation in the cell. This property of suppressors was exploited in *L. lactis* to construct and establish a food-grade plasmid (i.e., no foreign DNA) containing the suppressor genes in a suppressible purine auxotroph; this plasmid is stable in a milk media which cannot sustain growth of a purine auxotroph (204).

Higher Antigenicity

Studies have compared the effectiveness of presentation of different antigens as bacterial cytoplasmic, surface-anchored, or secreted proteins. Cell wall-associated antigens seem to induce a greater immune response than secreted or cytoplasmically expressed proteins (205, 206). Furthermore, immune response was reportedly enhanced in mutant strains with cell wall defects due to mutation of the alanine racemase (207).

CONCLUSIONS

L. lactis is likely the microorganism most eaten by humans. It belongs to a family comprised of pathogens (e.g., *S. pneumoniae*, *S. pyogenes*), commensal and opportunist microorganisms (e.g., *Streptococcus gordonii*, *S. mutans*), and food microorganisms (e.g., *S. thermophilus* and *L. lactis*). Studies of *L. lactis* reveal that differences between pathogens and nonpathogens are limited. As a bacterium that acidifies its own medium, *L. lactis* may have a high capacity for stress resistance when preadapted; stress-resistant mutants with constitutive stress resistance can be selected. Its metabolic flexibility by shifting to respiration metabolism can dispense with most acid production. As a food microorganism, *L. lactis* comes into close contact with, and may cross-feed, other bacteria in both the food environment and in the gut; as such, it may impact the behavior of other bacteria in complex ecosystems. As a nontoxic bacterium that secretes relatively few proteins in quantity, *L. lactis* may also be an organism of choice for oral vaccine or protein delivery design and biotechnological uses (see 165, 208, 209 for reviews). As a simple organism with diverse biotopes, including plants, milk products, and the gut, *L. lactis* may be a good choice for studies of the influence of environmental stress on evolution.

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