Mouse Intestine Selects Nonmotile flhDC Mutants of Escherichia coli MG1655 with Increased Colonizing Ability and Better Utilization of Carbon Sources

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β-Gluconate which is primarily catabolized via the Entner-Doudoroff (ED) pathway, has been implicated as being important for colonization of the streptomycin-treated mouse large intestine by Escherichia coli MG1655, a human commensal strain. In the present study, we report that an MG1655 Δedd mutant defective in the ED pathway grows poorly not only on gluconate as a sole carbon source but on a number of other sugars previously implicated as being important for colonization, including L-fucose, D-glucuronate, D-glucuronate, N-acetyl-D-glucosamine, D-mannose, and D-ribose. Furthermore, we show that the mouse intestine selects mutants of MG1655 Δedd and wild-type MG1655 that have improved mouse intestinal-colonizing ability and grow 15 to 30% faster on the aforementioned sugars. The mutants of MG1655 Δedd and wild-type MG1655 selected by the intestine are shown to be nonmotile and to have deletions in the flhDC operon, which encodes the master regulator of flagellar biosynthesis. Finally, we show that ΔflhDC mutants of wild-type MG1655 and MG1655 Δedd constructed in the laboratory act identically to those selected by the intestine; i.e., they grow better than their respective parents on sugars as sole carbon sources and are better colonizers of the mouse intestine.

Bacterial colonization of the intestine is defined as the indefinite persistence of a bacterial population in stable numbers in an animal’s intestine without repeated introduction of the bacterium into that animal. Persistence in the intestine is reflected by persistence in feces. Colonization resistance refers to the ability of a complete intestinal microflora to resist colonization by an invading bacterium (45). As an example, when healthy human volunteers are fed Escherichia coli strains isolated from their own feces, those strains do not colonize (1). Due to colonization resistance, studies aimed at determining the nutritional basis of E. coli intestinal colonization are difficult, if not impossible, with conventional animals.

The nutritional basis of E. coli intestinal colonization can be studied in the streptomycin-treated mouse. Streptomycin treatment alters the microecology of the cecum, decreasing the populations of facultative anaerobes (enterococci, streptococci, and lactobacilli) and strict anaerobes (lactobacilli and bifidobacteria). Accompanying these changes in microflora is a general decrease in the concentration of volatile fatty acids, which may play a role in the natural resistance of the conventional mouse intestine to invading E. coli strains (18, 19). Nevertheless, populations of the genera Bacteroides and Eubacterium in cecal contents of streptomycin-treated mice remain largely unchanged (19). Moreover, the overall number of strict anaerobes in the cecal contents of streptomycin-treated and conventional mice are essentially identical (1 × 10^9 to 2 × 10^9 CFU/g of contents) (19). Therefore, while the streptomycin-treated mouse model is not perfect, invading microorganisms must compete for nutrients with a large number of strict anaerobes in the intestine, just as they do in conventional animals.

By using the streptomycin-treated mouse model, it has been shown that when 10^7 CFU of either E. coli, Salmonella enterica serovar Typhimurium, or Klebsiella pneumoniae strains are fed to streptomycin-treated mice, they grow from low numbers at 5 h postfeeding (10^5 CFU/g of feces) to high numbers (10^8 to 10^9 CFU/g of feces) within 1 to 3 days postfeeding (11, 29, 33, 34). Following this initiation stage, a maintenance stage is reached in which stable populations of 10^8 to 10^9 CFU/g of feces persist indefinitely (11, 29, 33, 34). Studies of the human commensal E. coli F-18 and K-12 strains strongly implicated β-glucuronate, which is catabolized via the Entner-Doudoroff (ED) pathway, as being important for colonization of the streptomycin-treated mouse large intestine during both initiation and maintenance (8, 35, 43, 44). Furthermore, it has been shown that the likely source of the glucuronate is mouse intestinal tissue and not food (44).

Since E. coli colonization of the mouse intestine appears to require the ability to grow in mucus (23, 30, 34, 43, 44, 46), the power of DNA microarrays was used to focus attention on identifying genes induced by growth in mouse cecal mucus in vitro relative to growth in minimal medium containing glucose as the carbon source. This approach allowed the identification of additional nutrients, including N-acetyl-D-glucosamine, N-acetylmuramic acid, and N-acetylmuramic acid, as being necessary for the maximum ability of E. coli MG1655 to colonize the intestine (8). E. coli MG1655 was chosen as the strain to be tested since it has been completely sequenced (6).
In the present study, while examining the role of the ED pathway in the ability of E. coli MG1655 to colonize the mouse intestine, we made the discovery that the mouse intestine selects nonmotile MG1655 flhDC mutants that are unable to make the master regulator of flagellar biosynthesis. We show that these mutants grow significantly faster than their parent on several sugars that have been shown previously to be involved in the colonization process, that they are better colonizers of the mouse intestine than their parent, and that the mutations in the flhDC operon are indeed responsible for these effects.

### MATERIALS AND METHODS

**Bacterial strains, media, and growth conditions.** The bacterial strains used in this study are listed in Table 1. Luria broth (LB) was made as described by Revel (39). Luria agar is LB containing 12 g of Bacto Agar (Difco) per liter. MacConkey agar (Difco) was prepared according to package instructions. M9 minimal medium (27) was supplemented with reagent grade key agar (Difco) was prepared according to package instructions. M9 minimal glucose medium and then incubated overnight. These cultures (10 ml) were grown at 37°C with shaking in 125-ml tissue culture bottles. Inocula were prepared as follows. Overnight cultures on LB were started from a single colony on a plate, and 10-μl volumes of the washed cultures were transferred to M9 minimal medium, and plated on MacConkey agar plates with appropriate antibiotics. Plates contained streptomycin sulfate (100 μg/ml) and kanamycin sulfate (40 μg/ml), or streptomycin sulfate (100 μg/ml) and kanamycin sulfate (40 μg/ml) or kanamycin sulfate (100 μg/ml). Antibiotics were purchased from Sigma-Aldrich (St. Louis, MO). All plates were incubated for 18 to 24 h at 37°C prior to counting. In some experiments, mice were precolonized for 9 days, starved overnight for food and water, and then fed 10^8 CFU of a second strain, after which food and streptomycin-water were returned. Each colonization experiment was performed at least twice with essentially identical results. Pooled data from at least two independent experiments are presented in the figures.

**Motility.** Motility agar is LB containing 3.5 g of Bacto Tryptone, and 10-μl volumes of the washed cultures were transferred to M9 minimal glucose medium and then incubated overnight. These cultures were washed twice as described above, and M9 minimal media (10 ml) containing various carbon sources were then inoculated with 10-μl volumes of the washed cultures, which were grown overnight. The next morning, each culture was diluted to an A_{600} of about 0.455 into fresh M9 medium (30 ml) containing the same carbon source and the cultures were incubated at 37°C with shaking in 125-ml tissue culture bottles. Growth was monitored spectrophotometrically (A_{600}) with a Pharmacia Biotech Ultraspec 2000 UV/Visible Spectrophotometer. Generation times were calculated during exponential phase from three independent experiments.

**In vitro growth in mouse cecal mucus.** Mouse cecal mucus was isolated as previously described (9). Briefly, mice (5 to 8 weeks old) were fed Charles River Valley Rat, Mouse, and Hamster Formula for 5 days after being received. The mucus was washed out with sterile distilled water. Cecal mucus was scraped into HEPES-Hanks buffer (pH 7.4), centrifuged, and sterilized by UV irradiation as described previously (9) and was adjusted to a concentration of 1 mg/ml with respect to protein with sterile HEPES-Hanks buffer (pH 7.4) as described previously (9). Five-milliliter aliquots were inoculated at an A_{600} of about 0.1 with either MG1655, MG1655*, MG1655 Δedd, or MG1655 Δedd*. Three 1-ml aliquots of each strain in cecal mucus were transferred to polystyrene cuvettes, which were then incubated standing at 37°C in a water bath, and the A_{600} of each culture was determined hourly. Uninoculated sterile cecal mucus was used as a blank. Generation times were determined when growth was in exponential phase, as determined from semilogarithmic plots. Cecal contents (1-ml aliquots) were inoculated to about 10^6 CFU/ml with each of the strains as described above for cecal mucus, the cultures were incubated standing at 37°C, and samples taken at 6, 2, 4, 6, and 24 h were diluted, plated, and counted as described previously (30, 46).

**Mouse colonization experiments.** The method used to compare the large-intestine-colonizing abilities of E. coli strains in mice has been described previously (43, 44, 46). Briefly, three male CD-1 mice (5 to 8 weeks old) were given drinking water containing streptomycin sulfate (5 g/liter) for 24 h to eliminate resident facultative bacteria (28). Following 18 h of starvation for food and water, the mice were fed 1 ml of 20% (wt/vol) sucrose containing LB-grown MG1655 strains as described in Results. After ingestion of the bacterial suspension, both the food (Charles River Valley Rat, Mouse, and Hamster Formula) and streptomycin-water were returned to the mice and 1 g of feces was collected after 5 h, after 24 h, and on odd-numbered days at the indicated times. Mice were housed individually in cages without bedding and were placed in clean cages daily. Fecal samples (no older than 24 h) were homogenized in 1% Bacto Tryptone, diluted in the same medium, and plated on MacConkey agar plates with appropriate antibiotics. Plates contained streptomycin sulfate (100 μg/ml) and nalidixic acid (50 μg/ml), streptomycin sulfate (100 μg/ml) and kanamycin sulfate (40 μg/ml), or streptomycin sulfate (100 μg/ml) and chloramphenicol (30 μg/ml). Antibiotics were purchased from Sigma-Aldrich (St. Louis, MO). All plates were incubated for 18 to 24 h at 37°C prior to counting. In some experiments, mice were precolonized for 9 days, starved overnight for food and streptomycin-water, and then fed 10^8 CFU of a second strain, after which food and streptomycin-water were returned. Each colonization experiment was performed at least twice with essentially identical results. Pooled data from at least two independent experiments are presented in the figures.

### TABLE 1. Bacterial strains used in this study

<table>
<thead>
<tr>
<th>E. coli strain*</th>
<th>Relevant characteristic(s)</th>
<th>Source or reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG1655 Str*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MG1655 Str* Nal* (MG1655)</td>
<td>Spontaneous streptomycin-resistant mutant of MG1655</td>
<td>29</td>
</tr>
<tr>
<td>MG1655 ΔeddK:cam ΔiddK (MG1655 ΔeddK ΔiddK)</td>
<td>Lacks glucuronases II and III and fails to grow using glucuronate as sole carbon and energy source</td>
<td>This study</td>
</tr>
<tr>
<td>MG1655 Str* Δedd:kan (MG1655 Δedd)</td>
<td>Lacks β- phosphogluconate dehydrogenase and grows poorly using glucuronate as sole carbon and energy source</td>
<td>8</td>
</tr>
<tr>
<td>MG1655 Str* Nal* (MG1655*)</td>
<td></td>
<td>Colony isolated from feces 15 days postfeeding of MG1655 Str* Nal*; this study</td>
</tr>
<tr>
<td>MG1655 Str* Δedd:kan (MG1655 Δedd)</td>
<td>2,384-bp deletion immediately downstream of ISF in regulatory region of fkhD through fkhD</td>
<td>Colony isolated from feces 20 days postfeeding of MG1655 Str* Δedd:kan; this study</td>
</tr>
<tr>
<td>MG1655 Str* Δedd::kan ΔiddD:cam (MG1655 Δedd ΔiddD)</td>
<td>546-bp deletion encompassing region immediately downstream of ISF in regulatory region of fkhD and into fkhD</td>
<td>This study</td>
</tr>
<tr>
<td>MG1655 Str* Δedd::kan ΔiddD:cam (MG1655 Δedd ΔiddD)</td>
<td>546-bp deletion encompassing region immediately downstream of ISF in regulatory region of fkhD and into fkhD</td>
<td>This study</td>
</tr>
</tbody>
</table>

* The designations in parentheses are those used in the text.
upstream of the TGA stop codon. The \textit{idnK} deletion primers (upstream primers, MG1655 DNA; lower case, chloramphenicol resistance DNA) were as follows: primer 1, 5' ATGGGCGGTAGTTGTGGTCTCTCTCTG-3'; primer 2, 5'-AGGGCCGGGCCTTACTTACGGAATCTTGTATGACTTACGACTTACGTTTCTG-3'. The MG1655 \textit{idnK} double-deletion mutant was then used to construct the MG1655 \textit{gntK idnK} double-deletion mutant. Four hundred base pairs, beginning 42 bp downstream of the ATG start codon and ending 41 bp upstream of the TAA stop codon, were deleted from the \textit{gntK} (glucuronate kinase I) gene of the MG1655 \textit{idnK} mutant with PCR product containing the chloramphenicol resistance cassette flanked by upstream and downstream \textit{gntK}-specific sequences as described by Datsenko and Wanner (10). The specific PCR primers used to define the size of the deletion in MG1655* were as follows: forward, 5'/H11032 -CGCATAACGTGATGTGCCTTG-3'; primer 2, 5'CTTGGTGTGATCTGCATCACGCATTATTGAAAATgtgtaggctggagctgcttcg-3'. The MG1655 \textit{gntK idnK} double-deletion mutant was confirmed phenotypically as being unable to grow in M9 minimal medium with gluconate as the sole carbon and energy source and by sequencing (see below).

An MG1655 \textit{idd} deletion mutant and an MG1655 \textit{edd} \textit{idd} double-deletion mutant (Table 1) were constructed by removing 546 bp originating immediately downstream of \textit{isi} in the \textit{fidD} promoter and extending into \textit{bdd} in MG1655 and in MG1655 \textit{idd} with a PCR product containing the chloramphenicol resistance cassette flanked upstream and downstream of \textit{bdi}-specific sequences as described by Datsenko and Wanner (10). The specific PCR primers used to construct and confirm the \textit{bdd} deletions (upstream primers, MG1655 DNA; lower case, chloramphenicol resistance cassette DNA) were as follows: primer 1, immediately downstream of \textit{isi}, 5' TTAAGATCTTGCCAAACATAGCTC-3'; primer 2 (within \textit{bdi}), 5'-AGGGCCGGGCTTTCTGCGGTGCTTTATGgtaggccattagtatataggggagctggagctgcttcg-3'; primer 2 (within \textit{bdi}), 5'-AGGGCCGGGCTTTCTGCGGTGCTTTATGgtaggccattagtatataggggagctggagctgcttcg-3'; primer 2 (within \textit{bdi}), 5'-AGGGCCGGGCTTTCTGCGGTGCTTTATGgtaggccattagtatataggggagctggagctgcttcg-3'; primer 2 (within \textit{bdi}), 5'-AGGGCCGGGCTTTCTGCGGTGCTTTATGgtaggccattagtatataggggagctggagctgcttcg-3'.

The MG1655 \textit{idd} mutant strain was constructed previously (8). The primers upstream and downstream of the \textit{edd} gene used to amplify both the 2,300-bp wild-type \textit{edd} gene and the 1,900-bp \textit{edd} gene containing the kanamycin resistance cassette (8) were as follows: forward, 5'-GCTTACACATGGTTGATC-3'; reverse, 5'-GCTTACACATGGTTGATC-3'. The mutations were confirmed phenotypically by failure to spread on motility agar, genetically by PCR with primers specific to upstream and downstream flankng sequences, and by sequencing (see below).

The MG1655 \textit{edd} mutant was grown in M9 minimal medium with gluconate as a sole carbon and energy source (4). Since the MG1655 \textit{edd} mutant still grows slowly on gluconate as a carbon source because it contains neither \textit{gntK} nor \textit{idnK} (Nakazawa et al., submitted), we used gluconate as a carbon source initially to confirm that the two generation times are not significantly different, whereas upper case letters indicate that the two generation times are significantly different. See text for \textit{P} values.

\textbf{RESULTS}

The ED pathway is important for \textit{E. coli} MG1655 growth in the mouse intestine. The \textit{edd} (ED dehydratase) gene, which is the promoter-proximal gene in the \textit{edd-edd} operon, encodes 6-phosphogluconolactone dehydratase, which converts 6-phospho-

\textbf{TABLE 2. Growth of MG1655, MG1655* and MG1655 \textit{edd}}, and MG1655 \textit{edd}* on various carbon sourcesa

<table>
<thead>
<tr>
<th>Carbon source</th>
<th>MG1655</th>
<th>MG1655*</th>
<th>MG1655 \textit{edd}</th>
<th>MG1655 \textit{edd}*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose</td>
<td>109 ± 4</td>
<td>4±4</td>
<td>101 ± 4±4</td>
<td>98.8 ± 1±4</td>
</tr>
<tr>
<td>Galactose</td>
<td>169 ± 6</td>
<td>5±6</td>
<td>152 ± 1±6</td>
<td>159 ± 5±6</td>
</tr>
<tr>
<td>Glucose</td>
<td>87 ± 5</td>
<td>6±5</td>
<td>89 ± 4±4</td>
<td>85 ± 4±4</td>
</tr>
<tr>
<td>N-AcGlcNH2b</td>
<td>92 ± 3</td>
<td>3±3</td>
<td>95 ± 3±3</td>
<td>80 ± 5±3</td>
</tr>
<tr>
<td>Gluconate</td>
<td>77 ± 5</td>
<td>5±5</td>
<td>135 ± 5±5</td>
<td>70 ± 4±4</td>
</tr>
<tr>
<td>Glucuronate</td>
<td>93 ± 3</td>
<td>3±3</td>
<td>85 ± 3±3</td>
<td>80 ± 3±3</td>
</tr>
<tr>
<td>Mannose</td>
<td>159 ± 6</td>
<td>6±6</td>
<td>136 ± 3±3</td>
<td>135 ± 3±3</td>
</tr>
<tr>
<td>Ribose</td>
<td>134 ± 4</td>
<td>4±4</td>
<td>125 ± 1±4</td>
<td>113 ± 1±4</td>
</tr>
<tr>
<td>Acetate</td>
<td>203 ± 14</td>
<td>14±14</td>
<td>172 ± 12±12</td>
<td>172 ± 12±12</td>
</tr>
<tr>
<td>Succinate</td>
<td>106 ± 4</td>
<td>4±4</td>
<td>87 ± 3±3</td>
<td>88 ± 3±3</td>
</tr>
<tr>
<td>Celiculose</td>
<td>105 ± 2</td>
<td>2±2</td>
<td>100 ± 1±1</td>
<td>90 ± 2±2</td>
</tr>
</tbody>
</table>

a Each for carbon source, the comparison of the generation time of any two strains is indicated by the same superscript letter, e.g., MG1655 and MG1655 \textit{edd} by the letter a, MG1655 \textit{edd} and MG1655 \textit{edd}* by the letter d, MG1655 \textit{edd}* and MG1655* by the letter f, etc. Lowercase letters indicate that the two generation times are not significantly different, whereas uppercase letters indicate that the two generation times are significantly different. See text for \textit{P} values.

b N-AcGlcNH2, N-acetylgluconamine.

Gluconate to 2-keto-3-deoxy-6-phosphogluconolactone in the ED pathway, the primary route for glucuronate catabolism. The \textit{eda} (ED aldolase) gene encodes 2-keto-3-deoxy-6-phosphoglucononolactone aldolase, which converts 2-keto-3-deoxy-6-phosphoglucononolactone to glyceraldehyde-3-phosphate and pyruvate. Gluconate can also be catabolized secondarily via the pentose phosphate pathway. The MG1655 \textit{edd} mutant therefore grows on glucuronate as a sole carbon and energy source with a generation time of about 80 min, whereas wild-type MG1655 grows with a generation time of about 80 min. Expression of \textit{eda} is not required for the maximum rate of glucuronate catabolism but is absolutely required for growth of \textit{E. coli} on glucuronate as a sole carbon and energy source (4).

The MG1655 \textit{edd} mutant, which was previously shown to be a poor colonizer of the mouse intestine, has been described previously (8). It has a kanamycin resistance cassette (10) in place of the \textit{edd} gene; however, the kanamycin resistance cassette insertion has a minimal, if any, effect on the downstream expression of \textit{eda} since the MG1655 \textit{edd} mutant grows well with glucuronate as a sole carbon and energy source (Table 2). Since the MG1655 \textit{edd} mutant still grows slowly on glucuronate, we constructed MG1655 \textit{gntK idnK} (Table 1), which is unable to use glucuronate as a carbon and energy source, to assess the true impact of glucuronate catabolism on MG1655 intestinal colonization (4). MG1655 \textit{gntK idnK} fails to grow on glucuronate as a carbon source because it contains neither glucuronate kinase I (\textit{gntK}) nor glucuronate kinase II (\textit{idnK}) and therefore cannot make 6-phosphogluconolactone from glucuronate. As shown previously (8), MG1655 \textit{edd} has a major colonization defect in the presence of wild-type MG1655 characterized by a failure to grow rapidly during the initial 24 h (the initiation stage), a significant drop between days 1 and 3 postfeeding (\textit{P} < 0.001, Student’s \textit{t} test), and a subsequent slow but continuous reduction thereafter (the maintenance stage) such that by 15 days postfeeding it colonized at a level about 3.5 orders of magnitude lower than that of MG1655 (Fig. 1A). In contrast, the MG1655 \textit{gntK idnK} double-deletion mutant had a defect in colonization, but by day 15 postfeeding it colonized at a
level only about 2.0 orders of magnitude lower than that of MG1655 (Fig. 1B). These results suggested the possibility that while gluconate is a major carbon source for MG1655 in the intestine, an intact ED pathway might also be used for catabolism of other carbon sources that are important for colonization. Indeed, MG1655 grows faster than the MG1655/edd strain on a variety of carbon sources that are not directly catabolized via the ED pathway, as described immediately below.

**Growth of MG1655 and MG1655 edd on various sole carbon and energy sources.** The generation times of MG1655 and MG1655 edd on a variety of carbon sources were determined as described in Materials and Methods. As shown in Table 2, although MG1655 edd grew at about the same rate as MG1655 on glucose ($P > 0.10$), fucose ($P > 0.10$), and succinate ($P > 0.10$), it grew 10 to 20% more slowly than MG1655 on N-acetylgalactosamine ($P < 0.01$), glucuronate ($P < 0.05$), glycerol ($P < 0.002$), mannose ($P < 0.01$), ribose ($P < 0.02$), and acetate ($P < 0.02$). Therefore, a functional ED pathway is essential for maximum growth rates of MG1655 on a variety of different carbon sources, including several that have been shown to be utilized by MG1655 during colonization (8). By contrast, with the exception of gluconate, MG1655 and the MG1655 gntK idnK double-deletion mutant grew at the same rate on glucose, fucose, succinate, N-acetylglucosamine, glucuronate, glycerol, ribose, and acetate (data not shown).

**Intestinal growth of low numbers of wild-type MG1655 bacteria in the presence of high numbers of the MG1655 edd mutant.** Mice were fed high numbers ($10^{10}$ CFU/mouse) of MG1655/edd bacteria in the mouse large intestine. At the indicated times after feeding, fecal samples were homogenized, diluted, and plated as described in Materials and Methods. Bars represent the standard error of the log$_{10}$ mean number of CFU per gram of feces. The data presented are from six experiments (18 mice) with MG1655 edd and four experiments (12 mice) with MG1655 gntK idnK.

**FIG. 1.** E. coli MG1655 gntK idnK and MG1655 edd colonization of the mouse large intestine. Sets of three mice were fed either $10^5$ CFU of E. coli MG1655 Strr Nalr (○) and $10^5$ CFU of E. coli MG1655 Strr edd::kan (□) (A) or $10^5$ CFU of E. coli MG1655 Strr Nalr (○) and $10^5$ CFU of E. coli MG1655 Strr gntK::cam idnK (△) (B). The indicated times, fecal samples were homogenized, diluted, and plated as described in Materials and Methods. Bars represent the standard error of the log$_{10}$ mean number of CFU per gram of feces. The data presented are from six experiments (18 mice) with MG1655 edd and four experiments (12 mice) with MG1655 gntK idnK.

**FIG. 2.** Growth of low numbers ($10^5$ CFU/mouse) of E. coli MG1655 bacteria in the presence of high numbers ($10^{10}$ CFU/mouse) of E. coli MG1655 edd bacteria in the mouse large intestine. (A) Sets of three mice were fed $10^5$ CFU of E. coli MG1655 Strr Nalr (○) and $10^{10}$ CFU of E. coli MG1655 Strr edd::kan (□). At the indicated times, fecal samples were homogenized, diluted, and plated as described in Materials and Methods. Bars representing the standard error of the log$_{10}$ mean number of CFU per gram of feces for each set of six mice are presented for each time point. (B) Sets of three mice were fed $10^5$ CFU of E. coli MG1655 Strr edd::kan (□) and, on day 10 postfeeding, $10^5$ CFU of E. coli MG1655 Strr Nalr (○). At the indicated times, fecal samples were homogenized, diluted, and plated as described in Materials and Methods. Bars representing the standard error of the log$_{10}$ mean number of CFU per gram of feces for six mice are presented for each time point.
when mice were fed high numbers (10^{10} CFU/mouse) of bacteria of the wild-type MG1655 strain (resistant to streptomycin) and low numbers (10^5 CFU/mouse) of bacteria of the same wild-type strain (resistant to streptomycin and nalidixic acid), the bacteria maintained the initial ratio of their input values, as expected of two strains that use all nutrients equally well (data not shown).

To further explore the ability of the wild-type MG1655 strain to outcompete the MG1655 Δedd mutant, mice were precolonized with the MG1655 Δedd mutant for 10 days and then fed low numbers of bacteria of the MG1655 wild-type strain (10^5 CFU/mouse). Surprisingly, the wild-type MG1655 strain failed to grow to the level of the MG1655 Δedd mutant in the intestine and, in fact, stabilized at only about 10^2 CFU/g of feces (Fig. 2B). These data suggested that the MG1655 Δedd mutant either adapted physiologically in the intestine such that it could compete well with the nonadapted MG1655 wild type or that the intestine selected a mutant of the MG1655 Δedd strain that was a better colonizer than the input strain. In order to determine which of these hypotheses was correct, one colony of MG1655 Δedd present in feces at 20 days postfeeding was designated MG1655 Δedd* and selected for further study.

**MG1655 Δedd* is a better mouse intestinal colonizer than MG1655 Δedd.** After confirmation by PCR that the edd deletion in MG1655 Δedd* was intact (see Materials and Methods), MG1655 Δedd* and wild-type MG1655 bacteria were fed together to mice in low numbers (10^5 CFU/mouse). Under these conditions, both the wild-type MG1655 strain and MG1655 Δedd* cocolonized at a level between 10^6 and 10^7 CFU/g of feces (Fig. 3). Therefore, MG1655 Δedd* appeared to be a genetically stable derivative of the original MG1655 Δedd strain that was able to colonize as well as wild-type MG1655.

**Growth of MG1655 Δedd* on various carbon sources.** Since MG1655 Δedd* was found to be a better colonizer of the mouse large intestine than MG1655 Δedd, it was of interest to determine the in vitro growth rates of the two strains on various carbon sources. As shown in Table 2, MG1655 Δedd* and MG1655 Δedd grew equally well on glucose as a sole carbon and energy source (P < 0.10). In contrast, MG1655 Δedd* grew 15 to 30% faster than MG1655 Δedd on acetate (P < 0.001), fucose (P < 0.01), galactose (P < 0.01), N-acetylgalcosamine (P < 0.02), gluconate (P < 0.001), gluconurate (P < 0.01), glycerol (P < 0.001), mannose (P < 0.01), ribose (P < 0.01), and succinate (P < 0.002). It should be noted that although MG1655 Δedd* grew faster than MG1655 Δedd with gluconate as the sole carbon source (P < 0.001), it still grew far more slowly on gluconate (P < 0.001) than wild-type MG1655 (Table 2). However, MG1655 Δeddd* grew about 10 to 20% faster than wild-type MG1655 on gluconate (P < 0.02), glycerol (P < 0.002), mannose (P < 0.02), ribose (P < 0.02), and succinate (P < 0.01) (Table 2). These data suggest that the improved colonizing ability of MG1655 Δedd* relative to MG1655 may be due to its ability to grow more rapidly than wild-type MG1655 on a number of carbon sources present in the intestine.

**Low numbers of wild-type MG1655 bacteria cannot grow to high numbers in the presence of high numbers of MG1655 Δedd* mutant bacteria.** The results described above indicated that wild-type MG1655 was able to use gluconate better, but grew more slowly on several other carbon sources, compared to MG1655 Δedd* (Table 2). Since bacteria of both strains were equally good colonizers when they were simultaneously fed to mice in low numbers (Fig. 3), it became of interest to determine whether low numbers of bacteria of wild-type strain MG1655 could grow in the intestine in the presence of high numbers of bacteria of the MG1655 Δedd* strain, i.e., whether the gluconate concentration was high enough during initiation to overcome the advantage of MG1655edd* on other sugars. When mice were fed 10^{10} CFU of the MG1655 Δedd* strain and 10^5 CFU of the wild-type MG1655 strain, the wild type was unable to colonize in the presence of high numbers of MG1655 Δedd* bacteria and was, in fact, rapidly eliminated (Fig. 4A). This result can be compared to that described above (Fig. 2A), where low numbers of bacteria of the wild-type MG1655 strain were able to grow to much higher numbers in the intestine in the presence of high numbers of MG1655 Δedd bacteria. These data suggest that the more efficient use of carbon sources by MG1655 Δedd* prevented wild-type MG1655 from growing despite its advantage in the utilization of gluconate. Thus, it was of interest to test the hypothesis that the concentration of gluconate in the mouse intestine is not high enough to confer a growth advantage on wild-type MG1655 over the MG1655 Δedd* strain. In support of this view, when 2% gluconate was added to the drinking water, low numbers of wild-type MG1655 bacteria (10^5 CFU/mouse) were able to grow to much higher numbers in the presence of high numbers of MG1655 Δedd* bacteria (10^{10} CFU/mouse) (Fig. 4B).

In further support of the view that increased gluconate availability could confer a growth advantage on the wild-type MG1655 strain able to use it, mice were precolonized with MG1655 Δedd* and at day 10 postfeeding were fed wild-type MG1655 (10^5 CFU/mouse) with (Fig. 5A) or without (Fig. 5B) 2% gluconate in the drinking water. Under these conditions, low numbers of wild-type MG1655 bacteria failed to grow to high numbers in the intestine in the presence of high numbers of precolonized MG1655 Δedd* bacteria unless gluconate was present in the drinking water (compare Fig. 5A and B). These data indicate that if gluconate were not
limiting at 10 days postfeeding, small numbers of MG1655 bacteria could still grow to much higher numbers in the intestine in the presence of high numbers of precolonized MG1655*H9004edd* bacteria.

**Isolation and characterization of MG1655*.** To this point, the data suggested that MG1655/H9004edd* utilizes not only gluconate poorly relative to MG1655 but a number of other carbon sources as well. In addition, at some point after mice were fed MG1655/H9004edd*, it appeared that the mouse intestine selected better-colonizing mutants, among them MG1655/H9004edd*, that were better able to grow on at least some of the sugars known to be present in mouse cecal mucus and utilized for growth in the intestine, i.e., fucose, glucuronate, N-acetylglucosamine, glucuronate, mannose, and ribose (8, 13). It was therefore of interest to determine whether the mouse intestine would also select a mutant of the original wild-type MG1655 strain that was a better colonizer and grew faster than the original MG1655 strain on a variety of carbon sources. To that end, an MG1655 colony present in faeces at 15 days postfeeding was selected for further testing and was designated MG1655*.

**E. coli MG1655* grew at 10 to 25% faster rates than MG1655 on a variety of carbon sources, including acetate (P < 0.01), fucose (P < 0.02), N-acetylglucosamine (P < 0.02), glucuronate (P < 0.01), glycerol (P < 0.01), mannose (P < 0.01), ribose (P < 0.001), and succinate (P < 0.01), but not glucose (P > 0.10) (Table 2). It should also be noted that although wild-type MG1655 grew significantly slower than MG1655/H9004edd* on several carbon sources, MG1655* and MG1655/H9004edd* grew at about the same rate on acetate (P > 0.10), fucose (P > 0.10), glucuronate (P = 0.05), glycerol (P > 0.05), mannose (P > 0.10), and succinate (P > 0.10). In addition, MG1655* not only grew at about twice the rate of MG1655/H9004edd* on gluconate (P < 0.001), it also grew about 10 to 15% faster than MG1655/H9004edd* on N-acetylglucosamine (P < 0.01) and ribose (P < 0.002) (Table 2).**

When MG1655* and MG1655/H9004edd* bacteria were both fed to mice in low numbers (10^5 CFU/mouse), MG1655* proved to be a better colonizer than MG1655/H9004edd* (Fig. 6A). Further-
more, unlike MG1655, low numbers of MG1655* bacteria (10^5 CFU/mouse) were able to grow to higher numbers in the intestines of mice simultaneously fed high numbers (10^10 CFU/mouse) were able to grow to higher numbers in the intestines of mice simultaneously fed high numbers (10^10 CFU/mouse). To determine whether the MG1655* and MG1655 Δedd* strains had a growth advantage in cecal mucus, MG1655, MG1655*, MG1655 Δedd, and MG1655 Δedd* were each inoculated separately into cecal mucus that had been diluted 50-fold into HEPES-Hanks buffer, pH 7.4 (1 mg/ml with respect to protein), at an A_600 of 0.1. A_600 readings were taken at hourly intervals for 8 h. All four strains grew to a final A_600 of about 0.8 (approximately 1 × 10^8 to 2 × 10^8 CFU/ml), but MG1655* (P < 0.001) and MG1655 Δedd* (P < 0.02) grew more rapidly than their respective parents and MG1655* grew more rapidly than MG1655 Δedd* (P < 0.001) (Table 2). Moreover, MG1655 grew more rapidly in mucus than MG1655 Δedd (P < 0.02) and MG1655 Δedd* grew more rapidly than MG1655 (P < 0.01) (Table 2). Thus, the ability of these strains to grow in cecal mucus in vitro correlated with their relative intestinal colonizing abilities.

While E. coli strains grow extremely well in cecal mucus in vitro, they fail to grow or grow poorly in cecal contents (feces) (23, 30, 43, 44, 46), suggesting that colonization of the mouse intestine is due to the utilization of nutrients present in mucus for growth. However, strains of E. coli MG1655 isolated from feces during the maintenance stage of colonization had never been tested for the ability to grow in cecal contents in vitro. To that end, MG1655, MG1655*, MG1655 Δedd, and MG1655 Δedd* were each inoculated into cecal contents isolated directly from the mouse cecum (10^7 CFU/ml). The cultures were incubated at 37°C, and viable counts were determined at 0, 2, 4, 6, and 24 h. Each strain doubled only twice in 6 h to about 4 × 10^9 CFU/ml and then remained at about the 6-h level at 24 h (data not shown). Therefore, neither MG1655* nor MG1655 Δedd* appears to be a better colonizer because it grows or survives better in cecal contents than its parent.

MG1655* and MG1655 Δedd* are nonmotile. MG1655, MG1655*, MG1655 Δedd, and MG1655 Δedd* were subjected to 36 of the 41 biochemical tests listed in Table 5.3 of the 1984 edition of Bergey's Manual of Systematic Bacteriology (7) as described previously (30). The four strains were found to be identical with respect to all biochemical characteristics. Furthermore, the four strains contained approximately equal amounts of type 1 fimbriae. However, in contrast to MG1655 and MG1655 Δedd, MG1655* and MG1655 Δedd* were nonmotile; i.e., they failed to tumble or swim after growth in LB and failed to spread on Luria motility agar (Fig. 7). The serotype of MG1655* and MG1655 Δedd strains was OR:H48; i.e., both were rough and both contained the H48 flagellar antigen typical of K-12 strains. However, while both MG1655* and MG1655 Δedd* also typed as OR, neither strain contained the H48 flagellar antigen. Furthermore, in contrast to their parents, MG1655* and MG1655 Δedd* had no flagella when viewed by electron microscopy (data not shown). Therefore, MG1655* and MG1655 Δedd* are alike not only with respect to their more efficient utilization of carbon sources but in the loss of flagella and, consequently, motility.
Although unlikely, it was possible that our MG1655 and MG1655 Δedd frozen stock cultures contained a high percentage of nonmotile mutants. To test this possibility, overnight LB cultures of MG1655 and MG1655 Δedd were plated on MacConkey agar and 600 individual colonies of each strain were tested for motility on motility agar. All colonies tested were motile, indicating that the strains being fed to the mice were predominantly motile and therefore that the nonmotile MG1655* and MG1655 Δedd* strains were selected in the mouse intestine following colonization.

Identification of MG1655* and MG1655 Δedd* genetic defects. *E. coli* flhD mutants have been reported to grow more rapidly than their parents in a tryptone-based medium (38). The flhDC operon, consisting of the flhD and flhC genes, encodes the master regulator of the 40-gene flagellar regulon (3), which has been reported to simultaneously regulate *E. coli* genes involved in galactose transport, the ED pathway, and the tricarboxylic acid cycle (36, 37). Additionally, in MG1655, an IS1 element previously shown to be present in the regulatory region of the flhDC operon has recently been reported to enhance motility (2). It therefore seemed reasonable that MG1655* and MG1655 Δedd* might have been generated by IS1-mediated events, i.e., IS1 deletion from the regulatory region of the flhDC operon or IS1-mediated deletion of adjacent flhD/flhC DNA. Indeed, PCR revealed that MG1655* had a 400- to 500-bp deletion in the flhD/flhC region and that MG1655 Δedd* had an about 2-kb deletion in the same region, thereby explaining why the strains are nonmotile (Fig. 8). Sequencing revealed that both MG1655* and MG1655 Δedd* retained IS1 in the regulatory region of the flhDC operon but that the deletion in MG1655* (500 bp) had occurred immediately downstream of IS1 and extended into flhD, whereas in MG1655 Δedd*, the deletion (2,384 bp) extended from immediately downstream of IS1 through flhD, flhC, and motA and into motB (Fig. 8). The motA and motB genes encode proteins involved in flagellar motor rotation (5). Since the flhDC operon promoter was deleted in MG1655*, the flhC gene was also presumably inactivated. The deleted genes in MG1655* and MG1655 Δedd* failed to be amplified by PCR (data not shown), showing that they were indeed lost rather than inserted elsewhere in their respective chromosomes.

**Construction and characterization of ΔflhD mutants.** To be sure that MG1655* and MG1655 Δedd* are better intestinal colonizers and utilize carbon sources better because of the defects in the flhDC operon, an MG1655 ΔflhD mutant and an MG1655 Δedd ΔflhD mutant were constructed (see Materials and Methods). The 546-bp deletion in both strains was designed to begin immediately downstream of the IS1 element, i.e., to include the flhDC operon promoter and extend into flhD, thereby inactivating the entire operon (Fig. 8). Both strains were tested for colonizing ability relative to their parents and for utilization of ribose and mannose. By day 1 postfeeding, the MG1655 ΔflhD mutant had grown to a level about sixfold higher than the wild type in the intestine and beyond day 5 postfeeding maintained an about 20-fold advantage throughout the rest of the experiment (data not shown). Maintenance of the 20-fold advantage rather than a constantly increasing advantage would be expected if the intestine selected nonmotile, better-colonizing MG1655 mutants. Indeed, at 11 days postfeeding, of 600 MG1655 colonies tested for motility (100 from each of 6 mice), only 2 were found to be motile (1 in each of two mice). Similarly, the MG1655 Δedd ΔflhD mutant grew to a level about 60-fold higher than MG1655 Δedd by day1 postfeeding and colonized at a level of greater than 100-fold higher than MG1655 Δedd thereafter (data not shown). We were unable to determine the exact level of MG1655 Δedd at later times since MG1655 Δedd ΔflhD is resistant to both kanamycin and chloramphenicol, MG1655 Δedd is only resistant to kanamycin, and of 100 colonies toothpicked from kanamycin plates to chloramphenicol plates at each time point, none were sensitive to chloramphenicol. In addition, both the MG1655 ΔflhD and MG1655 Δedd ΔflhD mutants utilized both mannose and ribose at faster rates than their parents (data not shown). Therefore, the flhDC operon deletion mutants constructed in the laboratory behaved identically to those selected by the intestine, suggesting that loss of the flhDC operon is indeed responsible for improved utilization of carbon sources and better mouse intestine-colonizing ability.

**DISCUSSION**

The findings reported here can be considered in light of Freter’s nutrient/niche theory, which postulates that the approximately 500 species indigenous to the mammalian gut (32) can coexist as long as each member of the microflora is able to utilize one or a few limiting nutrients better than all the others and that its rate of growth during the colonization process is at least equal to the washout rate from the intestine (14, 15, 16). According to the theory, the growth rate of a particular bacterium in the intestine is determined by the nature of the limiting nutrients it utilizes and the density to which it grows is determined by the available concentration of those nutrients. It is also possible for a species that does not compete well for limiting nutrients to colonize if it is able to adhere to the intestinal wall and thereby avoid washout (16). The available evidence suggests that *E. coli* MG1655 does not adhere to epithelial cells in the intestine but is limited to the mucus layer
and the luminal contents (29, 30), both of which turn over. While commensal strains of *E. coli* are present in both mucus and luminal contents, a large body of experimental evidence shows that growth is rapid in intestinal mucus both in vitro and in vivo but is either poor or completely inhibited in luminal contents (23, 30, 34, 43, 44, 46). It is therefore highly likely that the ability of a commensal *E. coli* strain to grow and survive in intestinal mucus plays a critical role in its ability to colonize the intestine. In support of this view, the better-colonizing strains selected by the mouse intestine, MG1655* and MG1655/H9004edd*, grew more rapidly than their parents in cecal mucus in vitro (Table 2).

It had been previously shown that MG1655 utilizes gluconate, N-acetylglucosamine, and sialic acid as carbon sources for growth in the mouse intestine during the initiation stage of colonization and gluconate, glucuronate, mannose, fucose, and ribose for growth during the maintenance stage (8). The data presented here support the notion that MG1655* and MG1655edd* to utilize several carbon sources better than their parents (Table 2) that makes them better colonizers of the mouse intestine. This finding has broad implications with respect to colonization resistance. For example, low numbers of MG1655 bacteria were eliminated by high numbers of MG1655edd* bacteria when both were fed simultaneously to mice (Fig. 4A) and failed to grow to high numbers in mice precolonized with MG1655edd* (Fig. 5A). Therefore, selection of a mutant derivative of MG1655edd* (MG1655edd/H9004edd*) which uses several carbon sources better allowed the mouse colonized with this strain to resist colonization by MG1655.

The role of diet in microfloral stability is not clear (32). However, in the present study, we have shown that diet may play a role in minimizing colonization resistance as long as a specific preferred nutrient is not completely absorbed in the small intestine. That is, although it has been shown that the source of gluconate for *E. coli* colonization is the mouse intestinal tissue and not mouse chow (44), increasing the gluconate concentration in the intestine was possible since as much as 70% of the gluconate fed to animals reaches the cecum (20). Under these conditions, with 20 g/liter gluconate in the drinking water, small numbers of MG1655 bacteria were able to grow to high numbers in the presence of high numbers of

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**FIG. 8.** Deletions in the *flhDC* region of MG1655*, MG1655edd*, MG1655ΔflhD, and MG1655Δedd ΔflhD. (Top) Bars indicate the positions of deletions in MG1655* (500 bp) and MG1655edd* (2,324 bp) and a region (628 bp) that is deleted and replaced by the chloramphenicol resistance (CAM) cassette (1,154 bp) in MG1655ΔflhD and MG1655Δedd ΔflhD. Small arrows indicate the positions of primers PCR2 (5'-CCTCTTCTTTTTGCTTGCAG-3') and cheAr (5'-CGCTGAAGCCAAAGGTCTCTG-3'). Bent arrow indicates the transcription start site. (Bottom) PCR products obtained with primers PCR2 and cheAr with wild-type MG1655 (lane 1), MG1655* (lane 2), MG1655ΔflhD (lane 3), MG1655edd (lane 4), MG1655edd* (lane 5), and MG1655eddΔflhD (lane 6). Molecular size standards (lane M) are noted to the left (sizes are in base pairs).
MG1655 Δedd* bacteria when both were fed simultaneously to mice (Fig. 4B) or when low numbers of MG1655 bacteria were fed to mice precolonized with MG1655 Δedd* (Fig. 5B). These data suggest that in the streptomycin-treated mouse, colonization resistance, at least as it applies to E. coli MG1655, has a primarily nutritional basis and is not due to antimicrobials in the intestine.

We do not know whether the MG1655 flhDC operon deletion mutants utilize carbon sources better than their parents as a result of release of repression of genes normally regulated by the FlhD/FlIC regulatory complex (e.g., the complex is known to repress gltA [citrate synthase], sdhCDAEB [succinate dehydrogenase], mdh [malate dehydrogenase], and mglBC [galactose transport] [36, 37]) or because increased energy is available for other cellular processes in the absence of flagellar synthesis and rotation, which is estimated to be about 2% of the total that is normally consumed (24). In either case, it appears that at least one entero pathogen also benefits from loss of FlhD, as it was recently reported that an flhD mutant of S. enterica serovar Typhimurium was more virulent than its parent in C57BL/6J mice and appeared to grow more rapidly than its wild-type parent in the spleen and in mouse macrophages in tissue culture (40). Furthermore, nonmotile E. coli O157:H7 strains, found in up to 40% of human hemolytic-uremic syndrome cases in Germany, have recently been shown to contain a 12-bp deletion in flhC (31).

The IS1 element in the regulatory region of the flhDC operon presumably directed the downstream deletions identified in MG1655* and MG1655 Δedd*, which then allowed the isolation of stable, nonmotile, better-colonizing mutants selected by the intestine. However, it is possible that commensal E. coli strains that lack insertion elements in the regulatory region of the flhDC operon can also become nonmotile and utilize carbon sources better in the intestine by down regulating expression of flhD and flhC, perhaps via one or more of the known negative regulators of the operon, which include LrhA, OmpR, and RcsB (12, 21, 22, 41), but retain motility and utilize carbon sources normally after growth in the laboratory. In fact, it has been reported that after growth in cecal mucus in vitro, both E. coli F1-8, a human commensal strain, and an avirulent S. enterica serovar Typhimurium strain failed to tumble and swim but were motile upon subsequent growth in laboratory medium (25, 26). In this same vein, it has recently been shown that transcription of several Campylobacter jejuni flagellar genes was generally down regulated after 24 to 48 h in a rabbit ileal loop model (42). Despite these reports, it is important to emphasize that not all bacteria in the intestine benefit from becoming permanently nonmotile. In fact, stable nonmotile mutants of many enteric pathogens, including C. jejuni, have been reported to be impaired in both intestinal colonization and virulence (17).

In summary, in the present study, we present evidence that under the nutrient-limiting conditions in the mouse intestine, better-colonizing MG1655 mutants are selected with deletions in the regulatory region of the flhDC operon. The deletions render the mutants nonmotile and simultaneously make them able to grow faster than their parents on a number of sugars present in the mouse intestine and in cecal mucus in vitro. The selection of E. coli mutants better able to utilize sugars than their parents may play an important role in limiting the ability of invading strains, either commensal or pathogenic, to colonize the intestine. It will be of great interest to examine whether the specific strategy described here is peculiar to MG1655 or is shared by other commensal and pathogenic strains of E. coli.

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