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► To cite this version:

Julien Delmas, Lucie Gibold, Tiphany Faïs, Sylvine Batista, Martin Leremboure, et al.. Metabolic adaptation of adherent-invasive *Escherichia coli* to exposure to bile salts. Scientific Reports, 2019, 10.1038/s41598-019-38628-1 . hal-02060120

HAL Id: hal-02060120

<https://uca.hal.science/hal-02060120>

Submitted on 7 Mar 2019

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Metabolic adaptation of adherent-invasive *Escherichia coli* to exposure to bile salts

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short title: metabolic adaptation of AIEC induced by bile salts

Abstract

The adherent-invasive *Escherichia coli* (AIEC), which colonize the ileal mucosa of Crohn's disease patients, adhere to intestinal epithelial cells, invade them and exacerbate intestinal inflammation. The high nutrient competition between the commensal microbiota and AIEC pathobiont requires the latter to occupy their own metabolic niches to survive and proliferate within the gut. In this study, a global RNA sequencing of AIEC strain LF82 has been used to observe the impact of bile salts on the expression of metabolic genes. The results showed a global up-regulation of genes involved in degradation and a down-regulation of those implicated in biosynthesis. The main up-regulated degradation pathways were ethanolamine, 1,2-propanediol and citrate utilization, as well as the methyl-citrate pathway. Our study reveals that ethanolamine utilization bestows a competitive advantage of AIEC strains that are metabolically capable of its degradation in the presence of bile salts. We observed that bile salts activated secondary metabolism pathways that communicate to provide an energy benefit to AIEC. Bile salts may be used by AIEC as an environmental signal to promote their colonization.

Introduction

The adherent-invasive *Escherichia coli* (AIEC) pathogroup was initially characterized in isolates from the ileal mucosa of Crohn's disease (CD) patients¹⁻⁵. These bacteria strongly adhere to and invade intestinal epithelial cells (IECs), survive within macrophages, move into the deep tissues and activate immune cells to induce inflammatory cytokine secretion⁶⁻⁸. Several studies have identified genes that are important for AIEC ileal colonization: type 1 pili and flagella facilitate binding to and invasion of the epithelial cell; long polar fimbriae (LPF) aids in the binding of these bacteria to M cells overlying Peyer's patches; Vat-AIEC protease promotes mucins degradation. The expression of most these virulence factors is modulated by bile salts, suggesting that bile salts may be used by AIEC as an environmental signal to promote their colonization⁹⁻¹². Other genes identified to date as required for colonization of AIEC are involved in the acquisition and metabolism of essential nutrients¹³. In recent years, a huge body of literature has provided evidence that most enteropathogens are equipped with a large set of specific metabolic pathways to overcome nutritional limitations *in vivo*, thus increasing bacterial fitness during infection¹⁴. These adaptations include the degradation of myo-inositol, ethanolamine cleaved from phospholipids, fucose derived from mucosal glycoconjugates, 1,2-propanediol as the fermentation product of fucose or rhamnose and several other metabolites not accessible for commensal bacteria or present in competition-free microenvironments. Therefore, deciphering the metabolic requirements of AIEC is central to the understanding of their ability to colonize a host. In addition, little information is available regarding the effects of bile salts on *E. coli* metabolism. In the present study, we showed that secondary metabolic pathways in AIEC are modulated by bile salts, providing them with energy as well as carbon and nitrogen sources to colonize the intestinal mucosa.

Results

Bile salts altered expression of metabolic genes in LF82

For transcriptome analysis, an AIEC strain (LF82) isolated from a chronic ileal lesion of a patient with CD was grown for 24 h in the presence or absence of 1% bile salts ⁶. The analysis of data showed a profound effect of bile salts with 1796 differentially expressed genes (DEG), including 1138 genes that showed an increase and 658 genes that showed a decrease in mRNA abundance, representing approximately 40% of the genome (additional file 1: Methods, Fig. S1, S2). Among these DEGs, 517 genes (29%) encoded proteins of unknown function.

After classification into functional categories, we observed 255 DEGs among the 722 genes involved in metabolism (35%), including 182 up-regulated and 73 down-regulated genes. In the presence of bile salts, the expression of genes encoding proteins involved in the degradation, utilization and assimilation of compounds was significantly induced relative to the other overexpressed genes involved in metabolism (Fig. 1A). Conversely, bile salts induced a repression of genes involved in biosynthesis relative to the other underexpressed genes involved in metabolism. More particularly, the expression of genes involved in the degradation of amines, alcohols, carboxylates and in secondary metabolism were overexpressed for 47% of them (Fig. 1B). Thus, bile salts induce a global up-regulation of genes involved in degradation. We identified the most highly expressed genes, i.e., those showing an increase of at least 4-fold (i.e., $\log_2 = 2$) in mRNA abundance in bacteria grown with bile salts in comparison to bacteria grown without bile salts. These most up-regulated genes encoded proteins involved in sugar degradation (rhamnose, arabinose, galactose and mannose), L-ascorbate degradation, amino acid degradation (tryptophane, glutamine and arginine), citrate degradation, the methyl-citrate pathway and ethanolamine utilization. Ethanolamine (EA) can be used as a carbon and/or nitrogen source by many bacterial species and provide acetyl-CoA. Citrate degradation and the methyl citrate pathway provide acetate and pyruvate, respectively. Since acetyl-coA, acetate

and pyruvate are central metabolic intermediates, we focused on these three pathways (additional file 1: Fig. S3).

Induction of ethanolamine metabolism by bile salts

The genetic information required for the degradation and utilization of EA by *E. coli* is encoded by 17 genes in the *eut* operon. In the presence of bile salts, all of these genes were significantly up-regulated in AIEC LF82 (2.5 to 12.2-fold, Table 1). The intestinal tract provides a rich source of EA in the form of phosphatidylethanolamine due to its presence in bacterial and eukaryotic cell membranes and in the host diet. To evaluate the ability of the AIEC LF82 strain to utilize EA as a nitrogen source, EA was added along with 0.1% glucose to mM9 minimal medium supplemented with bile salts (mM9b). To test the ability of the bacterium to use EA as a carbon source, EA and NH₄Cl were added to mM9b. As shown in Fig. 2, the AIEC LF82 strain failed to grow in minimal medium supplemented with EA and NH₄Cl. This finding demonstrated that the LF82 strain is unable to utilize EA as a carbon source but can use EA as the sole nitrogen source. Ethanolamine ammonia lyase, encoded by the genes *eutB* and *eutC*, converts EA to ammonia and acetaldehyde (additional file 1: Fig. S3). While ammonia can serve as a cellular source of reduced nitrogen, acetaldehyde is further converted to acetyl-coenzyme A by an aldehyde oxidoreductase encoded by *eutE* and enters the carbon pool of the cell. As shown in Fig. 2, the mutant defective for EutB (LF82Δ*eutB*) was unable to grow in mM9b medium with EA as the sole nitrogen source, while complementation *in trans* with the *eutB* gene (LF82Δ*eutB*/*peutB*) restored bacterial growth. In contrast, the LF82Δ*eutE* mutant showed a growth phenotype similar to the LF82 strain. These results clearly demonstrated that the AIEC strain LF82 can use EA as a nitrogen source and that a functional ethanolamine ammonia lyase including EutB is required for the release of ammonia.

Utilization of ethanolamine confers a competitive advantage to AIEC strains

The *eut* operon is conserved within *E. coli* species. In order to determine whether the utilization of EA in presence of bile salts is a common trait shared by AIEC strains, we studied a collection of *Escherichia coli* isolates including AIEC (n=18) and non-AIEC strains (n=18). Non-AIEC strains grew more slowly in mM9b minimal medium supplemented with glucose (0.01%) and EA than AIEC strains (p=0.009, Fig. 3A, additional file 1: Fig. S4). Nevertheless, growth was similar between group strains in mM9b minimal medium supplemented with glucose (0.1%) and NH₄Cl (Fig. 3B, additional file 1: Fig. S4). Thus, ethanolamine metabolism could be a trait associated with AIEC strains. The growth of the AIEC LF82 strain was high in comparison to those of the *E. coli* strain MG1655 in mM9b-EA (Fig. 4A; additional file 1: Fig.S5). To explain the difference in growth, the ratio of the mRNA level of several genes of the *eut* operon was measured in both strains during the early phase of growth. The *eut* genes were found to be significantly up-regulated in AIEC strain LF82 when bile salts were added to the culture medium (Fig. 4B), and significantly up-regulated in comparison to the MG1655 strain (Fig. 4C). These data suggest that AIEC strain LF82 degrades EA more efficiently than other *E. coli* in the presence of bile salts. The utilization of EA could provide a nutritional advantage for AIEC. To test this hypothesis, competitive assays were performed between LF82 strain, its isogenic *eutB* mutant and the strain MG1655. The LF82 strain was able to grow in the presence of EA much more effectively than its isogenic mutant or the MG1655 strain (Fig. 4D). Interestingly, competitive index values close to 1 were obtained when the LF82 Δ *eutB* and MG1655 strains were co-incubated, indicating that EA present in mM9b-EA was poorly used by the *E. coli* strain MG1655. *Enterococci* are prominent members of the normal human intestinal microflora. To analyze the capacity of *Enterococcus* to catabolize EA, 4 strains (*Enterococcus faecium* and three strains of *Enterococcus faecalis*) were incubated in mM9-EA with bile salts, and no growth was observed while they grow in mM9 supplemented with

glucose and NH_4Cl (data not shown). Altogether, these data suggest that, in the presence of bile salts, EA might be a privileged substrate for AIEC.

We next evaluated the capacity of AIEC LF82 to use EA to colonize the gut. Mice, with colitis caused by dextran sulfate sodium (DSS), were orally challenged with an equal mixture of the LF82 strain and the LF82 ΔeutB isogenic mutant. Quantification of bacteria in stool samples and ileal and colonic tissues revealed approximatively a one-log reduction in the LF82 ΔeutB -AIEC mutant compared with wild-type LF82 (Fig. 5A and B). Analysis of the competitive index of LF82 bacteria growth compared with isogenic mutant growth revealed a median competitive index of 35, 18 and 16 for stool, ileum and colon, respectively (Fig. 5C).

These results indicate that AIEC may gain a competitive advantage in the intestine by using EA.

An increased intracellular acetyl-CoA pool was induced by bile salts

Acetyl-CoA can be produced by EA degradation. EA is converted to ammonia and acetaldehyde, which is converted to acetyl-CoA by EutE, a component that is significantly increased in the presence of bile salts (RNA-seq data: $\log_2 = 10.4$; Table 1). Inside bacteria, acetyl-CoA is central to energy generation and to several biosynthetic pathways that utilize the activated two-carbon acetyl unit. However, EA is not the exclusive source of acetyl-CoA generation. Through its oxidative decarboxylation, pyruvate is a major source of acetyl-CoA. Pyruvate is usually formed by glycolysis to be oxidized by the tricarboxylic acid (TCA) cycle. Genes involved in glycolysis and pyruvate decarboxylation (*aceE*, *aceF* and *lpd*) were not up-regulated during exposure to bile salts (Table 2). Phosphoenolpyruvate, which is the precursor of pyruvate in glycolysis, was present in the same amounts in bacterial cultures with or without bile salts (30.3 ± 2.1 and 29.2 ± 4.9 mg/L, respectively; $p = 0.886$), confirming that

the glycolysis pathway was not up-regulated by bile salts. Acetate, for example, could also lead to the production of acetyl-CoA. Interestingly, genes encoding citrate lyase (*citD*, *citE* and *citF*) were up-regulated under bile conditions (Table 3). The citrate lyase converts citrate to oxaloacetate and acetate (Fig. S3). One of two distinct pathways by which *E. coli* activates acetate to acetyl-CoA is the activation of acetyl-CoA synthetase (Acs) ¹⁵. The *acs* gene was significantly up-regulated in the presence of bile salts (fold change: 2.6). Up-regulation of *eutE* and *acs* genes suggested that AIEC strain LF82 is able to produce a pool of acetyl-CoA under bile stress.

In order to test this hypothesis, the intracellular acetyl-CoA concentration was measured from bacterial cultures. The intracellular acetyl-CoA pool of LF82 strain increased when bile salts were added (5.2 ± 0.6 to 17.5 ± 4.3 mg/L; $p = 0.0286$) but not in mutants defective for ethanolamine ammonia lyase (LF82 Δ *eutB*) or deficient for citrate lyase (LF82 Δ *citF*) (4.1 ± 0.3 and 5.9 ± 0.5 mg/L, respectively) (Fig. 6).

These observations confirmed that EA and citrate degradation pathways activated upon bile salts exposition lead to acetyl-CoA production by the AIEC strain LF82. In contrast, the intracellular acetyl-CoA pool of the strain MG1655 slightly decreased in the presence of bile salts (7.2 ± 0.8 to 4.3 ± 0.8 mg/L). The *eutB* and *citF* genes were found to be significantly down-regulated in the strain MG1655 grown in the presence of bile salts (12.5 and 4.2-fold, respectively; $p = 0.0286$). These data reinforce the fact that this strain and the AIEC strain LF82 have a different metabolism in the presence of bile salts.

Induction of 1,2-propanediol degradation and methyl-citrate pathway by bile salts

The results of the RNA-seq analysis showed that the entire group of genes (*pdu* operon) was induced in the presence of bile salts (Table 4) suggesting the formation of propionyl-CoA from 1,2-propanediol (Fig. S3). Interestingly, *pdu* operon is significantly correlated with the AIEC

pathotype ¹³. *E. coli* is known to ferment fucose and rhamnose to 1,2-propanediol ¹⁶. Genes involved in the catabolism of rhamnose were up-regulated in the presence of bile salts (Table 4). Propionyl-CoA can also derive from propionate. Interestingly, the *prpE* gene encoding the enzyme that converts propionate to propionyl-CoA ¹⁵ was significantly up-regulated by 9.8-fold (Table 3). The propionyl-CoA is the precursor of 2-methylcitrate, the coactivator needed for transcriptional activation of the *prpBCDE* operon by the PrpR activator protein. RNA-seq data analysis revealed that genes involved in the methyl-citrate pathway (*prpB*, *prpC*, *prpD*, *prpE*, *prpR*) were strongly up-regulated (2.3 to 23.6-fold), with the exception of *acnB*, a gene that is constitutively expressed (Table 3). The methyl-citrate cycle converts propionyl-CoA to pyruvate and succinate (Fig. S3). Thus, pyruvate might be produced from 1,2-propanediol *via* a pathway that is activated under bile conditions in AIEC strain LF82.

Interactions between metabolic pathways

To obtain 2-methylcitrate and subsequently pyruvate, propionyl-CoA must be condensed with oxaloacetate by the PrpC enzyme (Fig. S3). Interestingly, *prpC* mRNA exhibited a 12.3-fold increase in LF82 upon bile salt exposure. Oxaloacetate may have several origins, including the oxidation of L-malate. However, the gene encoding malate dehydrogenase was not deregulated in the presence of bile salts. Oxaloacetate is also derived from tartrate and citrate fermentation. RNA-seq analysis revealed that genes involved in those fermentations were induced in the presence of bile salts (Table 3). Interestingly, the intracellular oxaloacetate concentration of the LF82 strain significantly increased when bile salts were added to the culture medium (1.4 to 41.9 mg/L; $p = 0.029$), showing that oxaloacetate was available in the cell. Thus, bile salts may favor concomitant activation of (i) tartrate and citrate pathways, leading to the formation of oxaloacetate, (ii) rhamnose, propionate and 1,2-propanediol degradation, leading to the formation of propionyl-coA and subsequently the (iii) methylcitrate

pathway leading to pyruvate (Fig. S6). Pyruvate can be transformed to acetyl-CoA by formate acetyltransferase II. Since *pflD* encoding formate acetyltransferase II was up-regulated 4.5-fold, pyruvate may also contribute to the increased intracellular acetyl-CoA pool under bile conditions. Thus, our results suggest that, in the presence of bile salts, these pathways act together to favor the formation of acetyl-CoA and to provide an energetic advantage to AIEC LF82 strain (Fig. S6).

Alternative metabolic pathways of LF82 strain in mice in the presence of bile salts

Our RNA-seq data clearly indicate that bile salts activate *in vitro* secondary metabolic pathways in AIEC strain LF82. As a test to elucidate whether bile salts are an *in vivo* metabolic activator of EA and 1,2 propanediol utilization and citrate and methyl-citrate pathways, the bile acid sequestrant cholestyramine was administered to C57BL/6J mice. Cholestyramine decreases bile-acid pool size and is associated with decreased *Ibabp* and *Shp* levels in the ileum ^{17,18}. Down-regulation of these host genes in the group treated with cholestyramine indicates that the treatment was efficient (additional file 1: Fig. S7). The levels of bacterial mRNA extracted from the ileum of untreated mice were significantly increased in comparison with those treated with cholestyramine (Fig. 7). This observation strengthens the hypothesis that bile salts in the small intestine alter the metabolism of AIEC strain LF82 by inducing alternative metabolic pathways.

Discussion

In this study, global RNA sequencing (RNA-seq) of AIEC reference strain LF82 has been used to decipher the impact of bile salts on the expression of metabolic bacterial genes. The results revealed a global up-regulation of genes involved in degradation and a down-regulation of those implicated in several biosynthetic pathways. The following four pathways were most

noteworthy: ethanolamine utilization, citrate and 1-2 propanediol degradation, and methylcitrate pathway. Importantly, in LF82 bacteria isolated from the ileal mucosa of infected mice, the mRNA level of genes involved in these pathways were increased in comparison to mice treated with cholestyramine resin, which is a bile acid sequestrant, suggesting that these pathways are activated *in vivo* under bile conditions. Our results indicate that activation of these secondary metabolic pathways in LF82 AIEC favor the formation of acetyl-CoA (Fig. S6). Acetyl-CoA is a potential energy source because it can be converted to acetyl-PO₄²⁻. The EutD phosphotransacetylase, for which the gene was up-regulated upon exposure to bile salts, can modify acetyl-CoA into acetyl-PO₄²⁻. This enzyme is a more efficient phosphotransacetylase than *E. coli* Pta, which has activity linked to acetate excretion and to the operation of the Tricarboxylic Acid cycle¹⁹. Thus, the present study provides insight into the pathways favored by AIEC LF82 for optimal energy generation.

Comparative genomic analysis of AIEC strains from different collections (Europe, North America and Australia) show that this pathobiont does not harbour an exclusive molecular signature^{20,21}, suggesting that AIEC strains have evolved from commensal *E. coli* by different mechanisms to favour their implantation in genetically susceptible CD patients. Our results identified two pathways, ethanolamine utilization and 1-2 propanediol degradation, that may be associated with the metabolic adaptation of the AIEC strains to their environments. The propanediol utilization (*pdu*) operon, which is prevalent among enteropathogenic bacteria such as *Salmonella*, *Yersinia*, *Listeria*, and *Clostridium perfringens*, is significantly correlated with the AIEC pathobiont²²⁻²⁴. In AIEC, the presence of *pduC*, which is significantly up-regulated in the presence of bile salts in our study, has been correlated with increased cellular invasion and bacterial persistence¹³. The utilization of 1,2-propanediol is therefore associated with virulent strains, and its utilization in this redirected metabolism in AIEC strain LF82 strengthens the hypothesis that this compound is important for the virulence of bacteria. Interestingly, we

demonstrated that ethanolamine can be used as a source of nitrogen and acetyl-CoA by the LF82 AIEC and confers a growth advantage to AIEC strains. It has been shown in the same way that the pathogenic *E. coli* O157:H7 strain EDL933 uses EA as a nitrogen source in the bovine intestine, whereas EA is poorly metabolized by the endogenous microbiota of the bovine small intestine, including commensal *E. coli* ²⁵. EA is abundant in the intestinal tract due to the turnover and exfoliation of enterocytes as well as the high concentration of bacterial cells ²⁶. However, EA does not contribute to the colonization of all gut bacteria. EA catabolism in *Enterococcus faecalis* modestly reduces gut colonization efficiency ²⁷. The ability of AIEC to utilize EA might therefore provide them with a competitive advantage to successfully colonize the intestinal mucosa as observed in the present study with LF82 in a mouse colitis model. Recently, it has been shown that uropathogenic *Escherichia coli* (UPEC) ethanolamine metabolism is required for effective bladder colonization in mice and that UPEC upregulates the expression of ethanolamine utilization genes during uncomplicated UTIs in humans ²⁸. Thus, we can speculate that optimization of the use of EA might be a metabolic adaptation of pathogenic *E. coli*.

EA is not only important for nitrogen metabolism but that it is also used as a signaling molecule in cell-to-cell signaling to activate virulence gene expression in EHEC ^{29,30}. The *eut* operon encodes the transcriptional regulator EutR that was found to bind promoters and directly activate the expression of the locus of enterocyte effacement (LEE) in EHEC ³¹. Interestingly, EA promotes also expression of fimbriae in EHEC, in particular of long polar fimbriae (LPF) ³⁰. AIEC strains express LPF, which are known to target Peyer's patches in a mouse CD model ³². AIEC might therefore exploit EA as a metabolite but also coopt EA as a signaling molecule to recognize gastrointestinal environment and promote virulence expression. Further work is required to establish this. Nevertheless, the above-described accessory metabolic pathways may interact with synthetic pathways involved in biofilm formation. Indeed, these metabolic

pathways can lead to the formation of acetate and pyruvate, which may participate in the formation of side chains of colanic acid. RNA-seq data analysis showed a global increase in the transcription of genes involved in the biofilm formation under bile conditions (genes involved in the formation of the colanic acid and of curli fimbriae, gene clusters encoding group 2 capsule³³, the *auf* and *yeh* genes involved in adhesion³⁴, ...) (additional file 1: Table S2). In consistent with these data, the crystal violet assay revealed an increased of biofilm biomass and an autoaggregation of LF82 bacteria in presence of bile salts (additional file 1: Fig. S8). Thus, bile salts might favor AIEC gut colonization by inducing biofilm formation. Most strains of *E. coli*, *Salmonella* and *Shigella* forms a biofilm in the presence of bile salts; it is an important resistance mechanism for many bacterial pathogens^{35,36}. Moreover, virulence factor expression of enteric pathogens and AIEC, is regulated during exposure to bile salts^{9,10,12}. Given the dual control of resistance to bile salts and virulence factor expression in the presence of bile salts, it has been proposed that the enteric bile salt-induced biofilm is a transient phenotype that would allow a more rapid dispersion as the bacteria reach the epithelial cell surfaces in the small intestine³⁶. The metabolic adaptation of AIEC presented in this work might be associated with this transient phenotype.

Studies examining the interactions between bacteria and bile have frequently been performed with cholic acid and deoxycholic acid, which are among the most abundant in the intestine³⁷. Since more than 20 bile acid metabolites can be produced from primary bile acids by the gut microbiota, the use of only two bile acids in our this study has limitation and needs further investigation. The study of Chassaing et al.⁹ reported that the concentration of bile salts has no significant effect on *lfp* transcription, in contrast to the chemical nature of bile salts. That might be similar in our study. CD-associated intestinal dysbiosis leads to modifications in the luminal bile salt composition³⁸. Thus, it is possible that the expression of AIEC genes (*eut*, *pdu*, *lfp*...) in the gut of CD patients is different from that of healthy subjects. In contrast to the study by

Chassaing et al, we did not find a significant difference in LF82 *lpf* expression when LF82 was grown for 24 h at 37°C in a minimal medium (M9) with or without bile salts, suggesting that bacterial culture medium is also crucial for *lpf* gene expression. Further studies, which take these variables into account, are therefore necessary.

To conclude, in conjunction with previous work, our results support the notion that AIEC under bile conditions modulate expression of their virulence genes as well as secondary metabolic pathway genes to overcome nutritional limitations and compete with the indigenous microbiota. Thus, our study highlight a metabolic adaptation of AIEC to bile salt exposure that may favor their colonization.

Methods

Bacterial strain and bacterial growth conditions

The bacterial strains used in this study are listed in additional file 1 (Methods, Table S3). The ability of *E. coli* LF82 to grow with bile salts and ethanolamine (EA) was tested on minimal medium mM9 as previously described ²⁵ (additional file 1: Methods). This medium was supplemented with bile salts (1%: 50% cholic acid sodium salt, 50% deoxycholic acid sodium salt, Sigma) when needed (mM9b).

For absolute quantification by RNA-seq, LF82 bacteria was grown for 24 h at 37°C in mM9 medium supplemented with D-glucose (0.1% w/v) and NH₄Cl (20 mM) in a 20 mM Tris buffer with a pH = 7.5, in the presence or absence of 1% bile salts. Each assay was performed in triplicate. Utilization of EA as a nitrogen source or as the sole carbon source was investigated in the mM9b medium supplemented with EA hydrochloride (mM9b-EA, additional file 1: Methods). For the other growth curves and for qRT-PCR of the *eut* genes, the growth medium used was the mM9-EA supplemented with 0.01% glucose. Bile salts (1%) were added or not in this medium. For quantification of metabolites in bacteria, *E. coli* strains were grown at 37°C to an OD₆₀₀ of 0.7 in mM9 with 20% Lysogeny broth (LB). Then, bile salts (1%) were added or not for 4 h.

RNA extraction, reverse transcription and quantitative PCR

The AIEC reference strain LF82 was grown for 24 h at 37°C in a minimal medium with or without bile salts. Total RNAs were isolated from LF82 bacteria, and following rRNA depletion, the remaining RNA was reverse-transcribed into cDNA, fragmented and sequenced (for detailed Methods, see additional file 1: Methods). For qRT-PCR, extracted RNAs were quantified using a NanoPhotometer P-Class (Implen) and then reverse transcribed with random hexamers (Invitrogen) and NxGen M-MuLV Reverse Transcriptase (Lucigen) according to the

manufacturer's recommendations. RNAs were then amplified using specific primers to the *prpB*, *folX*, *pfkA*, *cfa*, *LF_715*, *eut*, *tufA* or *16SrRNA* genes (Additional file 1: Methods, Table S1 and S4). Amplification of a single expected PCR product was confirmed by electrophoresis on a 2% agarose gel. qRT-PCR were performed using an Eppendorf Realplex with the following program: 95°C for 5 min and 40 cycles of 95°C for 15 s, 60°C for 20 s and 72°C for 40 s. For absolute qRT-PCR, the transcript levels in each sample were determined by absolute quantification using serial dilutions of PCR products as previously described ³⁹. Each experiment was performed in triplicate. For relative qRT-PCR, each gene expression was normalized to *tufA* using the $2^{-\Delta\Delta C_t}$ method.

RNA-seq data analysis

The RNA-seq data analysis was performed using the R software, Bioconductor packages including edgeR and the SARTools package developed at PF2-Institut Pasteur ⁴⁰ (additional file 1: Methods).

Construction and transcomplementation of mutants

Isogenic mutants of *E. coli* LF82 was generated by using the lambda red recombination system described by Datsenko and Chaverche ^{41,42} (Additional file 1: Methods).

Competition experiments

Precultures of *E. coli* strains (inoculated from a single colony) were incubated in LB with the appropriate antibiotic (32 mg/L amoxicillin for LF82 bacteria and 50 mg/L kanamycin for *LFΔeutB*). The bacterial cultures were diluted 50-fold in LB broth and grown overnight at 37°C without shaking. The mM9b-EA medium previously used was supplemented with glucose (0.1%), inoculated with approximately $5 \cdot 10^7$ bacteria per milliliter of each of the two strains tested in competition assays and incubated at 37°C without shaking. At each time point, the co-culture was diluted in phosphate-buffered saline (PBS) and spotted onto trypticase soy (TS)

agar plates with and without antibiotic. Co-cultures of LF82/LF Δ *eutB* bacteria were spotted on plates without antibiotic and on plates containing kanamycin (50 mg/L). Co-cultures of LF82 or LF Δ *eutB*/MG1655 bacteria were spotted on plates without antibiotic and on plates containing amoxicillin (32 mg/L). The plates were then incubated overnight at 37°C before counting the colony-forming units (CFU). The CFU counts of the antibiotic-sensitive strain for each competition assay were calculated by subtracting the number of CFU that were resistant to amoxicillin or kanamycin from the number of CFU counted on an agar plate without antibiotic. Each experiment was repeated three times, and a competitive index (CI) was calculated.

Metabolite extraction

Bacteria were harvested by centrifugation (10,000 g for ten minutes at 4°C). Quantified concentrations of metabolites were normalized to $3 \cdot 10^{10}$ bacteria. The supernatant was stored at -80°C, and the pellet was frozen at -20°C, thawed on ice, resuspended in cold extraction buffer (10 mM phosphate buffer, 10 mM MgCl₂, 1 mM EDTA) and then disrupted by ultrasonic treatment (five times for 30 seconds). The extract was clarified by centrifugation at 10,000 g for 10 min. After addition of DNase I, the supernatant extract was centrifuged at 4°C, 10,000 g for 20 min, passed through a 0.2- μ m filter and frozen to -80°C.

Metabolite quantification

LC/MS analyses were performed on a ThermoScientific UHPLC Ultimate 3000 RSLC coupled to an Orbitrap Q-Exactive analyser. The samples were diluted before the LC–MS analyses and injected directly in the LC–MS system without any further treatment. The calibration solutions were prepared from analytical standards dissolved in water. The UHPLC was equipped with a Luna Omega Polar C18 (100 \times 2.1 mm; 1.6 μ m) (Phenomenex) at 30°C with a gradient of acetonitrile + 0.1% formic acid and water + 0.1% formic acid. The analyses were carried out in negative mode (ESI -) with a spray voltage at 3.0 kV.

Murine model of gut colonization

The study was carried out in strict accordance with the recommendations of the Guide for the Care and Use of Laboratory Animals of the Université Clermont Auvergne. The animal protocol was approved by the committee for ethical issues, CEMEA Auvergne (Permit Number: CEMEAA, 2015032716314007), and all animals were used in accordance with the European Community Directive in the care and use of animals (86/609/CEE).

For *in vivo* competition assays, ten twelve-week-old C57BL/6 mice (body weight $\approx 26\text{--}28\text{ g}$)⁴³ were pretreated by administering oral antibiotics and 3% dextran sulfate sodium salt (Sigma) before being orally challenged with 10^9 bacteria (50% LF82 - 50% LF Δ *eutB*) (Supplementary information in addition file 1: Methods). Three days after bacterial infection, fresh fecal pellets (100–200 mg) were collected from individual mice and resuspended in PBS (addition file 1: Methods). Then, the mice were anesthetized with isoflurane and then euthanized by cervical dislocation. Colonization of the two strains was studied by enumerating the mucosa-associated AIEC bacteria by homogenizing 0.5 cm of ileum and 1 cm of colon, beginning at 0.5 cm from the cecal junction, in sterile PBS solution.

To determine the bacterial mRNA levels in the ileum of mice, the mice were pretreated by administering oral antibiotics for four days. From the day of infection until sacrifice, 2% cholestyramine was mixed with the drinking water, as recommended for human patients, in the group of treated mice. This suspension was regularly resuspended. All animals were orally challenged with 10^9 LF82 bacteria. The day after infection, the mice were anesthetized with isoflurane, euthanized by cervical dislocation and the ileum was removed.

Statistical analysis

Statistical comparisons were performed using the Mann-Whitney nonparametric test. An analysis of variance (ANOVA) was performed for experiments with multiple treatment groups, followed by pairwise comparisons with Bonferroni's multiple comparison tests. A *p* value less

than 0.05 was considered statistically significant (* $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$). For RNA-seq, mRNAs that were differentially expressed below the p -value threshold of 0.001 were considered significant.

Acknowledgements

We thank Anne-Sophie Marinelli and Virginie Bonnin for technical assistance. This study was supported by the Ministère de la Recherche et de la Technologie, Inserm (U1071), INRA (USC-2018).

Competing interests

The authors declare no competing interests.

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Table 1: Variations of the expression of *eut* genes

| name | gene size (bp) | RNA-seq values (minimal medium) | RNA-seq values (bile salts) | Fold change | Fold change (Log ₂) | p value |
|-------------|-------------------|------------------------------------|--------------------------------|-------------|------------------------------------|-----------|
| | | RPKM | RPKM | | | |
| <i>eutA</i> | 1403 | 36 | 223 | 6.3 | 2.65 | 2.151E-13 |
| <i>eutB</i> | 1361 | 61 | 358 | 5.9 | 2.55 | 1.818E-17 |
| <i>eutC</i> | 887 | 47 | 286 | 6.1 | 2.60 | 5.747E-17 |
| <i>eutD</i> | 1016 | 108 | 357 | 3.3 | 1.72 | 2.746E-11 |
| <i>eutE</i> | 1403 | 14 | 149 | 10.4 | 3.38 | 1.849E-16 |
| <i>eutG</i> | 1187 | 35 | 168 | 4.9 | 2.28 | 2.691E-11 |
| <i>eutH</i> | 1226 | 106 | 514 | 4.8 | 2.27 | 1.172E-15 |
| <i>eutJ</i> | 836 | 13 | 147 | 11.3 | 3.50 | 8.290E-18 |
| <i>eutK</i> | 500 | 37 | 94 | 2.5 | 1.34 | 9.218E-05 |
| <i>eutL</i> | 659 | 30 | 126 | 4.2 | 2.08 | 1.825E-09 |
| <i>eutM</i> | 335 | 55 | 177 | 3.2 | 1.69 | 1.128E-05 |
| <i>eutN</i> | 287 | 5 | 62 | 12.2 | 3.61 | 1.249E-12 |
| <i>eutP</i> | 479 | 39 | 166 | 4.2 | 2.08 | 7.469E-10 |
| <i>eutQ</i> | 701 | 24 | 192 | 8.1 | 3.01 | 1.052E-12 |
| <i>eutR</i> | 1052 | 142 | 308 | 2.2 | 1.12 | 3.639E-05 |
| <i>eutS</i> | 335 | 20 | 76 | 3.9 | 1.96 | 8.018E-07 |
| <i>eutT</i> | 803 | 13 | 83 | 6.4 | 2.68 | 6.423E-10 |

¹ values shown in bold are significant

Table 2: Variations of the expression of genes involved in glycolysis, TCA cycle and formation of acetyl-coA

| name | product | gene size (bp) | RNA-seq values (minimal medium) RPKM | RNA-seq values (bile salts) RPKM | Fold change | Fold change (Log2) | p value |
|-------------|---|-------------------|--|--|----------------|--------------------------|-----------|
| <i>aceE</i> | Pyruvate dehydrogenase E1 Dihydrolipoyllysine-residue | 2663 | 6420 | 11797 | -1.8 | -0.88 | 1.188E-02 |
| <i>aceF</i> | acetyltransferase | 1892 | 2620 | 3886 | -1.5 | -0.57 | 6.618E-02 |
| <i>ackA</i> | acetate kinase | 1202 | 2740 | 4056 | -1.5 | -0.57 | 7.020E-02 |
| <i>acs</i> | acetyl-coenzyme A synthetase | 1958 | 2188 | 837 | 2.6 | 1.39 | 1.897E-04 |
| <i>eno</i> | Enolase | 1298 | 9777 | 15019 | -1.5 | -0.62 | 6.921E-02 |
| <i>fbaA</i> | Fructose-bisphosphate aldolase class 2 | 1079 | 3314 | 3828 | -1.2 | -0.21 | 4.847E-01 |
| <i>fbaB</i> | Fructose-bisphosphate aldolase class 1 | 1124 | 943 | 837 | 1.1 | 0.17 | 4.857E-01 |
| <i>fbp</i> | Fructose-1,6-bisphosphatase | 998 | 3314 | 5750 | -1.7 | -0.79 | 1.384E-02 |
| <i>fumA</i> | Fumarate hydratase class I. aerobic | 1646 | 7038 | 9348 | -1.3 | -0.41 | 1.869E-01 |
| <i>fumB</i> | Fumarate hydratase class I. anaerobic | 1646 | 771 | 415 | 1.9 | 0.90 | 5.607E-05 |
| <i>fumC</i> | Fumarate hydratase class II glyceraldehyde-3-phosphate | 1403 | 1122 | 884 | 1.3 | 0.34 | 1.468E-01 |
| <i>gapA</i> | dehydrogenase A | 995 | 25736 | 36899 | -1.4 | -0.52 | 1.405E-01 |
| <i>glk</i> | glucokinase | 965 | 832 | 912 | -1.1 | -0.13 | 6.037E-01 |
| <i>gltA</i> | Citrate synthase | 1283 | 7479 | 15175 | -2.0 | -1.02 | 7.423E-04 |
| <i>gpmA</i> | bisphosphoglycerate-dependent phosphoglycerate | 752 | 10216 | 19188 | -1.9 | -0.91 | 4.772E-03 |
| <i>gpmM</i> | bisphosphoglycerate-independent phosphoglycerate | 1544 | 1282 | 1810 | -1.4 | -0.50 | 7.967E-02 |
| <i>icd</i> | Isocitrate dehydrogenase [NadP] | 1250 | 17987 | 30473 | -1.7 | -0.76 | 1.944E-02 |
| <i>lpd</i> | Dihydrolipoyl dehydrogenase | 1424 | 10039 | 20656 | -2.1 | -1.04 | 1.135E-03 |
| <i>mdh</i> | Malate dehydrogenase | 938 | 5402 | 8506 | -1.6 | -0.66 | 2.854E-02 |
| <i>pfkA</i> | 6-phosphofructokinase isozyme 1 | 962 | 1283 | 4244 | -3.3 | -1.72 | 1.369E-11 |
| <i>pgi</i> | glucose-6-phosphate isomerase | 1649 | 4480 | 5251 | -1.2 | -0.23 | 4.652E-01 |
| <i>pgk</i> | Phosphoglycerate kinase | 1163 | 2762 | 4408 | -1.6 | -0.67 | 3.299E-02 |
| <i>pta</i> | Phosphate acetyltransferase | 2144 | 1355 | 1764 | -1.3 | -0.38 | 1.523E-01 |
| <i>pykA</i> | Pyruvate kinase II | 1442 | 1163 | 1360 | -1.2 | -0.23 | 3.798E-01 |
| <i>pykF</i> | Pyruvate kinase I | 1412 | 2019 | 5004 | -2.5 | -1.31 | 7.772E-07 |
| <i>sdhA</i> | Succinate dehydrogenase flavoprotein subunit | 1766 | 8036 | 14377 | -1.8 | -0.84 | 1.123E-02 |
| <i>sdhB</i> | Succinate dehydrogenase iron-sulfur subunit | 716 | 4221 | 6984 | -1.7 | -0.73 | 2.521E-02 |
| <i>sdhC</i> | Succinate dehydrogenase cytochrome b556 subunit | 389 | 4494 | 8916 | -2.0 | -0.99 | 1.946E-03 |
| <i>sdhD</i> | Succinate dehydrogenase hydrophobic membrane | 347 | 2126 | 3986 | -1.9 | -0.91 | 6.527E-04 |
| <i>sucA</i> | 2-oxoglutarate dehydrogenase E1 component | 2801 | 18453 | 38038 | -2.1 | -1.04 | 1.922E-03 |
| <i>sucB</i> | Dihydrolipoyllysine-residue succinyltransferase | 1217 | 9625 | 19122 | -2.0 | -0.99 | 5.780E-03 |
| <i>sucC</i> | Succinyl-CoA synthetase beta chain Succinyl-CoA ligase [adP-forming] | 1168 | 7109 | 12688 | -1.8 | -0.84 | 1.840E-02 |
| <i>sucD</i> | subunit α | 869 | 9683 | 12034 | -1.2 | -0.31 | 3.924E-01 |
| <i>tpiA</i> | Triosephosphate isomerase | 767 | 4649 | 4399 | 1.1 | 0.08 | 8.098E-01 |

¹ values shown in bold are significant

Table 3: Variations of the expression of genes involved in citrate degradation and methyl-citrate pathway

| name | product | gene size (bp) | RNA-seq values (minimal medium) | RNA-seq values (bile salts) | Fold change | Fold change (Log ₂) | p value |
|-------------|---|-------------------|------------------------------------|-----------------------------------|----------------|---------------------------------------|-----------|
| | | | RPKM | RPKM | | | |
| <i>acnA</i> | aconitate hydratase 1 | 2675 | 1824 | 2317 | -1.3 | -0.34 | 2.142E-01 |
| <i>acnB</i> | aconitate hydratase 2 | 2597 | 11663 | 19016 | -1.6 | -0.70 | 2.362E-02 |
| <i>acs</i> | acetyl-coenzyme A synthetase | 1958 | 2188 | 837 | 2.6 | 1.39 | 1.897E-04 |
| <i>citC</i> | Citrate-lyase ligase | 1058 | 326 | 588 | 1.8 | 0.85 | 8.689E-04 |
| <i>citD</i> | Citrate lyase acyl carrier protein | 296 | 5 | 50 | 9.1 | 3.18 | 3.731E-10 |
| <i>citE</i> | Citrate lyase β subunit | 908 | 48 | 332 | 7.0 | 2.80 | 1.628E-17 |
| <i>citF</i> | Citrate lyase α chain | 1532 | 55 | 362 | 6.6 | 2.72 | 8.791E-16 |
| <i>citG</i> | dephosphocoenzyme-A | 878 | 32 | 183 | 5.6 | 2.49 | 5.951E-14 |
| <i>citT</i> | Citrate carrier | 1463 | 271 | 732 | 2.7 | 1.43 | 2.076E-09 |
| <i>citX</i> | Holo-citrate lyase synthase | 551 | 5 | 59 | 10.6 | 3.41 | 1.042E-13 |
| <i>ttdA</i> | L-tartrate dehydratase subunit α | 908 | 237 | 49 | 4.8 | 2.27 | 2.511E-13 |
| <i>ttdB</i> | L-tartrate dehydratase subunit β | 605 | 317 | 66 | 4.8 | 2.27 | 6.822E-12 |
| <i>ttdR</i> | transcriptional activator | 932 | 635 | 341 | 1.9 | 0.90 | 5.398E-04 |
| <i>ttdT</i> | tartrate carrier | 1463 | 724 | 312 | 2.3 | 1.21 | 1.002E-06 |
| <i>prpR</i> | operon regulatory protein | 1586 | 192 | 435 | 2.3 | 1.19 | 1.071E-04 |
| <i>prpB</i> | Methylisocitrate lyase | 890 | 131 | 3094 | 23.6 | 4.56 | 1.828E-37 |
| <i>prpC</i> | 2-methylcitrate synthase | 1169 | 106 | 1313 | 12.3 | 3.62 | 3.179E-30 |
| <i>prpD</i> | 2-methylcitrate dehydratase | 1451 | 66 | 609 | 9.3 | 3.21 | 2.654E-26 |
| <i>prpE</i> | Propionate-CoA ligase | 1886 | 80 | 786 | 9.8 | 3.30 | 5.999E-33 |

¹ values shown in bold are significant.

Table 4: Variations of the expression of genes involved in rhamnose and 1,2-propanediol degradation

| name | product | gene | RNA-seq values | | Fold | Fold | p value |
|-------------|--------------------------------------|------|------------------|--------------|-------------|---------------------|-----------|
| | | size | (minimal medium) | (bile salts) | change | change | |
| | | (bp) | RPKM | RPKM | | (Log ₂) | |
| <i>rhaA</i> | L-rhamnose isomerase | 1259 | 376 | 39 | 9.7 | 3.27 | 2.279E-24 |
| <i>rhaB</i> | Rhamnulokinase | 1469 | 452 | 65 | 7.0 | 2.80 | 3.564E-19 |
| <i>rhaD</i> | Rhamnulose-1-phosphate aldolase | 824 | 554 | 303 | 1.8 | 0.87 | 3.341E-03 |
| <i>fucO</i> | propanediol oxydoreductase | 1151 | 510 | 234 | 2.2 | 1.12 | 5.724E-06 |
| <i>pduB</i> | polyhedral bodies | 812 | 71 | 203 | 2.8 | 1.51 | 3.202E-07 |
| <i>pduC</i> | glycerol dehydratase large subunit | 1664 | 251 | 532 | 2.1 | 1.08 | 3.910E-06 |
| <i>pduD</i> | diol dehydratase medium subunit | 668 | 110 | 236 | 2.2 | 1.11 | 5.478E-04 |
| <i>pduE</i> | diol dehydratase small subunit | 518 | 39 | 118 | 3.1 | 1.62 | 7.898E-06 |
| <i>pduG</i> | diol dehydratase reactivation | 1832 | 185 | 494 | 2.7 | 1.42 | 8.661E-08 |
| <i>pduH</i> | diol dehydratase reactivation | 350 | 71 | 174 | 2.4 | 1.29 | 4.274E-05 |
| <i>pduJ</i> | polyhedral bodies | 275 | 42 | 135 | 3.2 | 1.69 | 2.362E-07 |
| <i>pduK</i> | polyhedral bodies | 422 | 16 | 59 | 3.7 | 1.89 | 1.644E-06 |
| <i>pduL</i> | Phosphate propanoyltransferase | 632 | 53 | 134 | 2.6 | 1.35 | 5.949E-05 |
| <i>pduM</i> | propanediol utilization protein | 491 | 78 | 233 | 3.0 | 1.59 | 2.260E-07 |
| <i>pduN</i> | polyhedral bodies | 275 | 48 | 90 | 1.9 | 0.91 | 1.456E-02 |
| <i>pduO</i> | propanediol utilization: B12 related | 1007 | 106 | 261 | 2.5 | 1.30 | 6.990E-06 |
| <i>pduP</i> | propionaldehyde dehydrogenase | 1112 | 81 | 211 | 2.6 | 1.39 | 2.872E-06 |
| <i>pduQ</i> | Propanol dehydrogenase | 1343 | 125 | 416 | 3.3 | 1.74 | 3.516E-09 |
| <i>pduT</i> | polyhedral bodies | 554 | 55 | 157 | 2.8 | 1.51 | 1.503E-05 |
| <i>pduU</i> | polyhedral bodies | 350 | 95 | 102 | 1.1 | 0.11 | 7.703E-01 |
| <i>pduV</i> | propanediol utilization protein | 443 | 188 | 152 | -1.2 | -0.31 | 2.703E-01 |

¹ values shown in bold are significant

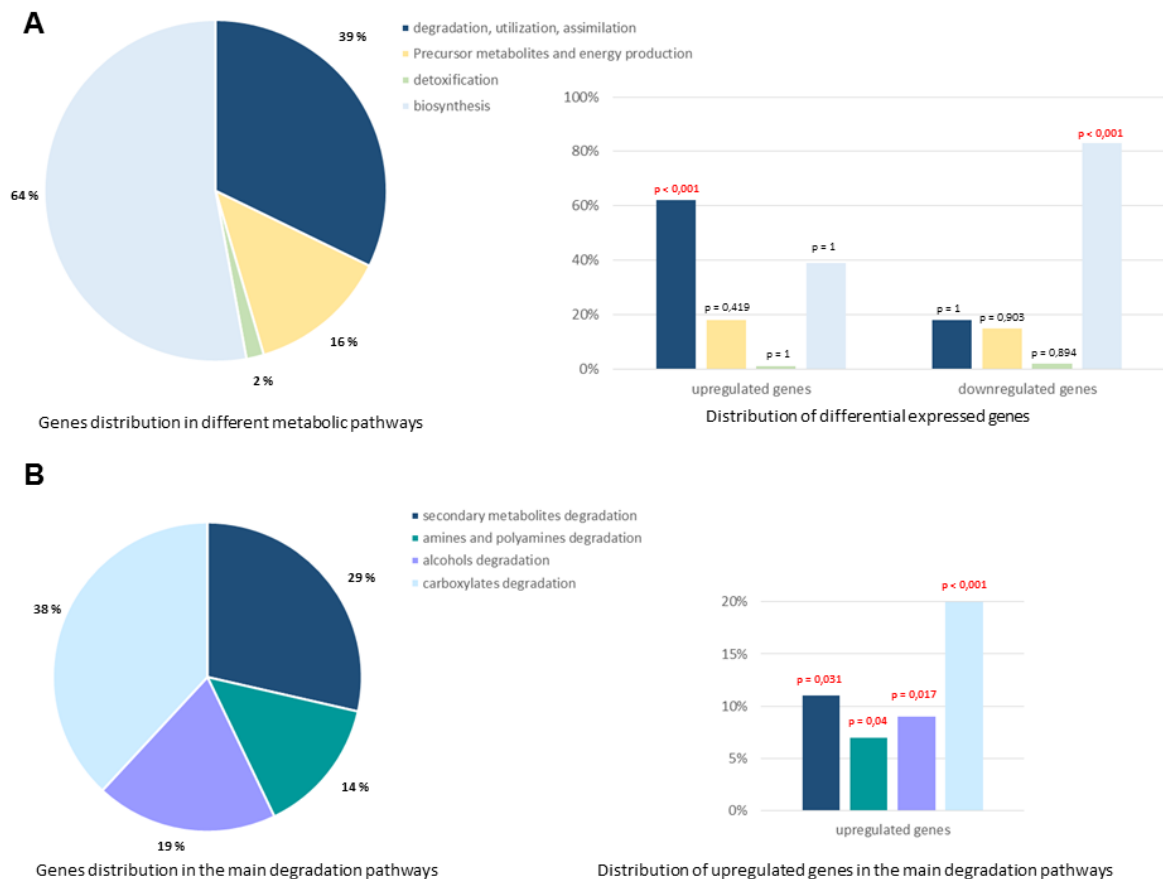


Figure 1: Bile salts induce a global up-regulation of LF82 genes involved in degradation pathways and a down-regulation of those implicated in biosynthetic pathways.

Gene expression from AIEC strain LF82 after growth in either mM9 minimal medium or mM9 supplemented with bile salts. The proportion of up- and downregulated genes (upon bile salts exposure relative to control) in major biological pathways of metabolism was compared to those in the whole transcriptome background using a hypergeometric test. A p value ≤ 0.05 was considered as significant. (A) Distribution of the upregulated and the downregulated genes in the different metabolic pathways. The percentage of LF82 genes involved in every metabolic pathway is indicated in pie chart. The percentage of increased transcript levels and of decreased transcript levels in every pathway are represented on the right: 62% genes encoding proteins involved in the degradation, utilization and assimilation of compounds were up-regulated ($p < 0,001$) and 83% genes involved in biosynthesis pathways were down-regulated ($p < 0,001$) in the presence of bile salts. (B) Distribution of the upregulated genes in main degradation pathways. The percentage of LF82 genes involved in each pathway is indicated in pie chart. The percentage of increased transcript levels in every degradation pathways are presented on the right.

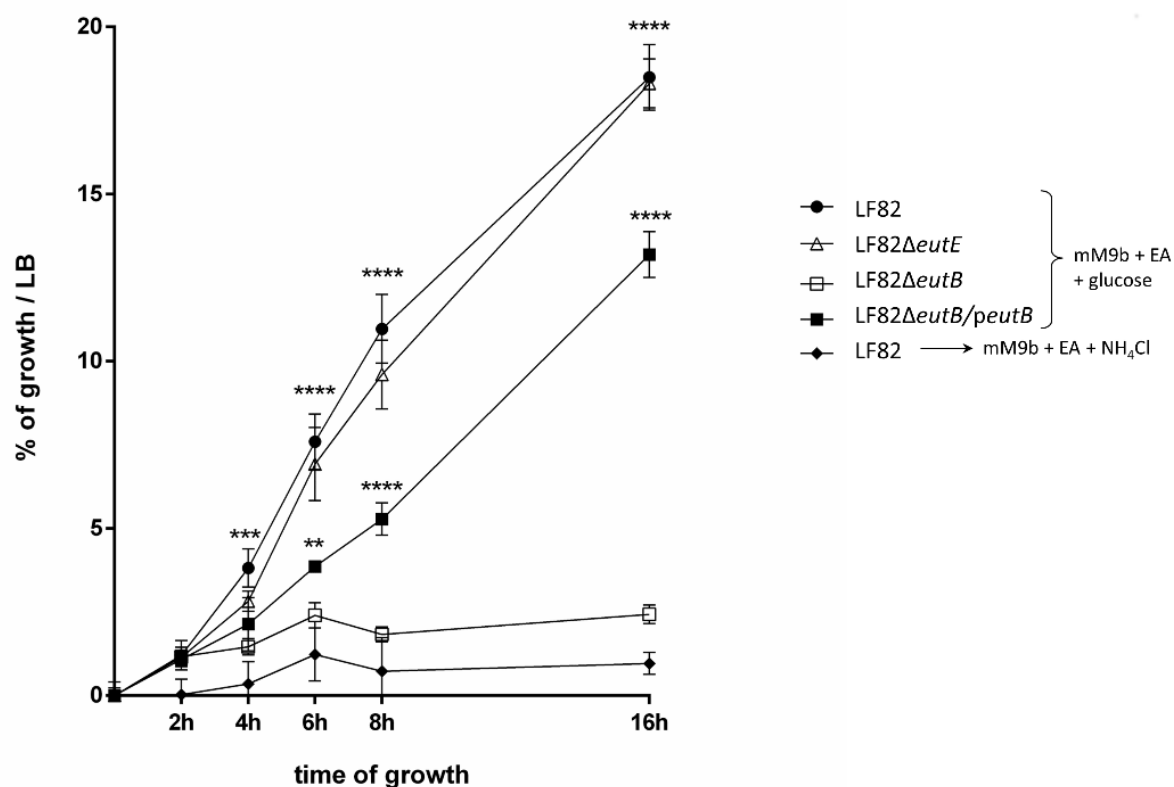


Figure 2: AIEC strain LF82 can use ethanolamine as a sole nitrogen source in presence of bile salts.

All the strains were incubated at 37°C with shaking in mM9 supplemented with bile salts (mM9b), ethanolamine (EA) and glucose or NH₄Cl. LF82 was incubated in mM9b with EA as the sole source of carbon (filled rhombus) and mM9b with EA as the sole source of nitrogen (filled circles); LF82Δ*eutB* (open squares), LF82Δ*eutE* (open triangles) and LF82Δ*eutB/peutB* (filled squares) were incubated in EA as the sole source of nitrogen. The growth of the strains was calculated as a percentage compared with their growth in LB medium for 16 h at 37°C. No difference in growth was observed in LB medium between the LF82 strain and its mutants. Values are means ± SEM of at least three independent experiments (ANOVA; ** $p < 0.01$; *** $p < 0.001$; **** $p < 0.0001$).

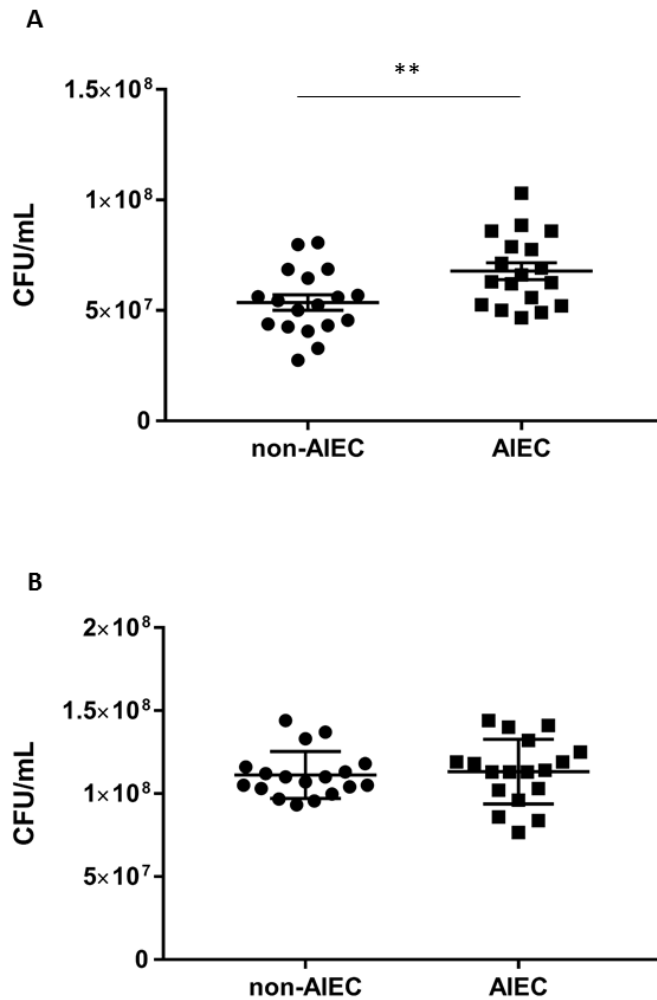


Figure 3: Comparison of ethanolamine utilization in AIEC and non-AIEC strains after 24h of incubation in minimal medium.

Data are presented as mean values \pm SEM of endpoint culture from AIEC (n=18) and non-AIEC strains (n=18) isolated of ileal mucosa of CD patients. **(A)** Number of bacteria in mM9b supplemented with ethanolamine after incubation for 24 h at 37°C. **(B)** Number of bacteria in mM9b supplemented with glucose and NH₄Cl after incubation for 24 h at 37°C. The growth of AIEC strains in mM9b-EA was slightly higher than that of non-AIEC strains. Values of each strains are means of two independent experiments. Statistical analysis was performed using a Student's t test; ** $p < 0.01$.

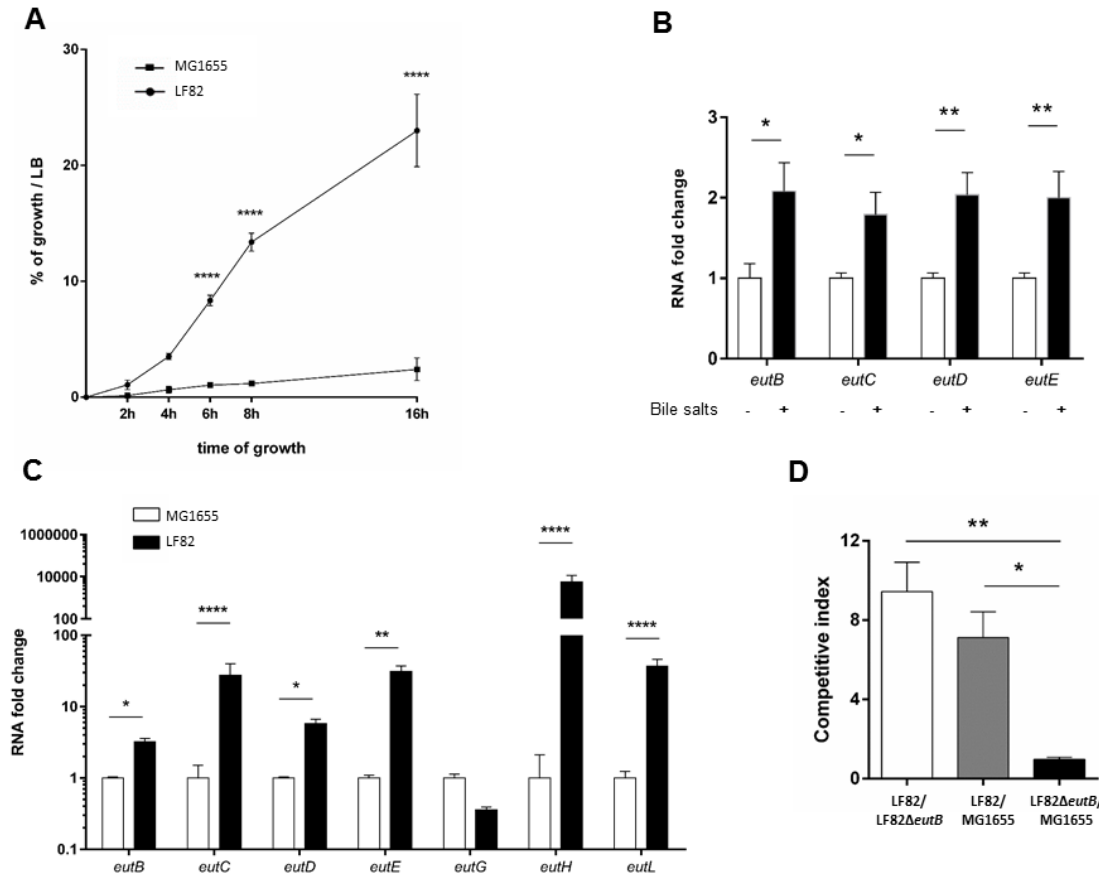


Figure 4: Ethanolamine utilization by AIEC strain LF82 provides a growth advantage against the avirulent *E. coli* MG1655 strain.

(A) Bacterial growth curves of LF82 and MG1655 strains in mM9-EA supplemented with bile salts. The growth of strains in minimal medium was evaluated in comparison to the maximal of growth of each strain in LB medium (B) Relative expression levels of the *eut* genes in the LF82 strain. LF82 strains were grown at 37°C to an OD600 of 0.6 in mM9-EA. Then, bile salts (1%) were added or not for 4 h. (C) Relative expression levels of the *eut* genes. The ratio of the mRNA level of each gene was measured in the LF82 strain and in the MG1655 strain after 8 hours of culture in the presence of bile salts. (D) Competitive index between LF82, LF82Δ*eutB* and/or MG1655 in mM9b-EA. Values are means ± SEM of at least three independent experiments. Statistical analysis was performed with the Mann-Whitney test or ANOVA test for multiple comparisons; * $p < 0.05$; ** $p < 0.01$; **** $p < 0.0001$.

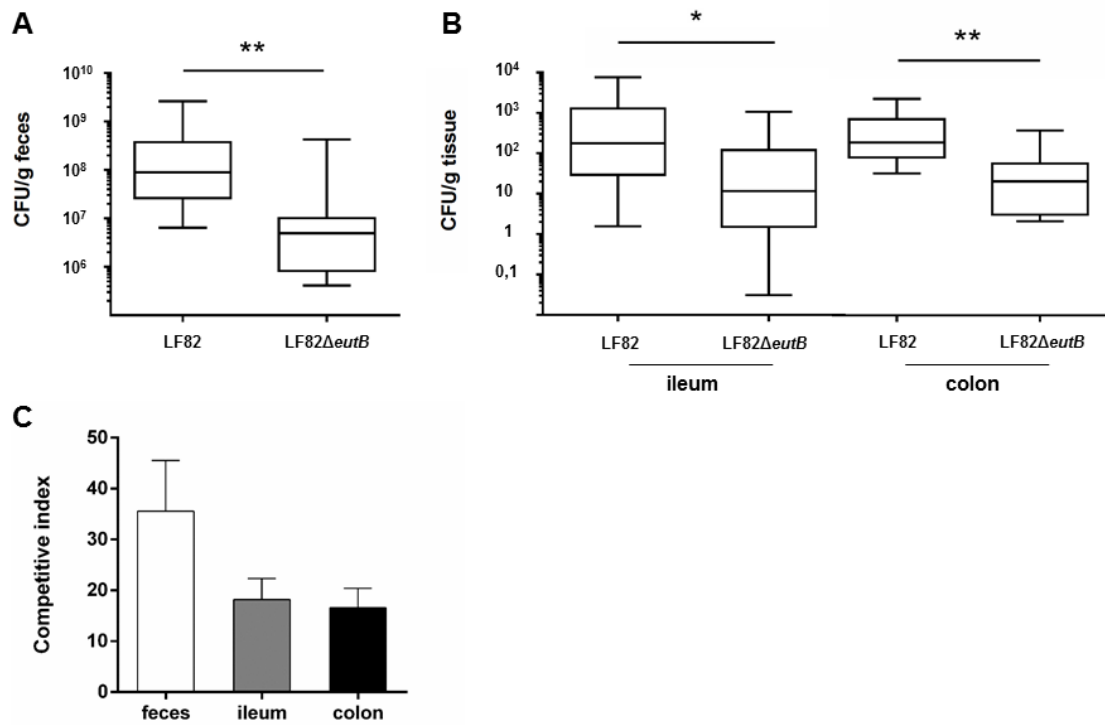


Figure 5: *eutB* favors AIEC strain LF82 gut colonization in mice.

Mice (n=10) were orally co-infected with 0.5×10^9 of the LF82 strain and 0.5×10^9 of the LF82 Δ *eutB* mutant. (A) Feces were collected three days post-infection, and LF82 and LF82 Δ *eutB* strains were counted. (B) Ileal and colonic mucosal-associated LF82 and LF82 Δ *eutB* bacteria were quantified three days post-infection. Boxes are extended from the 25th to 75th percentiles. All the values and the median are represented. (C) Competitive index between LF82 and LF82 Δ *eutB* bacteria in feces, ileum and colon collected three days post-infection. Values are means \pm SEM. Statistical analysis was performed with the Mann-Whitney test; *, $p < 0.05$; **, $p < 0.01$.

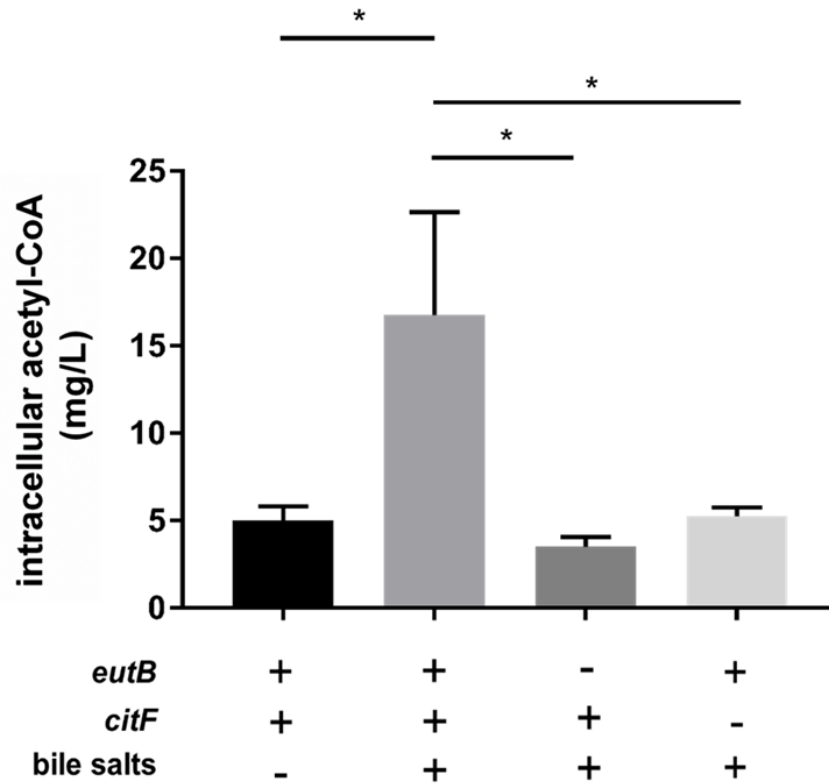


Figure 6: Bile salts increase the intracellular acetyl-CoA pool in the LF82 strain.

LF82 and its mutants LF Δ *eutB* and LF Δ *citF* were grown in mM9 with 20% LB with or without bile salts. Values are means \pm SEM of at least three independent experiments. Statistical analysis was performed with a Mann-Whitney test; * $p < 0.05$.

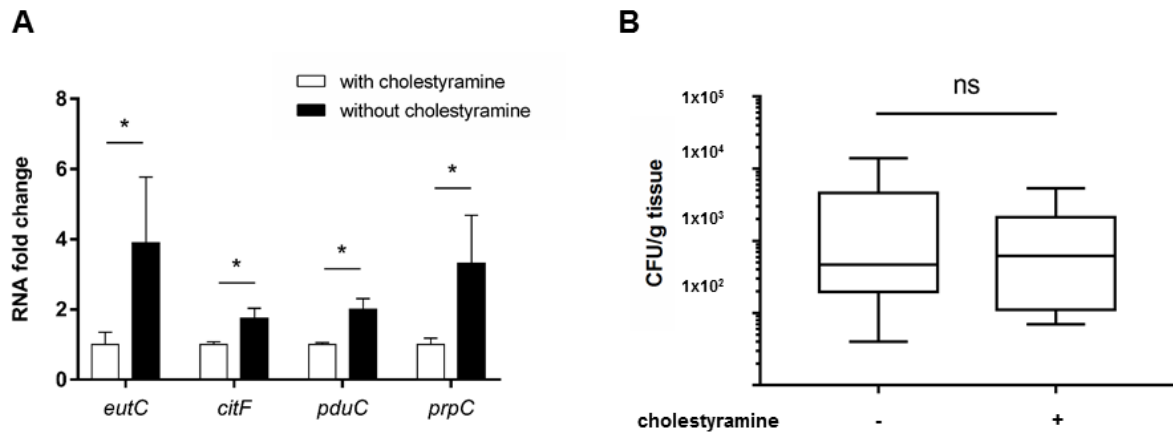


Figure 7: Alternative metabolic pathways in AIEC strain LF82 are induced in the small intestine of mice.

Sixteen mice were inoculated with AIEC strain LF82. Cholestyramine (2%), a bile acid sequestrant, was added or not to the drinking water. **(A)** The mRNA of AIEC strain LF82 was extracted from the ileum of mice, and qPCR was performed for representative genes of major metabolic pathways that we had identified in this study (ethanolamine and 1,2-propanediol utilization, citrate degradation and methyl-citrate pathway). **(B)** Ileal mucosal-associated LF82 bacteria from mice treated or not treated with cholestyramine (2%) were quantified. Values are means \pm SEM. Statistical analysis was performed with a Mann-Whitney test; * $p < 0.05$.

Metabolic adaptation of adherent-invasive *Escherichia coli* to exposure to bile salts

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Supplemental Methods

Bacterial strains

E. coli were isolated from ileal biopsies of patients. In this prospective multicentre study (8 centers), all the patients requiring ileocolonoscopy, regardless of the indication, were consecutively included between September 2015 and September 2016. The study was performed in accordance with the Declaration of Helsinki, Good Clinical Practice and applicable regulatory requirements. Study ethics approval was obtained on CPP Sud-Est 6, France (approval number AU 904). Suspicious *E. coli* colonies were identified by MALDI-TOF mass spectrometry (bioMérieux, France). Determination of *E. coli* strains as belonging to the AIEC pathovar was performed using the following criteria: (1) the ability to adhere to I-407 epithelial cells with an adhesion index equal or superior to 1 bacteria per cell, (2) the ability of the bacteria to invade I-407 with an invasion index equal or superior to 0.1% of the original inoculum ¹.

Strain LF82, isolated from a patient with ileal CD, is the archetypal AIEC strain, belongs to the *E. coli* serotype O83:H1 ² (additional file 1: Table S3). This strain contains cephalosporinase and can be selected on amoxicillin-containing agar plates. The non-pathogenic *E. coli* K-12 strain MG1655 does not display the AIEC phenotype.

Bacterial growth conditions

A modified M9 minimal medium (mM9) containing Na_2HPO_4 (48 mM), KH_2PO_4 (22 mM), and NaCl (8.5 mM) was supplemented with MgSO_4 (1 mM), CaCl_2 (0.1 mM), vitamin B12 (cyanocobalamin) (150 nM), vitamin B1 (thiamine, 5 mg/L) and trace metals (0.1 μM ZnSO_4 , 0.045 μM FeSO_4 , 0.2 μM $\text{Na}_2\text{Se}_2\text{O}_3$, 0.2 μM Na_2MoO_4 , 2 μM MnSO_4 , 0.1 μM CuSO_4 , 3 μM CoCl_2 and 0.1 μM NiSO_4) (2 mL/L). This medium was supplemented with bile salts (1%: 50% cholic acid sodium salt, 50% deoxycholic acid sodium salt, Sigma) when needed (mM9b).

Utilization of EA as a nitrogen source was investigated by addition of EA hydrochloride (5 mM) and glucose (0.1 %) to the mM9b medium (mM9b-EA). To test the capacity of the LF82 strain to use EA as the sole carbon source, the mM9b medium was supplemented with EA hydrochloride (5 mM) and NH_4Cl (20 mM). For each condition, three lysogeny broth (LB) cultures were each started from a single colony and grown overnight at 37°C with aeration. Cells were pelleted by centrifugation, resuspended in medium with EA as the sole nitrogen or carbon source and diluted 50-fold in the corresponding medium. Cultures were then incubated at 37°C, and growth was monitored in three parallel cultures by following the optical density ($\lambda=600$ nm).

RNA extraction

Total RNAs were extracted from bacteria using a Direct-zol RNA MiniPrep kit (Zymo research) and treated with a Turbo DNA-free kit (Ambion) to remove any contaminating genomic DNA. DNase-treated RNA samples were purified with RNA clean and concentrator-25 (Zymo research). For RNA-seq analysis, purified RNAs were then quantified using a NanoDrop 1000 spectrophotometer (Thermo Scientific). The integrity of the results (RNA integrity number [RIN]) was assessed using an Agilent 2100 bioanalyzer. A Ribo-zero Magnetic kit for Gram-negative bacteria (Epicentre) was used according to the manufacturer's recommendations to

remove the 23S and 16S rRNA from the total RNA samples. The samples were then purified using RNA clean and concentrator-5 (Zymoresearch). To evaluate the degree of rRNA depletion, the samples were analyzed using an Agilent 2100 bioanalyzer. The remaining RNA was sequenced using Illumina HiSeq 2500 technology with the genomic ProfileXpert platform (Claude Bernard University, Lyon, France). Three replicates from each experimental condition (with or without bile salts) were employed.

RNA-seq data analysis

We used RNA-seq to compare transcriptomes to understand the regulatory networks that control gene expression in AIEC strains during ileal colonization. Briefly, reads were mapped against the genomic sequence of *E. coli* LF82 (GenBank accession n° NC_011993; ³). Reads mapped to several positions and reads mapped to rRNA were removed from further analysis. The number of reads overlapping each gene based on GenBank annotation was recorded. Reads from replicate samples were pooled, and the number of reads per gene was normalized according to the total number of reads in each library and the gene size. To normalize the expression of genes in different RNA-seq samples, values corresponding to the number of reads per kilobase per million mapped (RPKM) were calculated as follows: (number of reads for the gene $\times 10^9$) / (total number of reads \times size of the gene). A *p*-value adjustment for differentially expressed genes (DEGs) was performed to take into account multiple testing and control the false positive rate to a chosen level $\alpha < 0.001$. Products of DEGs were classified by functional category according to metabolism pathways of the Ecocyc database (<http://ecocyc.org>) ⁴. The RPKM values for each gene were plotted and visualized as a circle using the Circos program ⁵. Metabolic pathways were analyzed using Ecocyc ⁶.

A total of 53,900,605 reads from minimal medium and 56,327,631 reads from medium supplemented with bile salts were obtained for each cDNA library. Among them, 50,353,549

(93.4%) and 53,246,854 (94.5%) reads mapped to the genome of *Escherichia coli* LF82, which has a total size of 4,773,108 bp. The average numbers of reads per region were 462 (without bile salts) and 747 (with bile salts), with a coverage of 98.4% and 98.6% of the 4376 encoding DNA-encoding sequences (CDS) of *E. coli* LF82 represented by at least one single read. The absolute and relative distributions of reads in the two media for the annotated genes of the LF82 strain are shown in Fig. S1. A dendrogram used to represent all the samples shows the grouping of the replicates and a difference between the biological conditions. Box plots and the volcano plot are also represented to show the quality of the normalization and the differential expression of genes (Fig. S1). To assess the reliability of RNA-seq for determining the relative abundances of individual transcripts in the absence and presence of bile salts, we used absolute quantification of mRNAs for three up-regulated genes (*prpB*, *eutB* and *LF82_715*), two downregulated genes (*pfkA* and *cfa*) and one unchanged gene (*folX*) by qRT-PCR. The data for these genes provided an r^2 value of 0.9708, confirming the data obtained by RNA-seq (Fig. S2; Table S1).

Construction and transcomplementation of isogenic mutants

Isogenic mutants of *E. coli* LF82 was generated by using the lambda red recombination system. *E. coli* LF82 was transformed with pKOBEG, a plasmid encoding the Red proteins that protect linear DNA from degradation in bacteria. The plasmid was maintained in bacteria at 30°C with 25 mg/l of chloramphenicol and 1 mM of L-arabinose. The Flp recognition target-flanked cassette harboring the kanamycin resistance cassette was generated by PCR from *E. coli* BW25141 with d-*eutB*-F/d-*eutB*-R, d-*eutE*-F/d-*eutE*-R and d-*citF*-F/*citF*-R primers (Table S2) and High Fidelity Platinum Taq polymerase (Invitrogen) according to the manufacturer's instructions. The PCR products were electroporated into previously glycerol-washed *E. coli* LF82. The resulting LF82 Δ *eutB*, LF82 Δ *eutE* and LF82 Δ *citF* isogenic mutants (Km^R) were

selected on LB agar containing 50 mg/L kanamycin. Replacement of the *eut* and *citF* genes by the kanamycin resistance cassette was confirmed by PCR. The kanamycin resistance cassette was then removed from LF82 Δ *eutB* bacteria by the transient expression of the Flp recombinase from the pCP20 plasmid, creating the LF82 Δ *eutB* (Km^S) strain.

The *eutB* gene was amplified by PCR from *E. coli* LF82 genomic DNA using *eutB*EcoRI-F and *eutB*BamHI-R primers (Table S2). The amplified DNA was purified with a NucleoSpin extract kit (Macherey-Nagel), digested with EcoRI and BamHI (New England Biolabs), and ligated to the EcoRI-BamHI-digested expression vector pBK-CMV (Agilent Technologies). This construct was electroporated into LF82 Δ *eutB* (Km^S) electrocompetent strains and selected on Mueller Hinton agar containing 50 mg/L kanamycin. The presence of the *eutB* gene was confirmed by PCR. The construction was checked by double-stranded DNA sequencing (GATC biotech, Germany).

Murine model of gut colonization

For the *in vivo* experiments, we used C57BL/6 mice, which were housed in specific pathogen-free conditions in the animal care facility at the Université Clermont Auvergne, Clermont-Ferrand, France. For *in vivo* competition assays, ten twelve-week-old mice (body weight \approx 26–28 g) were pretreated by administering oral amoxicillin (1 g/L), vancomycin (500 mg/L), metronidazole (500 mg/L) and neomycin (1 g/L) for four days, and 3% dextran sulfate sodium salt (Sigma) for the last day. At 24 h after stopping the antibiotic treatment, the animals were orally challenged with 10⁹ bacteria (50% LF82 - 50% LF Δ *eutB*). Three days after bacterial infection, fresh fecal pellets (100–200 mg) were collected from individual mice and resuspended in PBS. After serial dilutions, the bacteria were enumerated by plating on TS agar medium containing amoxicillin to isolate the two bacteria and amoxicillin + kanamycin to isolate LF Δ *eutB*. The plates were then incubated overnight at 37°C before counting the CFU.

The CFU count of the LF82 strain for each mouse was calculated by subtracting the number of CFU that were resistant to kanamycin from the number of CFU counted on an agar plate containing only amoxicillin. Three days after infection, the mice were anesthetized with isoflurane and then euthanized by cervical dislocation. Colonization of the two strains was studied by enumerating the mucosa-associated AIEC bacteria by homogenizing 0.5 cm of ileum and 1 cm of colon, beginning at 0.5 cm from the cecal junction, in sterile PBS solution. Samples were plated on TS agar containing amoxicillin or amoxicillin + kanamycin and incubated overnight at 37°C.

Biofilm formation assay

Biofilm assays were used as previously described with some modifications ^{7,8}. Briefly, 6 µL of a 3-hour culture in mM9-EA medium supplemented or without 1% bile salts was inoculated into 144 µL of the same medium in a 96-well culture-treated polystyrene microtiter plate (Nunc). Wells filled with growth medium alone were included as negative controls. After 4 h and 30 min of incubation at 37°C, surface-adherent biofilm formation was measured by staining bound cells for 15 min with a 0.5% (w/v) aqueous solution of crystal violet. After rinsing with distilled water, the bound dye was released from the stained cells using 95% ethanol, and the OD at 540 nm was determined.

Autoaggregation assay

After an overnight culture at 37°C in M9 minimal medium supplemented with glucose (0.1%) and bile salts (1%) when needed, cells were diluted in the same medium and grown at 37°C to the exponential phase. Next, 20 µL of each culture was Gram-stained and visualized by microscopy.

Supplemental data

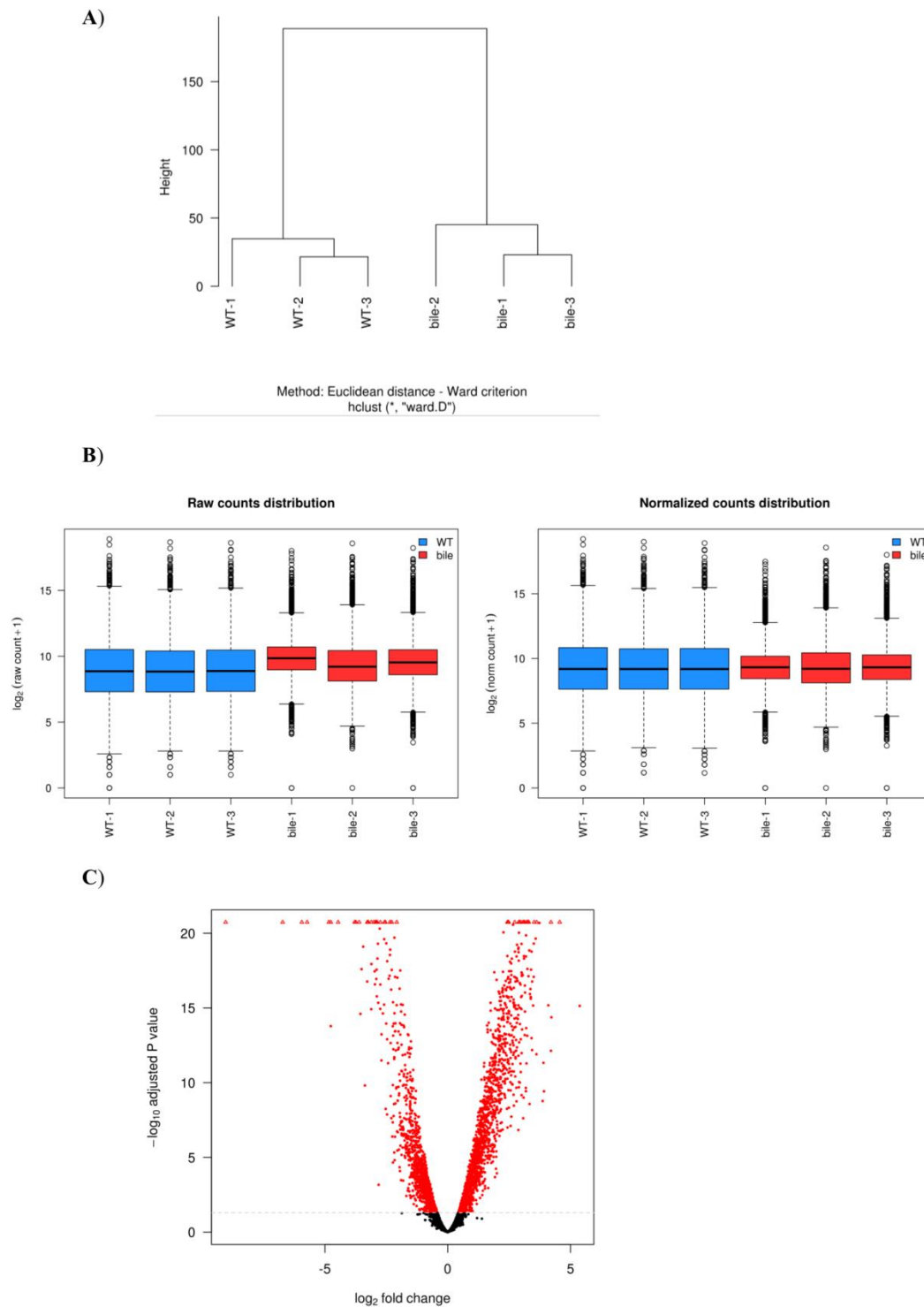


Figure S1: Global data retrieved by RNA-seq. (A) Dendrogram built based on the Ward criteria, which show variability in raw data within the experimental conditions. (B) Boxplots of raw (left) and normalized (right) data to assess the quality of the normalization process. (C) Volcano plot (bile salts containing medium *versus* medium) representing the log of the adjusted p value as a function of the log ratio of differential expression.

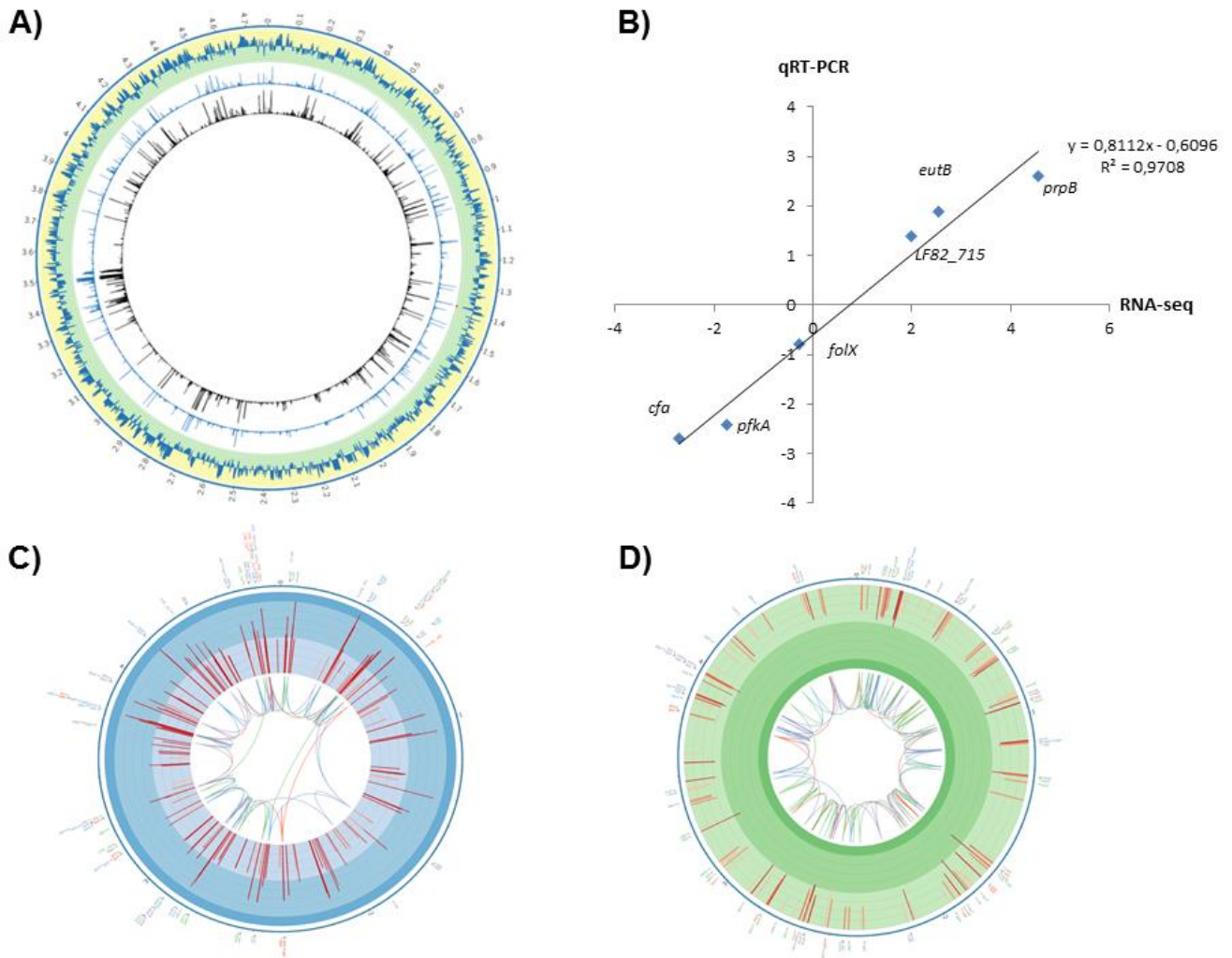


Figure S2: Analysis and validation of the RNA-seq experiments.

(A) Global analysis of transcript levels in *E. coli* LF82 by RNA-seq. The gray circular lines represent a $\log_2 = 1$ (i.e., RPKM bile salts containing medium/minimal medium ratio values) of each gene among the upregulated genes (yellow background) and downregulated genes (green background). Black and blue circles on a white background correspond to the expression of each gene (represented as RPKM values) in bacteria grown under minimal conditions and bile salts-containing medium, respectively. The outermost circle represents the 4,773,108 bp of the LF82 genome. **(B)** Validation of the RNA-seq results by qRT-PCR for selected genes. Mean \log_2 ratios of values determined in the qRT-PCR experiments are plotted against the mean \log_2 ratios of values determined in the RNA-seq experiments (Supporting Information Table S1). **(C)** Global analysis of increased transcript levels of genes involved in metabolism in *E. coli* LF82 with connections with each metabolic pathway. The gray circular lines represent a $\log_2 = 0.5$ (i.e., RPKM bile salts containing medium/minimal medium ratio values) of each gene among the upregulated genes. **(D)** Global analysis of decreased transcript levels of genes involved in metabolism in *E. coli* LF82 with associations with each metabolic pathway. The gray circular lines represent a $\log_2 = 0.5$ (i.e., RPKM bile salts containing medium/minimal medium ratio values) of each gene among the downregulated genes.

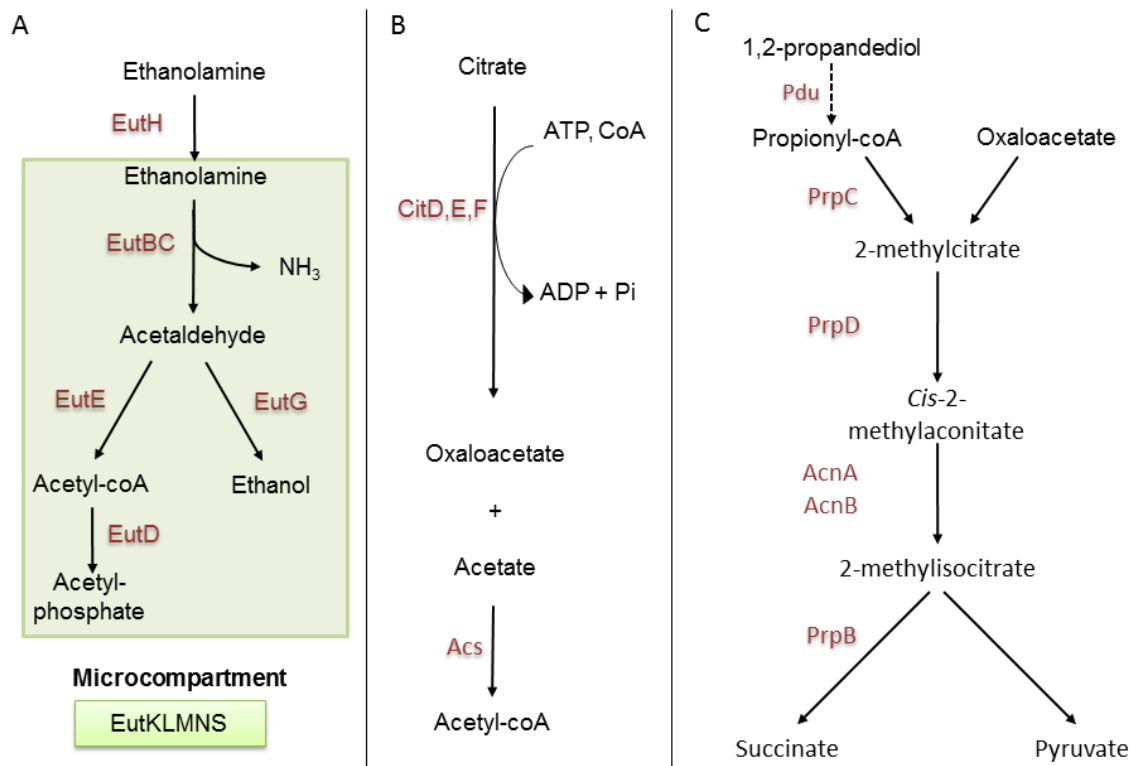


Figure S3: Schematic pathways of ethanolamine catabolism (A), citrate degradation (B) and the methylcitrate pathway (C).

(A) EutS, EutM, EutN, EutL and EutK are shell proteins constituting a carboxysome, an organelle that is required to conserve volatile metabolites and to concentrate the EA catabolic enzymes. Ethanolamine ammonia lyase, encoded by the genes *eutB* and *eutC*, converts EA to ammonia and acetaldehyde. This process requires the cofactor adenosylcobalamin, which is produced from cobalamin by the corrinoid cobalamin adenosyltransferase protein encoded by *eutT*. While ammonia can serve as a cellular source of reduced nitrogen, the acetaldehyde is further converted to acetyl-coenzyme A by an aldehyde oxidoreductase encoded by *eutE*, and it enters the carbon pool of the cell. In the case of acetyl-CoA accumulation, acetaldehyde can be converted to alcohol by another oxidoreductase encoded by *eutG*. (B) Citrate is cleaved to oxaloacetate and acetate by citrate lyase enzyme, which is a complex of three subunits. (C) The methylcitrate cycle is initiated by the synthesis of 2-methylcitrate from propionyl-CoA, and oxaloacetate. 2-methylcitrate is then converted into 2-methylisocitrate, which is subsequently split into pyruvate and succinate.

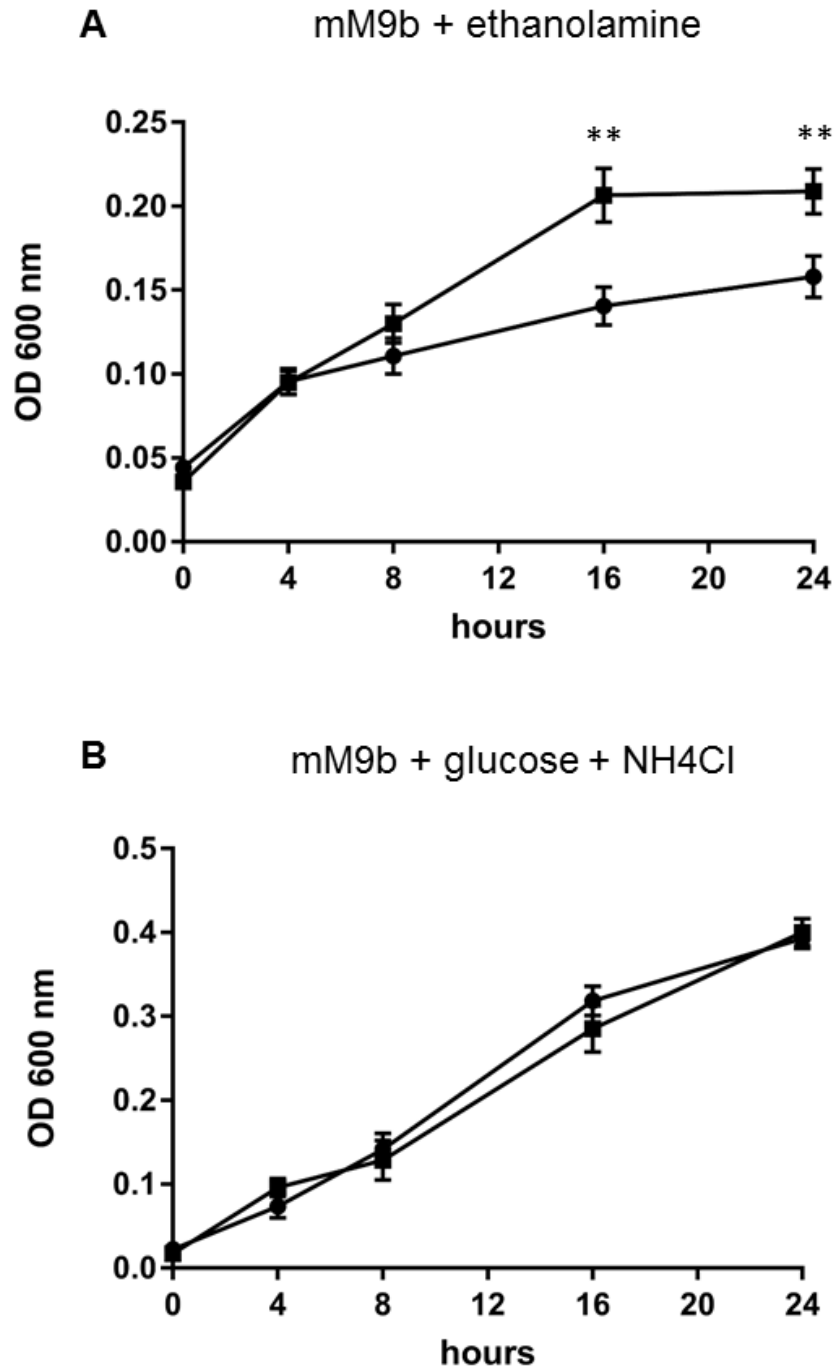


Figure S4: Comparison of growth of AIEC and non-AIEC strains in minimal medium.

Data are presented as mean values \pm SEM of bacterial growth curves from AIEC (n=18) and non-AIEC strains (n=18) isolated of ileal mucosa of CD patients. (A) Bacterial growth curves of AIEC and non-AIEC strains in mM9b supplemented with ethanolamine. (B) Bacterial growth curves of AIEC and non-AIEC strains in mM9b supplemented with glucose and NH₄Cl. Statistical analysis was performed using a Student's t test; ** $p < 0.01$.

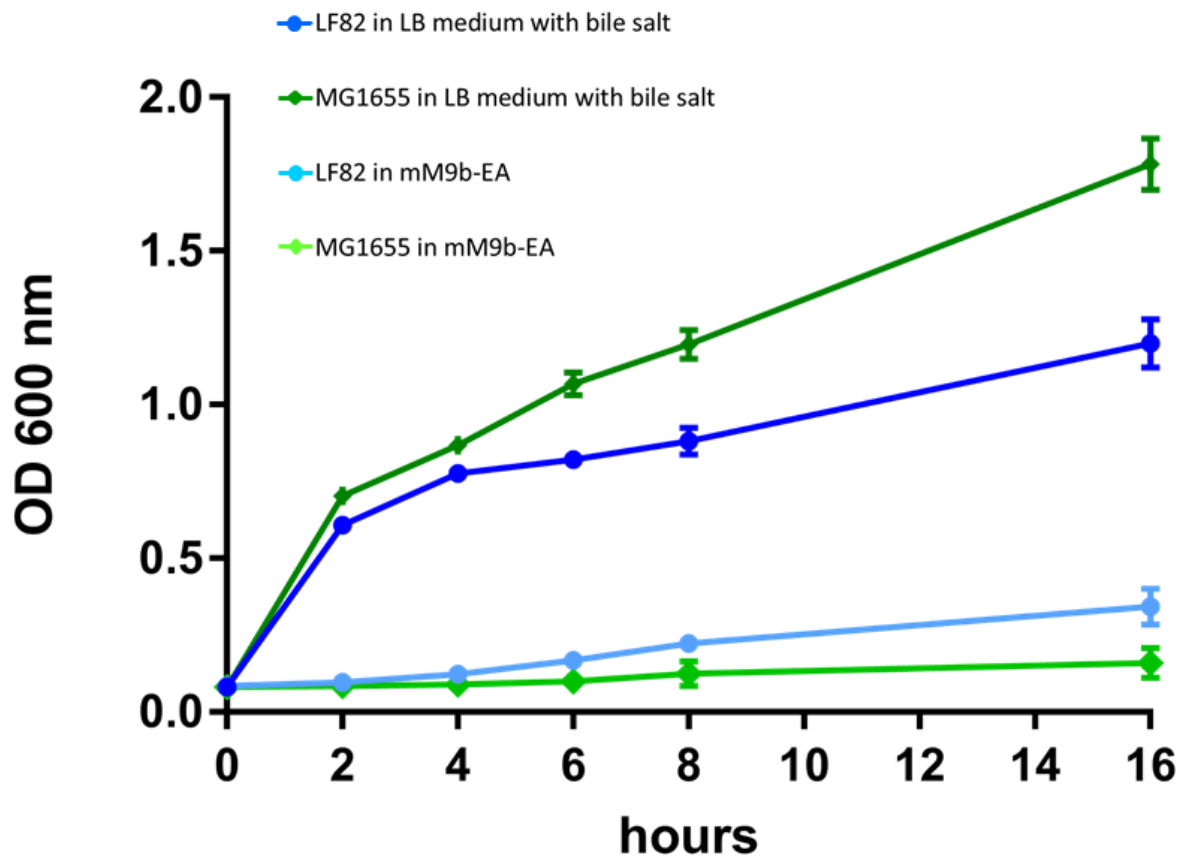


Figure S5: Bacterial growth curves of LF82 and MG1655 strains in LB and mM9-EA supplemented with bile salts. Values are means \pm SEM of at least three independent experiments. The growth difference between both media was 68 and 90% for LF82 and MG1655, respectively.

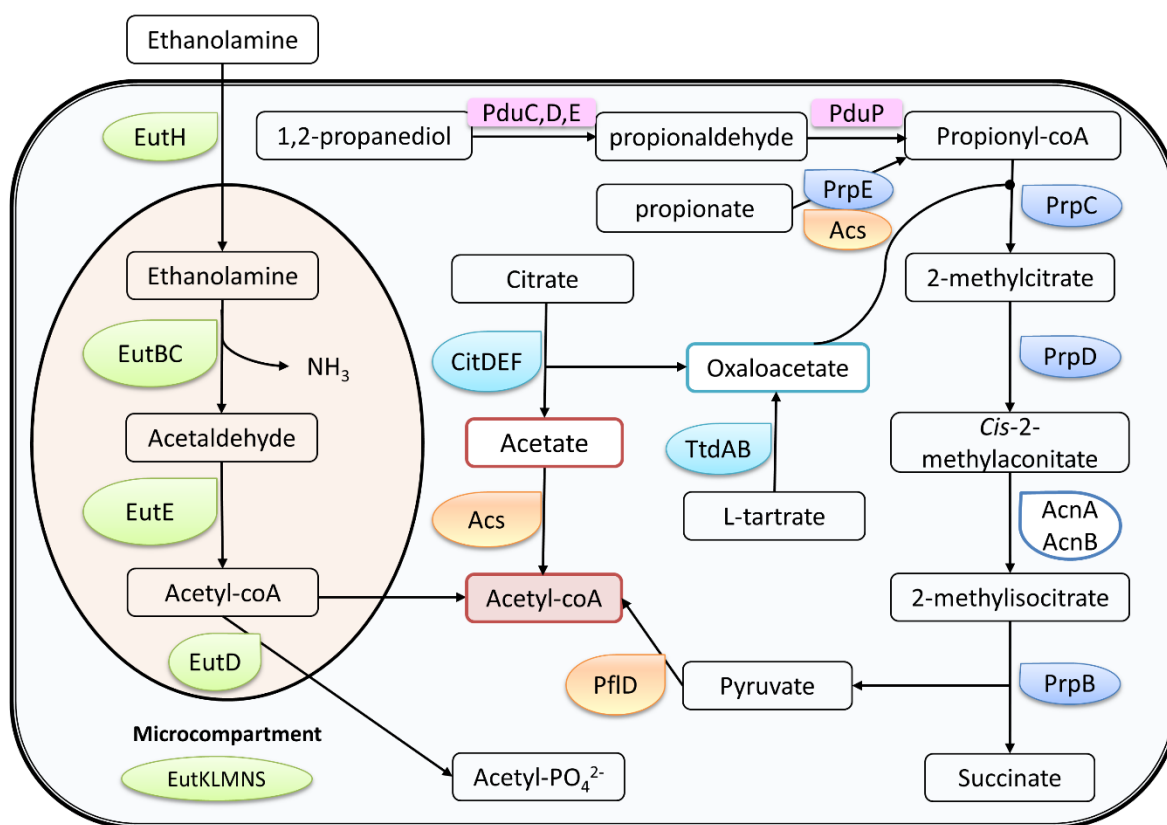


Figure S6: Schematic showing the interplay between ethanolamine degradation, citrate and L-tartrate fermentation and the 2-methylcitrate pathway under bile conditions.

Ethanolamine is metabolized by AIEC to produce nitrogen and acetyl-CoA. Citrate is converted to acetate and oxaloacetate by citrate lyase. Oxaloacetate, which is necessary for the methylcitrate pathway, is also supplied for L-tartrate fermentation and amino acid degradation. Propionyl-coA from various degradation products is metabolized to produce pyruvate, which can be converted to acetyl-coA. The genes that exhibited an increase in mRNA concentrations in bacteria grown with bile salts in comparison to without bile salts encoded proteins involved in ethanolamine degradation (green boxes), 2-methylcitrate pathway (blueberry boxes), citrate and L-tartrate fermentation (cyan boxes) and 1,2-propandiol degradation (pink boxes).

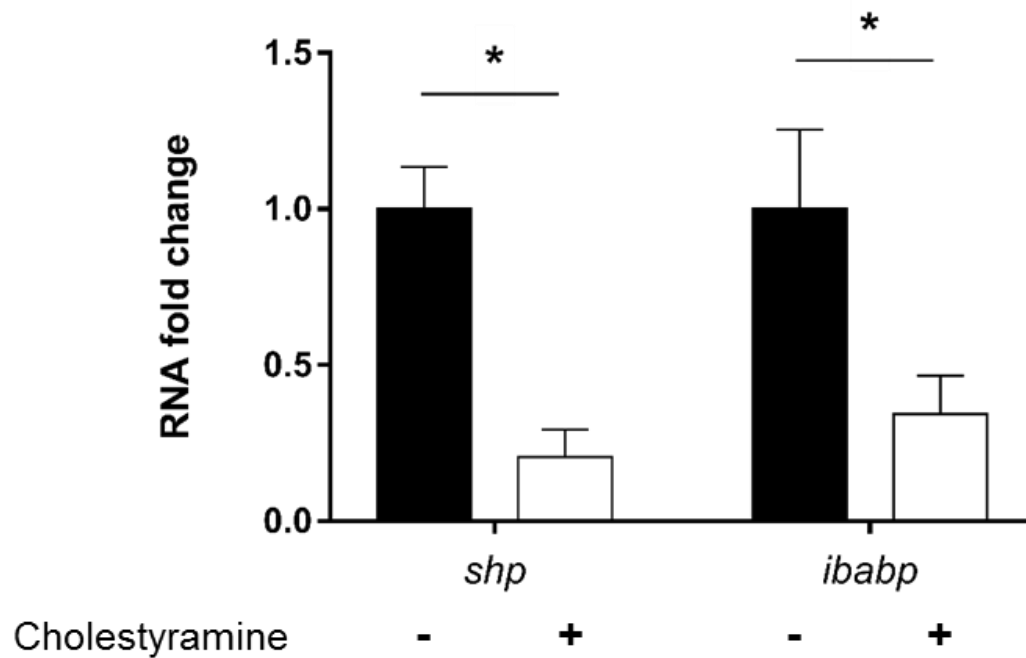


Figure S7: Effect of cholestyramine on mRNA levels of *shp* and *ibabp* in the ileum of mice. Cholestyramine is a bile-acid sequestrant that binds bile acids in the intestine to prevent their reabsorption. As a result, this decreases the feedback suppression of hepatic bile-acid synthesis from cholesterol. Values are means \pm SEM. Statistical analysis was performed with a Mann-Whitney test; * $p < 0.05$.

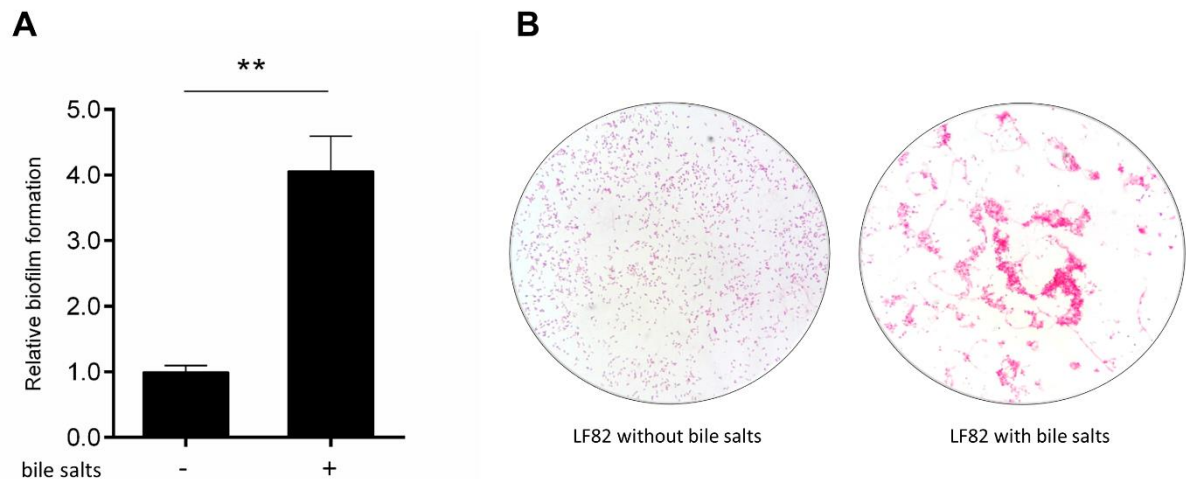


Figure S8: Bile salts induce biofilm formation and autoaggregation of bacteria.

(A) Crystal violet quantification of biofilm formation. Strains were grown in mM9-EA medium supplemented or not with 1% bile salts. After 4 h and 30 min of incubation at 37°C, surface-adherent biofilm formation was measured by staining. Values are means \pm SD of at least three independent experiments. (B) Autoaggregation of bacteria from visualized by microscopy after Gram staining (1000x magnification). Statistical analysis was performed with a Mann-Whitney test; **, $p < 0.01$.

Table S1: qRT-PCR validation of selected genes

| Gene number | Gene name | Product name | qRT-PCR | RNA-seq |
|-------------|-------------|---|------------------------------------|------------------------------------|
| | | | fold change (Log ₂) | fold change (Log ₂) |
| LF82_0581 | <i>eutB</i> | ethanolamine ammonia-lyase heavy chain | 1.882 | 2.55 |
| LF82_1739 | <i>prpB</i> | Methylisocitrate lyase | 2.59 | 4.561 |
| LF82_0729 | <i>folX</i> | D-erythro-7.8-dihydroneopterin triphosphate epimerase | -0.802 | -0.262 |
| LF82_1619 | <i>pfkA</i> | 6-phosphofructokinase isozyme 1 | -2.43 | -1.725 |
| LF82_0286 | <i>cfa</i> | Cyclopropane-fatty-acyl-phospholipid synthase | -2.70 | -2.70 |
| LF82_p715 | LF82_p715 | Ornithine carbamoyltransferase chain I | 1.383 | 1.99 |

Table S2: Variations of the expression of genes involved in biofilm formation

| name | product | gene size (bp) | RNA-seq values (minimal medium) | RNA-seq values (bile salts) | Fold change | Fold change (Log2) | p value | type of virulence gene |
|-------------|--|-------------------|------------------------------------|--------------------------------|----------------|--------------------------|-----------|------------------------|
| | | | RPKM | RPKM | | | | |
| <i>acrE</i> | acriflavine resistance protein E | 1157 | 619 | 127 | 4.9 | 2.29 | 1.181E-15 | biofilm |
| <i>acrF</i> | acriflavine resistance protein F | 3104 | 1355 | 665 | 2.0 | 1.03 | 2.395E-05 | biofilm |
| <i>bcsA</i> | Cellulose synthase catalytic subunit [UDP-forming] | 2618 | 2103 | 1498 | 1.4 | 0.49 | 5.361E-02 | biofilm |
| <i>bcsB</i> | Cyclic di-GMP-binding protein | 2339 | 993 | 612 | 1.6 | 0.70 | 2.248E-03 | biofilm |
| <i>bcsC</i> | Cellulose synthase operon protein C | 3473 | 1450 | 978 | 1.5 | 0.57 | 1.407E-02 | biofilm |
| <i>bcsZ</i> | endoglucanase | 1112 | 693 | 519 | 1.3 | 0.42 | 6.640E-02 | biofilm |
| <i>cpsB</i> | Mannose-1-phosphate guanylyltransferase [GDP] | 1436 | 448 | 83 | 5.4 | 2.44 | 4.227E-15 | biofilm |
| <i>cpsG</i> | Phosphomannomutase (colanic acid biosynthesis) | 1370 | 160 | 25 | 6.3 | 2.65 | 2.972E-14 | biofilm |
| <i>csgA</i> | Major curlin subunit | 455 | 74 | 206 | 2.8 | 1.48 | 4.550E-06 | pili |
| <i>csgB</i> | Minor curlin subunit | 455 | 67 | 138 | 2.1 | 1.05 | 8.281E-04 | pili |
| <i>fcl</i> | GDP-L-fucose synthetase | 965 | 163 | 41 | 4.0 | 1.99 | 6.025E-09 | biofilm |
| <i>fimA</i> | Type-1 fimbrial protein. A chain | 548 | 7094 | 21306 | 3.0 | 1.59 | 1.812E-06 | pili |
| <i>fimB</i> | Type 1 fimbriae regulatory protein fimB | 602 | 413 | 428 | 1.0 | 0.05 | 8.898E-01 | pili |
| <i>fimC</i> | chaperone protein fimC | 725 | 2840 | 3333 | 1.2 | 0.23 | 4.971E-01 | pili |
| <i>fimD</i> | Outer membrane usher protein fimD | 2636 | 3624 | 6328 | 1.7 | 0.80 | 9.777E-03 | pili |
| <i>fimE</i> | Type 1 fimbriae regulatory protein fimE | 596 | 809 | 450 | -1.8 | -0.84 | 1.584E-04 | pili |
| <i>fimF</i> | Protein fimF | 530 | 206 | 415 | 2.0 | 1.008 | 1.064E-04 | pili |
| <i>fimG</i> | Protein fimG | 503 | 208 | 528 | 2.5 | 1.34 | 4.303E-08 | pili |
| <i>fimH</i> | Protein fimH | 902 | 574 | 920 | 1.6 | 0.681 | 5.124E-03 | pili |
| <i>fimI</i> | Fimbrin-like protein fimI | 539 | 3699 | 5088 | 1.4 | 0.46 | 2.335E-01 | pili |
| <i>flhC</i> | flagellar transcriptional activator flhC | 578 | 1026 | 2437 | -2.4 | -1.249 | 2.296E-05 | pili |
| <i>flhD</i> | Transcriptional activator flhD | 350 | 1331 | 5144 | -3.9 | -1.95 | 6.999E-08 | pili |

| name | product | gene size (bp) | RNA-seq values (minimal medium) | RNA-seq values (bile salts) | Fold change | Fold change (Log2) | p value | type of virulence gene |
|-------------|---|-------------------|------------------------------------|--------------------------------|----------------|--------------------------|-----------|------------------------|
| | | | RPKM | RPKM | | | | |
| <i>gmd</i> | GDP-mannose 4.6-dehydratase | 1121 | 321 | 67 | 4.8 | 2.256 | 7.842E-12 | biofilm |
| <i>ppdD</i> | Prepilin peptidase-dependent protein D | 440 | 116 | 128 | 1.1 | 0.14 | 6.745E-01 | pili |
| <i>tnaA</i> | Tryptophanase | 1430 | 2970 | 545 | 5.5 | 2.45 | 8.555E-15 | other |
| <i>tnaB</i> | Low affinity tryptophan permease | 1247 | 1573 | 558 | 2.8 | 1.495 | 4.406E-11 | other |
| <i>wcaA</i> | colanic acid biosynthesis glycosyl transferase | 839 | 264 | 52 | 5.1 | 2.34 | 1.053E-11 | biofilm |
| <i>wcaB</i> | colanic acid biosynthesis acetyltransferase | 488 | 109 | 22 | 4.9 | 2.305 | 5.687E-10 | biofilm |
| <i>wcac</i> | colanic acid biosynthesis glycosyl transferase | 1217 | 405 | 63 | 6.4 | 2.684 | 2.750E-16 | biofilm |
| <i>wcad</i> | colanic acid polymerase | 1217 | 656 | 150 | 4.4 | 2.13 | 6.018E-13 | biofilm |
| <i>wcae</i> | colanic acid biosynthesis glycosyl transferase | 746 | 275 | 60 | 4.6 | 2.202 | 5.112E-12 | biofilm |
| <i>wcaF</i> | colanic acid biosynthesis acetyltransferase | 548 | 116 | 26 | 4.4 | 2.14 | 8.126E-09 | biofilm |
| <i>wcaI</i> | colanic acid biosynthesis glycosyl transferase | 1214 | 241 | 25 | 9.8 | 3.29 | 7.506E-18 | biofilm |
| <i>wcaJ</i> | colanic biosynthesis UDP-glucose lipid carrier | 1394 | 461 | 65 | 7.0 | 2.81 | 1.056E-17 | biofilm |
| <i>wcaK</i> | colanic acid biosynthesis protein wcaK | 1280 | 244 | 58 | 4.2 | 2.08 | 3.060E-10 | biofilm |
| <i>wcaL</i> | colanic acid biosynthesis glycosyltransferase | 1220 | 449 | 564 | -1.3 | -0.33 | 1.687E-01 | biofilm |
| <i>wcaM</i> | colanic acid biosynthesis protein wcaM | 1394 | 826 | 546 | 1.5 | 0.598 | 1.219E-02 | biofilm |
| <i>wza</i> | polysaccharide export protein wza | 1139 | 349 | 74 | 4.7 | 2.226 | 5.062E-13 | biofilm |
| <i>wzb</i> | Low molecular weight protein-tyrosine-phosphatase | 443 | 107 | 20 | 5.4 | 2.434 | 9.992E-08 | biofilm |
| <i>wzc</i> | Tyrosine-protein kinase wzc | 2162 | 650 | 139 | 4.7 | 2.23 | 9.343E-17 | biofilm |
| <i>yadC</i> | fimbrial-like protein yadC | 1262 | 1607 | 1611 | 1.0 | 0.004 | 9.912E-01 | pili |
| <i>yadK</i> | orf | 596 | 103 | 271 | 2.6 | 1.392 | 1.260E-01 | pili |
| <i>yadL</i> | orf | 608 | 92 | 160 | 1.8 | 0.81 | 3.809E-03 | pili |
| <i>ydeP</i> | Protein ydeP | 2279 | 568 | 862 | 1.5 | 0.601 | 1.532E-02 | pili |
| <i>ydeQ</i> | fimbrial-like protein ydeQ | 914 | 113 | 250 | 2.2 | 1.148 | 5.470E-04 | pili |

| name | product | gene size (bp) | RNA-seq values (minimal medium) | RNA-seq values (bile salts) | Fold change | Fold change | p value | type of virulence gene |
|------------------|--|-------------------|------------------------------------|--------------------------------|----------------|----------------|-----------|------------------------|
| | | | RPKM | RPKM | | (Log2) | | |
| <i>ydeR</i> | fimbrial-like protein ydeR | 503 | 339 | 421 | 1.2 | 0.315 | 2.302E-01 | pili |
| <i>ydes</i> | fimbrial-like protein ydes | 530 | 181 | 323 | 1.8 | 0.83 | 7.688E-03 | pili |
| <i>yehA</i> | orf | 1034 | 351 | 465 | 1.3 | 0.41 | 1.382E-01 | pili |
| <i>yehB</i> | outer membrane usher protein yehB | 2480 | 243 | 822 | 3.4 | 1.761 | 2.152E-11 | pili |
| <i>yehC</i> | fimbrial chaperone yehC | 674 | 27 | 223 | 8.1 | 3.02 | 7.172E-18 | pili |
| <i>yehD</i> | orf | 542 | 28 | 124 | 4.4 | 2.14 | 5.677E-11 | pili |
| <i>yehE</i> | orf | 281 | 438 | 452 | 1.0 | 0.04 | 8.737E-01 | pili |
| <i>LF82_p366</i> | orf | 857 | 683 | 608 | -1.1 | -0.169 | 4.454E-01 | pili |
| <i>LF82_p367</i> | fimbrial-like protein yfcP | 446 | 40 | 149 | 3.7 | 1.89 | 1.704E-08 | pili |
| <i>LF82_p368</i> | Yfc fimbriae subunit YfcQ | 479 | 39 | 99 | 2.5 | 1.33 | 1.296E-04 | pili |
| <i>LF82_p369</i> | orf | 503 | 28 | 47 | 1.7 | 0.74 | 8.409E-02 | pili |
| <i>LF82_p370</i> | periplasmic chaperone YfcS | 752 | 100 | 261 | 2.6 | 1.38 | 5.212E-06 | pili |
| <i>LF82_p371</i> | outer membrane usher YfcU | 2654 | 980 | 1178 | 1.2 | 0.27 | 3.152E-01 | pili |
| <i>LF82_p372</i> | Yfc fimbriae subunit YfcV | 566 | 429 | 143 | -3.0 | -1.58 | 2.635E-08 | pili |
| <i>LF82_p461</i> | orf | 983 | 140 | 680 | 4.8 | 2.273 | 8.694E-21 | PAI-IV/group 2 capsul |
| <i>LF82_p462</i> | Polysialic acid capsule synthesis protein KpsE | 1148 | 187 | 629 | 3.4 | 1.75 | 1.511E-15 | PAI-IV/group 2 capsul |
| <i>LF82_p463</i> | KpsD protein | 1676 | 260 | 802 | 3.1 | 1.625 | 2.746E-14 | PAI-IV/group 2 capsul |
| <i>LF82_p464</i> | 3-deoxy-manno-octulosonatecytidyltransferase | 740 | 54 | 296 | 5.4 | 2.443 | 1.120E-17 | PAI-IV/group 2 capsul |
| <i>LF82_p465</i> | KpsC protein | 2027 | 324 | 1002 | 3.1 | 1.627 | 4.229E-14 | PAI-IV/group 2 capsul |
| <i>LF82_p466</i> | KpsS protein | 1259 | 246 | 916 | 3.7 | 1.90 | 4.083E-18 | PAI-IV/group 2 capsul |
| <i>LF82_p467</i> | Transposase within prophage | 1124 | 212 | 547 | 2.6 | 1.37 | 2.025E-08 | PAI-IV/group 2 capsul |
| <i>LF82_p468</i> | orf | 983 | 222 | 544 | 2.4 | 1.29 | 5.044E-06 | PAI-IV/group 2 capsul |
| <i>LF82_p469</i> | orf | 1166 | 333 | 773 | 2.3 | 1.22 | 8.374E-07 | PAI-IV/group 2 capsul |

| name | product | gene size (bp) | RNA-seq values (minimal medium) | RNA-seq values (bile salts) | Fold change | Fold change (Log2) | p value | type of virulence gene |
|-----------|---|-------------------|------------------------------------|--------------------------------|----------------|--------------------------|-----------|------------------------|
| | | | RPKM | RPKM | | | | |
| LF82_p470 | orf | 1190 | 430 | 709 | 1.6 | 0.72 | 6.277E-04 | PAI-IV/group 2 capsul |
| LF82_p471 | orf | 1250 | 212 | 476 | 2.3 | 1.17 | 8.775E-04 | PAI-IV/group 2 capsul |
| LF82_p472 | glycerol-3-phosphate cytidyltransferase | 395 | 137 | 490 | 3.6 | 1.842 | 5.837E-14 | PAI-IV/group 2 capsul |
| LF82_p473 | KpsT protein | 674 | 119 | 280 | 2.4 | 1.233 | 1.382E-05 | PAI-IV/group 2 capsul |
| LF82_p474 | KpsM protein | 776 | 250 | 498 | 2.0 | 1.00 | 6.626E-05 | PAI-IV/group 2 capsul |
| LF82_p509 | Yqi fimbriae subunit YgiL | 563 | 129 | 206 | 1.6 | 0.69 | 1.835E-02 | pili |
| LF82_p510 | outer membrane usher protein YqiG | 2522 | 1748 | 1134 | -1.5 | -0.62 | 8.810E-03 | pili |
| LF82_p511 | fimbrial chaperone yqiH | 749 | 779 | 620 | -1.3 | -0.33 | 1.175E-01 | pili |
| LF82_p512 | Yqi fimbrial adhesin | 1049 | 3757 | 1483 | -2.5 | -1.34 | 1.502E-06 | pili |
| LF82_p527 | fimbrial adhesin (<i>auf</i>) | 1130 | 190 | 558 | 2.9 | 1.552 | 4.169E-09 | pili |
| LF82_p528 | fimbrial chaperone (<i>auf</i>) | 749 | 116 | 377 | 3.3 | 1.71 | 1.416E-09 | pili |
| LF82_p529 | minor fimbrial subunit precursor (<i>auf</i>) | 515 | 129 | 277 | 2.1 | 1.103 | 1.024E-04 | pili |
| LF82_p530 | minor fimbrial subunit precursor (<i>auf</i>) | 563 | 187 | 481 | 2.6 | 1.361 | 4.641E-07 | pili |
| LF82_p531 | Outer membrane usher protein AufC | 2594 | 422 | 1586 | 3.8 | 1.91 | 1.131E-11 | pili |
| LF82_p532 | Auf fimbrial chaperone 1 | 752 | 324 | 487 | 1.5 | 0.589 | 1.275E-02 | pili |
| LF82_p533 | | 704 | 882 | 621 | -1.4 | -0.51 | 2.276E-02 | pili |
| LF82_p548 | major fimbrial subunit | 524 | 180 | 294 | 1.6 | 0.71 | 1.020E-02 | pili |
| LF82_p549 | fimbriae | 1052 | 1495 | 1122 | -1.3 | -0.414 | 1.111E-01 | pili |
| LF82_p550 | Outer membrane usher protein lpfC precursor | 2531 | 1297 | 1444 | 1.1 | 0.154 | 5.427E-01 | pili |
| LF82_p551 | Fimbrial chaperone protein | 686 | 96 | 193 | 2.0 | 1.00 | 1.393E-03 | pili |
| LF82_p552 | fimbrial-like protein | 524 | 244 | 188 | -1.3 | -0.37 | 1.943E-01 | pili |

Table S3: Bacterial strains and plasmids used in this study

| Strain or plasmid | Relevant characteristics | Reference |
|--|--|------------------|
| LF82 | AIEC reference strain | ⁹ |
| LF82 Δ <i>eutB</i> | LF82 isogenic mutant deleted for the <i>eutB</i> gene | this study |
| LF82 Δ <i>eutE</i> | LF82 isogenic mutant deleted for the <i>eutE</i> gene | this study |
| LF82 Δ <i>eutB</i> / <i>peutB</i> | LF82 Δ <i>eutB</i> containing plasmid pBK-CMV carrying <i>eutB</i> | this study |
| LF82 Δ <i>citF</i> | LF82 isogenic mutant deleted for the <i>citF</i> gene | this study |
| MG1655 | <i>Escherichia coli</i> K-12 OR:H48:K- | Laboratory stock |
| BW25141 | Plasmid pKD4 carrying a kanamycin resistance cassette | ¹⁰ |
| pKOBEG | pBAD cloning vector harboring a λ phage red $\gamma\beta\alpha$ operon; chloramphenicol resistant | ¹¹ |
| pCP20 | Ampicillin and chloramphenicol resistant plasmid that shows temperature-sensitive replication and thermal induction of FLP synthesis | ¹⁰ |

7 **Table S4: Primers used in this study**

| Primer | Sequence (5'→3') | PCR product size | Use |
|-------------|---|---------------------|---------------------------------|
| d-eutB-F | GTGCGGTGACGGTGAAATCACTCGCATTTCTTCCTGAGG | - | construction of isogenic mutant |
| | GAACGACTTGTAGGCTGGAGCTGCTTC | | |
| d-eutB-R | TACAATTTCTTCAATCTGTTTTTGATCCATGATGTGTTATC | | |
| | TCCGCGTCACATATGAATATCCTCCTTAG | | |
| d-eutE-F | GAGGTGGTGTCTGGCGGTCAGGTCATTTTCCACAAATAA | - | construction of isogenic mutant |
| | GGCAGAACATCGTAGGCTGGAGCTGCTTC | | |
| d-eutE-R | TTGCAGACGTGGAGTGAGCCATTGTTTCATCGTGCGCCATC | | |
| | GGTTACTCCTCATATGAATATCCTCCTTAG | | |
| d-citF-F | TTATTCCTTCACCTGATGCACAACATCGATCACCGAGCCA | - | construction of isogenic mutant |
| | TCGCGGTAACGTAGGCTGGAGCTGCTTCG | | |
| d-citF-R | ATGACGCAGAAAATTGAACAATCTCAACGACAAGAACG | | |
| | GGTAGCGGCCTGCATATGAATATCCTCCTTAG | | |
| eutBEcoRI-F | GGAATTCATGAACTAAAGACCAC | 1.362 bp | eutB cloning |
| eutBBamHI-R | CGGGATCCCGGGATCCTCAGAAGAACA | | |
| eutB-F | AGTATCGCCGCGCAAATCTA | 151 bp | RT-PCR amplification |
| eutB-R | CCCTGGGTCGGAATGTTGAA | | |
| eutC-F | GCAGGTCGTTATTTCTGATG | 228 bp | RT-PCR amplification |
| eutC-R | GCTTTCTGACTGCCCCAACC | | |
| eutD-F | GTTTTTCGGATGCGTTAGA | 198 bp | RT-PCR amplification |
| eutD-R | CCAGCGATGAGCAAATTCTT | | |
| eutE-F | TGAAACTGACCGCAGAGCAG | 206 bp | RT-PCR amplification |
| eutE-R | TCAGTTCGGTCACGGCAAAC | | |
| eutG-F | GCTGGTTTCTGACATCTCTG | 213 bp | RT-PCR amplification |
| eutG-R | CCTGGCCGTTAAAGGCATC | | |
| eutH-F | CTGGTGGTCTGGTAGCGAT | 206 bp | RT-PCR amplification |
| eutH-R | CAAGACCGAGGGTGATCAAT | | |
| eutL-F | GCGTACCGGTTCTTATCTCT | 191 bp | RT-PCR amplification |
| eutL-R | TGGCTACCGGTTAAAAATGC | | |

| Primer | Sequence (5'→3') | PCR product size | Use |
|----------|-----------------------|---------------------|----------------------|
| citF-F | CGTGCCGGGTTAACAGCGAT | 248 bp | RT-PCR amplification |
| citF-R | GGTACTGAGCGCGCTGGAAA | | |
| prpB-F | TGGATGCGAAAACCGATCCT | 149 bp | RT-PCR amplification |
| prpB-R | TGGCGAGTTCGGTAATTGCT | | |
| folX-F | CCACTACCCCGCCGATAAAG | 174 bp | RT-PCR amplification |
| folX-R | TAGCATACGTCACCCAGTG | | |
| pfkA-F | TCGTGGCGATTACCGAACAT | 178 bp | RT-PCR amplification |
| pfkA -R | CAGCAGCAGATCGATAGCGT | | |
| cfa-F | TTTGCGGTGGTGGATCGTAA | 157 bp | RT-PCR amplification |
| cfa -R | TCGCTGGACTGAGCAATCTG | | |
| LF_715-F | GGGAGAGCCAAAAGAAGCCT | 182 bp | RT-PCR amplification |
| LF_715-R | CAGTCCTTTGAGGCCGTAGG | | |
| tufA-F | GACATGGTGATGACGAAGA | 199 bp | RT-PCR amplification |
| tufa-R | GCTCTGGTTCCGGAATGTA | | |
| 16S-F | ATGACCAGCCACACTGGAAC | 150 bp | RT-PCR amplification |
| 16S-R | CTTCCTCCCCGCTGAAAGTA | | |
| Shp-F | CGATCCTCTTCAACCCAGATG | - | RT-PCR amplification |
| Shp-R | AGGGCTCCAAGACTTCACACA | - | RT-PCR amplification |
| IBABP-F | CAGGAGACGTGATTGAAAGGG | - | RT-PCR amplification |
| IBABP-R | GCCCCCAGAGTAAGACTGGG | - | RT-PCR amplification |

8

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