Role of the DksA-Like Protein in the Pathogenesis and Diverse Metabolic Activity of Campylobacter jejuni

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DksA is well known for its regulatory role in the transcription of rRNA and genes involved in amino acid synthesis in many bacteria. DksA has also been reported to control expression of virulence genes in pathogenic bacteria. Here, we elucidated the roles of a DksA-like protein (CJ81176_0160, Cj0125c) in the pathogenesis of Campylobacter jejuni. As in other bacteria, transcription of stable RNA was repressed by the DksA-like protein under stress conditions in C. jejuni. Transcriptomic and proteomic analyses of C. jejuni 81-176 and an isogenic mutant lacking the DksA-like protein showed differential expression of many genes involved in amino acid metabolism, iron-related metabolism, and other metabolic reactions. Also, the C. jejuni DksA-like protein mutant exhibited a decreased ability to invade intestinal cells and induce release of interleukin-8 from intestinal cells. These results suggest that the DksA-like protein plays an important regulatory role in diverse metabolic events and the virulence of C. jejuni.

When exposed to nutrient depletion, many bacteria show global changes in gene expression called the stringent response (15, 38). The effector molecule of the stringent response is guanosine tetraphosphate (ppGpp). Upon amino acid starvation, the abundance of uncharged tRNA results in ribosome stalling, activating ribosome-associated RelA or SpoT and producing ppGpp (15, 38). ppGpp binds to the β and β’ subunits of the RNA polymerase (RNAP) core enzyme and affects transcription of genes primarily at the stage of transcription initiation during the formation of the open promoter complex (4, 15, 38, 47). In many bacteria, ppGpp-dependent regulation affects bacterial physiology, including the functionality of some sigma factors and the virulence of pathogenic bacteria (15, 18, 58). The best-known types of regulation by ppGpp include negative regulation of rRNA transcription and positive regulation of amino acid biosynthesis, in which ppGpp potentiates direct activation or repression in concert with an RNAP-associated protein designated DksA (6, 7, 20, 48).

DksA was originally identified in Escherichia coli as a multicopy suppressor of the temperature-sensitive phenotype of dnaKJ mutants in 1990 (30). Analysis of bacterial genomes revealed the ubiquitous distribution of dksA open reading frames, which encode highly conserved amino acid sequences (50). DksA is reported to have pleiotropic effects, such as frames, which encode highly conserved amino acid sequences.
sigma factor rpoS (46), which is essential for stress and stationary-phase responses in many gram-negative bacteria (26). Since C. jejuni is able to use ppGpp as its stringent signal, DksA is expected to play a regulatory role in concert with ppGpp and to affect the physiology and virulence of C. jejuni. To examine this possibility, we characterized a DksA-like protein in C. jejuni. It was found that the DksA-like protein in C. jejuni modulates gene expression and affects the virulence, as well as the physiology, of this bacterium.

MATERIALS AND METHODS

Bacterial strains, plasmids, cell lines, and growth conditions. C. jejuni 81-176 (11), a pathogenic strain, and derivatives of this strain were used in this study. E. coli DH5α was used as a cloning host. C. jejuni 81-176 and an isogenic mutant lacking the DksA-like protein (pMB1104) were cultured using Mueller-Hinton (MH) broth or agar at 37°C under microaerobic conditions generated with MART (Anoxomat). Mammalian-mitotically free morpholinepropanesulfonic acid (MOPS)-MG8 medium (50 mM MOPS [pH 7.4], 2 mM MgSO4, 0.25 mM CaCl2, 19 mM glutamic acid, 0.084 mM biotin) was used as a minimal medium for C. jejuni to induce the stringent response (18). A human intestinal epithelial cell line, INT-407, was used for the invasion assay and was grown in minimal essential medium supplemented with 10% fetal bovine serum (MEM-FBS) containing penicillin (100 U/ml) and streptomycin (50 μg/ml) in a humidified atmosphere containing 5% CO2 and 95% air.

DNA manipulations. All DNA manipulations, including cloning, transformation into E. coli, isolation of DNA from agarose gels, PCRs, and DNA sequencing, were performed by using standard techniques (55) and the manufacturer’s instructions. The oligonucleotide primers used in PCRs are described elsewhere (http://plaza.smu.ac.kr/~imb/main/pu-01.htm). DNA sequencing was performed using a BigDye terminator cycle sequencing kit (Applied Biosystems) and an ABI Prism 3700 DNA analyzer (Perkin-Elmer) at the National Institutional Center for Environmental Management (Seoul, Korean Republic) using an RNeasy mini kit (Qiagen). After DNase treatment of the total RNA solution with a Turbo DNA-free kit (Ambion), cDNA was synthesized using an Omniscript RT kit (Qiagen) and random hexamers. cDNA labeling system (Promega) according to the manufacturer’s instructions. After purification, aminoallylabeled cDNA was fluorescently labeled with a CyDye postlabeling reactive pack (Amersham Bioscience, Piscataway, NJ). After purification, the fluorescent labeling of the cDNA was quantified, and equal amounts of labeled cDNA of the wild type and the mutant were mixed and dried in a vacuum centrifuge. After resuspension with hybridization buffer provided by the slide manufacturer, the mixture was denatured by heating at 95°C for 3 min. The hybridization mixture was loaded onto a microarray slide (OciChip; Oicmum Biosolutions, Indianapolis, IN) and hybridized in a shaking incubator at 42°C for 24 h. The slides were washed using the manufacturer’s recommendations and dried by centrifugation. In total, six slides were hybridized using RNA extracted from six independent cultures. For three cultures, the wild-type strain was labeled with Cy3 and the mutant strain was labeled with Cy5. For the remaining three slides, the dye-sample combination was reversed to control for differences in dye labeling of the cDNA samples. Further control for dye bias was achieved by adjusting the volume of cDNA hybridized based on the actual concentration of Cy dye incorporated as measured by a NanoDrop ND-1000 (NanoDrop Technologies).

(iii) Image acquisition and analysis. The data analysis was performed essentially as described by Madison et al. (37). Using a ScanArray Express laser scanner (Applied Biosystems Inc., Foster City, CA), each dye channel of each slide was scanned at 10-μm resolution with three predetermined laser power settings (high, medium, and low) to prevent saturation of high signals while ensuring adequate sensitivity for genes with low signals. ImaGene software (BioDiscovery, El Segundo, CA) was used to measure the spot-specific mean signal intensity and the spot-specific background level of each spot. Using the Ciphergen Biomarker Pattern Analysis software (version 2.0.1; The R Foundation for Statistical Computing), the spot-specific background median was subtracted from the spot-specific signal mean to obtain a background-subtracted value for each spot. The Natural logarithm of each background-subtracted value was obtained, and median centering was performed as previously described (37). The median of the individual spot signals for each gene obtained at different power settings was determined and used for all further calculations. Data obtained from the two dye channels were subjected to locally weighted scatterplot smoother (LOWESS) normalization (68) to balance the fluorescence intensities of the two dyes (Cy3 and Cy5) used to label cDNA. This normalization process was used to rescale the fluorescence intensity of each transcript, preventing the dye bias problem (16, 35).

(iv) Statistical analysis. The normalized data generated for individual probes of each array by dye combination were subjected to an independent mixed linear model using the SAS statistical software package (67). The model included fixed effects for treatment (wild type versus mutant) and dye (Cy3 versus Cy5) in addition to the random effect for slides. A t test was performed using the null hypothesis that there was no difference in the signal intensities of the treatment groups. The resulting P values for each of the probes were sorted in ascending order and converted to a Q value by the method of Storey and Tibshirani (59). Q values are used to estimate a false discovery rate for a subset of gene targets. Complete results of these experiments are available at the NCBI Gene Expression Omnibus (http://www.ncbi.nlm.nih.gov/geo) under accession number GSE8686.

Quantitative real-time RT-PCR (qRT-PCR). Total RNA was isolated from C. jejuni cultures using an RNeasy mini kit (Qiagen). After DNase treatment of the total RNA solution with a Turbo DNA-free kit (Ambion), cDNA was synthe-
sized using an Omniscript RT kit (Qiagen) and random hexamers (Invitrogen). Quantification of cDNA was carried out using IQ SYBR green PCR Supermix (Bio-Rad), and real-time amplification of PCR products was analyzed using the iCycler optical module (Bio-Rad). The amplification program consisted of one cycle of 95°C for 5 min, followed by 40 cycles of 95°C for 30 s, 50°C for 30 s, and 72°C for 30 s. The mRNA expression levels for target genes were normalized to the 16S rRNA gene (rrsA) and calculated using the 2^(-ΔΔCt) method (36). The primers used for real-time PCR are described elsewhere (http://plaza.snu.ac.kr/~fmb/main/pu-01.htm).

**Invasion assay.** Approximately 1 × 10^5 cells of INT-407 were seeded in each well of a 24-well plate and grown to semiconfluence in antibiotic-free MEM-FBS (Bio-Rad), and then each strain of C. jejuni in exponential phase was added at a multiplicity of infection of 100. The plates were centrifuged at 200 × g for 5 min to maximize bacterium-host cell contact and were incubated for 5 min at 37°C in the presence of 5% CO2. After three washes with phosphate-buffered saline, the monolayers were incubated in MEM-FBS containing gentamicin (100 μg/ml) for 2 h to kill extracellular bacteria. After three additional washes with phosphate-buffered saline, infected epithelial cells were lysed by 1% Triton X-100 for 5 min. Intracellular bacteria were enumerated by plating serial dilutions on MH agar plates.

**Interleukin-8 secretion assay.** As in the invasion assay, approximately 1 × 10^5 INT-407 cells were infected with C. jejuni at a multiplicity of infection of 100. The plates were centrifuged at 200 × g for 5 min to maximize bacterium-host cell contact and incubated for 4 h at 37°C in the presence of 5% CO2. The culture medium was harvested and centrifuged at 15,000 × g for 10 min to pellet the residual bacteria. The supernatant was collected and stored at 80°C until use. The interleukin-8 (IL-8) levels were determined using a BD OptEIA human IL-8 enzyme-linked immunosorbent assay II kit (BD Biosciences).

**Ferrous iron uptake assay.** The wild type and the mutant were grown to mid-log phase under microaerobic conditions in MEM (Invitrogen) at 37°C with rotation at 130 rpm for 6 h. The uptake of ferrous iron into C. jejuni was measured using 55FeCl3 (Perkin-Elmer) as described by Naikare et al. (42). The uptake of iron into bacteria was measured using 55Fe using a previously determined standard curve.

**RESULTS AND DISCUSSION**

**Identification of a DksA homolog in C. jejuni.** Analysis of the genomic sequence revealed that Campylobacter possesses DksA-like proteins, which are designated CjJ81176_0160 and CjJ81176_0158, respectively. All the C. jejuni strains whose genome sequences were available by March 2008 also possess DksA-like proteins (data not shown). The DksA-like protein is composed of 120 amino acids with a calculated molecular mass of 13.5 kDa. A BLASTP search showed that CjJ81176_0160 contains conserved DksA (26% identity and 53% similarity).

**Analysis of the DksA homologs.** The DksA-like proteins of bacteria belonging to the epsilon group of the Proteobacteria were available by March 2008 also possess DksA-like proteins (1, 61). The DksA-like protein of C. jejuni contains conserved sequences of DksA proteins (Fig. 1). However, Helicobacter pylori does not have a DksA homolog (1, 61). The DksA-like protein of C. jejuni contains conserved sequences of DksA proteins (Fig. 1).

**FIG. 1.** Amino acid sequence alignment of DksA homologs. The DksA-like protein of C. jejuni (CJJ81176_0160, YP_999849.1) was aligned with DksA homologs of Campylobacter coli RM2228 (ZP_00367836.1), H. hepaticus ATCC 51449 (NP_860767.1), W. succinogenes DSM 1740 (NP_906418.1), E. coli K-12 (NP_414687.1), and P. aeruginosa PA01 (NP_253411.1). A black background indicates dominant amino acid residues in the aligned sequences. Two Asp residues that are known to be critical for fixing the position of the ppGpp bound to Mg2+ are indicated by asterisks. Four Cys residues that are required for a canonical C2/Zn finger motif are indicated by plus signs.

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55Fe using a previously determined standard curve.
whereas the total amount of RNA was only slightly reduced in the wild type (244.1 ± 58.2 fg/CFU) in rich medium (MH broth) or shifted to minimal medium (MOPS-MGS medium). The nutrient downshift from rich medium to minimal medium was reported previously to confirm the transcription of CJ81176_0159 and dusB, which are downstream of CJ81176_0160. G, PCR performed with genomic DNA of the wild type; R, PCR performed with reverse transcriptase and C. jejuni mRNA; N, PCR performed without reverse transcriptase but with C. jejuni mRNA (negative control).

The best-known regulatory mechanism of DksA is regulation of the transcription of stable RNA, such as rRNA in E. coli (47, 53). In concert with ppGpp, DksA regulates rRNA transcription negatively by reducing the open complex lifetime and enhancing the effect of ppGpp (47). The effect of DksA on rRNA transcription has also been demonstrated in other bacteria, such as P. aeruginosa and S. flexneri (47, 51).

C. jejuni 81-176 was not commercially available, but C. jejuni 81-176, NCTC 11168 and FMB1104 are approximately 102, 74, and 82% of those in wild-type C. jejuni, respectively (data were not shown). Therefore, the insertion in CJ81176_0160 did not have a polar effect on the downstream genes. In addition, the mutant did not show growth defects in rich medium (MH medium) compared with the wild type in 24 h (data not shown).

The identified genes were down-regulated and 30 genes were up-regulated in the mutant. These genes are described elsewhere (http://plaza.snu.ac.kr/~fmb/main/pu-01.htm).

Profiles of protein expression for the wild type and the mutant were compared by using 2DGE. As shown in Fig. 3, many protein spots that showed differences in expression between the wild type and the mutant were detected, and protein spots with more-than-two-fold differences were selected and identified by matrix-assisted laser desorption ionization–time of flight analyses after digestion with trypsin. Fourteen proteins were identified as negative regulators of stable RNA transcription under stringent conditions, which is consistent with the findings for other bacteria (47, 51).

**Mutation of the DksA-like protein affected the expression of multiple genes in C. jejuni.** The DksA-like protein was expected to be a transcriptional regulator in C. jejuni, as it is in other bacteria. Transcriptomic profiles of the wild type (C. jejuni 81-176) and the isogenic mutant lacking the DksA-like protein were compared by using a DNA microarray. Since a microarray for C. jejuni 81-176 was not commercially available, we used a commercial oligomer chip (OciChip; Ocimum Biosolutions, Indianapolis, IN) that was designed based on the genome sequence of C. jejuni NCTC 11168. Thus, the genetic differences between C. jejuni NCTC 11168 and C. jejuni 81-176 had to be taken into consideration when the results were interpreted, because the 38 genes unique to the C. jejuni 81-176 chromosome and the genes of two plasmids in C. jejuni 81-176, pVir and pTet, were not present in the microarray slide (5, 10, 24, 44). A total of 51 of 1,633 genes on the array were determined to be differentially regulated by more than 1.5-fold (P < 0.05) based on the results of six microarray slides. Twenty-one genes were down-regulated, and 30 genes were up-regulated in the mutant. These genes are described elsewhere (http://plaza.snu.ac.kr/~fmb/main/pu-01.htm).

Profiles of protein expression for the wild type and the mutant were compared by using 2DGE. As shown in Fig. 3, many protein spots that showed differences in expression between the wild type and the mutant were detected, and protein spots with more-than-two-fold differences were selected and identified by matrix-assisted laser desorption ionization–time of flight analyses after digestion with trypsin. Fourteen proteins were down-regulated in the mutant, whereas nine proteins were up-regulated in the mutant. The identified proteins are indicated in Fig. 3 and are described elsewhere (http://plaza.snu.ac.kr/~fmb/main/pu-01.htm). The proteins showing differential expression in the wild type and the mutant identified by 2DGE did not agree with the results obtained from the transcriptome analyses. Correlations between DNA microar-
ray and proteomic results are known to be highly variable, and inconsistency in findings between the two methods has been reported in many studies (16, 21). The discrepancy between the transcriptomic and proteomic data is ascribed to the intrinsic differences between these two methods and the biological differences between the transcription and translation processes, such as posttranscriptional regulation, posttranslational modification, and proteolysis (16, 21). Despite the discrepancy, genes or proteins involved in amino acid metabolism and iron-related metabolism were determined to be expressed differently in the wild type and the mutant by both methods. These genes and proteins are categorized and discussed below.

The DksA-like protein is involved in amino acid metabolism in *C. jejuni*. The expression of several genes involved in amino acid synthesis and transport was affected by mutation of the DksA-like protein in *C. jejuni*, which is consistent with findings for other bacteria (43, 52). The results of 2DGE demonstrated that there were reductions in the expression of Ggt (γ-glutamyltransferase [GGT]), PepA (periplasmic ABC transporter of amino acids), AnsA (cytoplasmic L-asparaginase), PepD (aminoacyl-histidine dipeptidase), and CJJ81176_0265 (Cj0240c, cysteine desulfurase). Also, the DNA microarray results revealed that the transcriptional levels of the *trpABDEF* (tryptophan synthesis) operon, *pepA* (leucyl aminotransferase), and CJ1258 (CJJ81176_1274, possible phosphotyrosine pro-

FIG. 3. 2DGE images of whole-cell lysates from the wild type (A and C) and the mutant lacking the DksA-like protein (B and D). Proteins were separated by 2DGE using two ranges, pH 4 to 7 (A and B) and pH 6 to 11 (C and D). Protein spots with increased expression (more than twofold greater) in one gel are indicated by large letters, while the corresponding spots in the other gel are indicated by small letters and numbers in parentheses. A full list of the identified proteins is given elsewhere.
tein phosphatase) were reduced in the mutant. The down-regulation of these genes was confirmed by real-time PCR (Fig. 4).

Some of these genes have previously been reported to be involved in bacterial virulence. The GGT (EC.2.3.2.2) catalyzes transpeptidation and hydrolysis of the γ-glutamyl group of glutathione and related compounds and hence is known to be involved in glutathione metabolism in eukaryotes and prokaryotes (74). GGT is not present in C. jejuni NCTC 11168 but is present in C. jejuni 81-176 (24). Barnes et al. recently reported that the ggt gene is present in approximately 19.4% of C. jejuni isolates (8). Inactivation of ggt in C. jejuni reduced colonization in mice (24) and chickens (8). C. jejuni GGT also influenced the invasiveness of this bacterium and is involved in apoptosis of colon epithelial cells (8). Mutation of the DksA-like protein in C. jejuni also reduced the expression of PebA (or Peb1A as annotated in C. jejuni NCTC 11168). PebA is reported to be involved in amino acid transport as a component of an ABC transporter of aspartate and glutamate (34). PebA was originally identified as cell-binding factor 1, and inactivation of this protein in C. jejuni reduces interactions with epithelial cells and intestinal colonization of mice (49). Although other genes have not been functionally characterized in terms of amino acid metabolism, the multiple changes caused by mutation of the DksA-like protein strongly suggest that the DksA-like protein influences amino acid utilization and metabolism in C. jejuni.

The DksA-like protein is involved in iron-related metabolism in C. jejuni. Like other bacteria, Campylobacter has an absolute requirement for iron as a nutrient. However, iron also participates in the formation of reactive oxygen species, and bacteria must maintain intracellular iron homeostasis to cope with oxidative stress (62). To achieve successful iron homeostasis, many bacteria have a Fur (ferric uptake regulator) system regulating ferric iron transport proteins (3). Fur with its corepressor Fe²⁺ binds to a consensus sequence in the promoters of Fur-regulated genes. Thus, the transcription of Fur-regulated genes is repressed when the Fe²⁺ concentration is high. C. jejuni possesses several mechanisms to obtain iron from the environment, although there is diversity in the iron uptake system among C. jejuni strains (24). C. jejuni 81-176 contains genes encoding FeoAB for ferrous iron uptake, ChuABCD for heme/hemoglobin uptake, CeuBCDE for enterochelin transport, a putative iron uptake transport system (Cfbp, CJJ81176_0211), and a TonB-dependent siderophore receptor (CJJ81176_0471) (24). Expression of all of these genes except feoAB is dependent on Fur (25, 45, 54). In C. jejuni, there is another Fur-like regulator, PerR (63). PerR is known to form a PerR-Fe²⁺ complex like Fur and to act as a repressor of genes involved in oxidative stress responses (63).

Transcriptomic and proteomic analyses showed that mutation of the DksA-like protein in C. jejuni caused changes in the expression levels of several genes involved in iron-related metabolism. Proteomic analysis showed that the expression of iron transporter proteins, including ChuA, CJJ81176_0211 (Cj0175c, ferric iron ABC transporter periplasmic iron-binding protein), and CJJ81176_0471 (Cj0444, putative TonB-dependent iron uptake protein) was higher in the mutant than in the wild type. ChuZ (heme oxygenase, CJJ81176_1600 or Cj0163c) also was up-regulated in the mutant and was reported to be a Fur regulon (54). Transcriptomic analysis also demonstrated that there was up-regulation of genes associated with iron uptake (Cj0175c and Cj0173c) and chuZ and down-regulation of Cj0012c (bhr) encoding a nonheme iron protein, which was reported to be activated upon iron addition (25, 45). Changes in the transcriptional levels of these iron-related genes were also confirmed by qRT-PCR (Fig. 4 and 5A). The expression

![FIG. 4. Confirmation of expression levels by qRT-PCR. The transcript levels of genes that exhibited differential expression in the wild type (wt) and the mutant lacking the DksA-like protein (mu) as determined by transcriptomic or proteomic analyses were confirmed by qRT-PCR. Negative values indicate down-regulation in the mutant, while positive values indicate up-regulation in the mutant.](http://jb.asm.org/)
levels of other proteins that may be important for iron-related metabolism were also investigated by qRT-PCR (Fig. 5A). The expression of fur was reduced approximately 50% in the mutant compared to the wild type. Interestingly, the expression of perR was increased in C. jejuni FMB1104, unlike the expression of fur (Fig. 5A). The expression levels of perR-regulated genes, such as aphC and trxB, were reduced, which is consistent with the finding that perR expression was increased by the mutation (Fig. 5A).

The expression levels of a ferrous iron uptake gene (feoB) and the gene encoding ferritin (cfh), an iron storage protein, were also down-regulated in the mutant. The down-regulation of feoB transcription in the mutant was verified by a ferrous iron uptake assay, in which less ferrous iron was taken up by the mutant with the DksA-like mutant protein than by the wild type (Fig. 5B). Based on all the findings, we concluded that mutation of the DksA-like protein causes down-regulation of feoAB, which results in a reduction in ferrous iron uptake and a concomitant decrease in the concentration of the Fur-Fe$^{2+}$ complex. Therefore, Fur regulons are up-regulated in the mutant.

There has been only one report concerning the relationship between DksA and iron-related metabolism, and this report indicated that the transcription of fur in S. flexneri was reduced twofold in the absence of dksA (56). The relationship between iron-related metabolism and DksA in other bacteria has not been reported. Also, there have been no reports about ppGpp-dependent iron metabolism, except for one report for Geobacter sulfurreducens, which showed that genome-wide expression profiling of a ppGpp-negative mutant (relGsu deletion mutant) of G. sulfurreducens identified genes that possess Fur-regulated motifs (32). The ppGpp-negative mutant of C. jejuni (the spoT mutant) did not show any changes in iron-related metabolism in C. jejuni (18). Thus, the DksA regulation of iron-related genes is likely mediated in a ppGpp-independent manner. However, it is not certain whether the regulation of iron-related metabolism by the DksA-like protein in C. jejuni results directly from the regulation by the DksA-like protein or indirectly from other changes in the mutant, such as changes in amino acid metabolism.

Other metabolic activities affected by the DksA-like protein.

Other genes exhibiting differential expression in the wild type and the mutant included genes involved in flagellar synthesis, N-linked protein glycosylation, energy metabolism, and small-molecule metabolism.

Proteomic analysis of mutations in the DksA-like protein also demonstrated that some flagellar genes were down-regulated in the mutant. These genes encode flagellar hook protein (FlgE), flagellar capping protein (FliD), flagellin family protein (CJ81176_0894, FlaD), and flagellin (CJ81176_1338 and CJ81176_1339, FlaAB); however, the results of the DNA microarray analysis did not show any noticeable changes in flagellar genes. Also, some of the genes, such as wlaGH (pglAC), which are involved in N-linked protein glycosylation (60), showed up-regulation in C. jejuni FMB1104. Of the 30 putative glycoproteins (73), 5 (Cj0175c, PEB3, Cj0420, FpsA, and Ppa) were up-regulated in C. jejuni FMB1104 according to the results of 2DGE and microarray analyses.

Some genes involved in energy metabolism showed differential expression in the wild type and C. jejuni FMB1104. In the mutant, putative cytochrome c genes (Cj0037c and Cj1163), napA (periplasmic nitrate reductase), and oorA (2-oxoglutarate ferredoxin oxidoreductase) were down-regulated, whereas the nuoD operon (NADH dehydrogenase) was up-regulated. Genes that are involved in small-molecule metabolism were also influenced by the mutation in the DksA-like protein. In the mutant, acs (acetyl-coenzyme A synthetase) was down-regulated, whereas panB (3-methyl-2-oxobutanoate hydroxymethyltransferase), ppa (inorganic pyrophosphatase), and purB (adenylsuccinate lyase) were up-regulated.

**Invasion and IL-8 secretion were impaired by mutation of the DksA-like protein.** C. jejuni 81-176 is known to be a highly invasive strain among campylobacters. Human intestinal INT-407 cells were infected with C. jejuni 81-176 or the isogenic mutant lacking the DksA-like protein, and the total numbers of bacteria that invaded the INT-407 cells were determined. For the wild type the invasion level was 0.22% ± 0.03% of the input bacteria, while for the mutant the mutation level was 0.0018% ± 0.0006% of the input bacteria, which represents a 120-fold reduction in invasiveness. The differences were statistically significant (P < 0.001). Previous studies of the DksA protein of S. flexneri showed that DksA was involved in the intercellular spread of this bacterium but not in invasion (41).

The invasion of epithelial cells by C. jejuni is associated with its virulence in an animal model (71). Many factors have been reported to affect the invasiveness of C. jejuni. Motility is one factor associated with the invasion of host cells by C. jejuni (31, 70). Other factors affecting the invasiveness of C. jejuni include FlaC, Cia proteins, FspA, and Cj0977, and all of these proteins except Cj0977 require a flagellar export apparatus for secretion (19, 31, 52, 58). This is associated with the finding that mutation in the DksA-like protein of C. jejuni resulted in down-regulation of some flagellar genes at the protein level. In addition, the spoT gene of C. jejuni was up-regulated during bacterial infection of the INT-407 cells, and the spoT mutant of C. jejuni was defective in invasion and intracellular survival (18), suggesting that the stringent response of C. jejuni is associated with the invasiveness of this bacterium. Based on all the findings, the defect in invasiveness caused by mutation of the DksA-like protein in C. jejuni is likely associated with the stringent response.

**Campylobacter enterocolitis** is typically associated with a local acute inflammatory response, inducing inflammatory cytokine responses. IL-8 is a proinflammatory cytokine and a mediator of localized inflammatory responses. It has been reported that the invasiveness of C. jejuni is associated with IL-8 secretion (22). To determine if a mutation in the DksA-like protein influences IL-8 secretion, INT-407 cells were infected with C. jejuni 81-176 and FMB1104, and IL-8 secretion into the culture medium was determined. The level of IL-8 secretion induced by the wild type was 83.54 ± 7.61 pg/ml after 4 h of infection, while the level of IL-8 secretion induced by the mutant was 54.88 ± 3.91 pg/ml, which is approximately 65% of the wild-type value. The difference in IL-8 secretion was statistically significant (P < 0.05). The reduced secretion of IL-8 was likely due to the significant decrease in the invasiveness of the mutant. However, the reduction was modest considering the remarkable invasion defect, probably because the transcription of cytolethal distending toxin genes, another factor
that affects IL-8 secretion (23), was not influenced by mutation of the DksA-like protein (data not shown).

Concluding remarks. The DksA-like protein of C. jejuni was involved in expression of genes for amino acid metabolism, iron-related metabolism, and other metabolic activities. In addition, mutation of the DksA-like protein in C. jejuni resulted in reductions in invasiveness and IL-8 secretion. The results of this study suggest that the DksA-like protein plays a regulatory role in C. jejuni. The mechanism of these changes was not explained; this mechanism may be dependent on or independent of the stringent response and warrants further investigation.

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