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Role of capsular modified heptose in the virulence of *Campylobacter jejuni*

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SUMMARY

The *Campylobacter jejuni* capsular polysaccharide is important for virulence and often contains a modified heptose. In strain ATCC 700819 (a.k.a. NCTC 11168), the modified heptose branches off from the capsular backbone and is directly exposed to the environment. We reported previously that the enzymes encoded by *wcaG*, *mlghB*, and *mlghC* are involved in heptose modification. Here, we show that inactivation of any of these genes leads to production of capsule lacking modified heptose and alters the transcription of other capsule modification genes differentially. Inactivation of *mlghB* or *mlghC*, but not of *wcaG*, decreased susceptibility to bile salts and abrogated invasion of intestinal cells. All mutants showed increased sensitivity to serum killing, especially *wcaG::cat*, and had defects in colonization and persistence in chicken intestine, but did not show significant differences in adhesion, phagocytosis, and intracellular survival in murine macrophages. Together, our findings suggest that the capsular heptose modification pathway contributes to bacterial resistance against gastrointestinal host defenses and supports bacterial persistence via its role in serum resistance and invasion of intestinal cells. Our data further suggest a dynamic regulation of expression of this pathway in the gastrointestinal tract.
INTRODUCTION

_Campylobacter jejuni_ infections are the leading cause of enteritis worldwide (Rautelin and Hanninen, 2000; Wassenaar and Blaser, 1999). Infected patients can also develop neurological complications such as Guillain-Barre and Miller-Fischer syndromes (Godschalk et al., 2004; Godschalk et al., 2007). Numerous factors contribute to pathogenicity of _C. jejuni_ and successful host colonization, including production of toxins and glycoproteins (Guerry et al., 2006; Kakuda and DiRita, 2006; Karlyshev et al., 2004; Szymanski et al., 2002; Vijayakumar et al., 2006) and resistance to bile salts (Lin et al., 2003; Lin et al., 2005). Flagella-mediated motility also contributes to the virulence of _C. jejuni_ (Biswas et al., 2007), as it facilitates colonization of the mucus layer covering the intestinal epithelium (Beery et al., 1988; Lee et al., 1986) and subsequent invasion of epithelial cells (Jin et al., 2001; Konkel et al., 2005; Pei and Blaser, 1993; Vijayakumar et al., 2006). Survival of _C. jejuni_ within macrophages for several days is also a key virulence factor (Day et al., 2000; Kiehlbauch et al., 1985), and epithelial and macrophage cell damage resulting from invasion may be critical for the inflammatory response elicited by _C. jejuni_ infection (Biswas et al., 2000; Fauchere et al., 1986; Manninen et al., 1982; Newell and Pearson, 1984; Newell et al., 1985; Szymanski et al., 1995). Further, the surface expression of lipooligosaccharide (LOS), which in many _C. jejuni_ strains mimics human gangliosides, has been associated with autoimmune reactions implicated in the Guillain-Barre and Miller-Fischer syndromes (Godschalk et al., 2007; Mishu and Blaser, 1993; Salloway et al., 1996; Yuki et al., 1994).

_C. jejuni_ also produces a surface capsular polysaccharide (CPS) (Karlyshev et al., 2000; Karlyshev et al., 2001) initially identified as a heat-stable antigen and thought to be
a lipopolysaccharide (Preston and Penner, 1989). Mutational studies have demonstrated
that CPS is a virulence factor for *C. jejuni*. For example, a non-capsular *kpsE* mutant of
strain ATCC 81116 shows reduced adherence and invasion of intestinal epithelial cells
(Bachtiar *et al.*, 2007), and a non-capsular *kpsM* mutant of strain ATCC 81-176 has
reduced invasion of intestinal epithelial cells, is attenuated in a ferret model (Bacon *et al*.,
2001), and has decreased ability to colonize the gut in chickens (Jones *et al*., 2004). Non-
capsular mutants of invasive clinical isolates 84-25 and 84-19 are also more readily killed
by serum complement than wild type (Keo *et al*., 2011).

The CPS from strain ATCC 700819 (a.k.a. NCTC 11168) used in this study
consists of a phospholipid anchor (Corcoran *et al*., 2006) and repeating units containing a
backbone of β-D-ribofuranose (β-D-Rib), 2-acetamido-2-deoxy-β-D-galactofuranose (β-
D-GalNAc), and α-D-glucopyranuronic acid (α-D-GlcA) amidated with 2-amino-2-
deoxyglycerol (GroN) or ethanolamine (EtN) (Fig. 1A). The repeating units also
comprise a side branch consisting of a modified heptose: 6-O-methyl-D-glycero-α-L-
gluco-heptopyranose (6-O-Me-D-α-L-glucoHepp) (McNally *et al*., 2007; St Michael *et
al*., 2002; Szymanski *et al*., 2003) or 3,6-O-Me2-α-L-glucoHepp (McNally *et al*., 2007).
Addition of O-methyl phosphoramidate (MeOPN) moieties onto heptose and GalNAc
residues has also been reported (McNally *et al*., 2007; Szymanski *et al*., 2003). The role
of MeOPN modification of CPS in virulence and host colonization is controversial. A
contribution to insecticidal activity was demonstrated in one study (Champion *et al*.,
2010), but another study showed neither insecticidal activity nor any effect on chicken
colonization (van Alphen *et al*., 2014). The MeOPN modification may increase invasion
to epithelial cells and resistance to serum killing (van Alphen *et al*., 2014) or modulate
host immune responses (Maue et al., 2013). The contribution to virulence of the uniquely modified heptoses remains unknown. Due to their branch location in the CPS of strain ATCC 700819, the modified heptose residues protrude into the extracellular environment, becoming the outermost exposed carbohydrates of the CPS.

Various heptose derivatives are found in the CPS of C. jejuni (Aspinall et al., 1992; Aspinall et al., 1995a; Chen et al., 2008; Kilcoyne et al., 2006), C. coli (Aspinall et al., 1993) and Burkholderia pseudomallei (Perry et al., 1995; Reckseidler et al., 2001), in the exopolysaccharide of C. lari (Aspinall et al., 1995b), and in the lipopolysaccharide of Yersinia pseudotuberculosis (Samuelsson et al., 1974). We previously demonstrated that the modified heptoses play a role in Y. pseudotuberculosis virulence (Ho et al., 2008; Kondakova et al., 2008). Variations in the heptose structure (ring configuration and modifications) among different isolates and species suggest specific adaptations of the heptose residue to its function within the polysaccharide. We therefore hypothesized that the modified heptoses and their unusual ring configurations are important to fine tune host-bacteria interactions.

Genomic sequence data of strain ATCC 700819 suggest that the C. jejuni CPS is related to group II and group III CPS of other Gram-negative bacteria (Karlyshev et al., 2000). CPS gene clusters of E. coli strains that produce type II and III CPS show a conserved organization of the genes into three regions (Boulnois et al., 1987; Boulnois and Roberts, 1990). Regions 1 and 3 include genes involved in CPS export, such as the gene for the CPS ABC-transporter component KpsM for transport across the inner membrane (Cuthbertson et al., 2010; Whitfield, 2006). The central region 2 comprises genes for the synthesis of serotype-specific sugars and their assembly into repeating units.
(Roberts et al., 1988a; Roberts et al., 1988b). These features apply to *C. jejuni* strain ATCC 700819 (Fig. 1B). In the CPS cluster of this strain and also in *B. pseudomallei*, region 2 contains genes devoted to the synthesis of GDP-\(\text{d-glycero-\(\text{\alpha-d-manno-heptose}\)}\) (Kneidinger et al., 2001; Parkhill et al., 2000; Reckseidler et al., 2001), suggesting that this compound is likely the precursor for the synthesis of the modified heptose present in their CPS, as demonstrated previously for the 6-deoxy-\(\text{d-manno-heptose}\) in *Y. pseudotuberculosis* (Butty et al., 2009).

We recently elucidated the biochemical synthesis pathways of the 6-deoxy-\(\text{d-altro-heptose}\) present in *C. jejuni* 81-176, which involved the sequential activity of the C4, C6 dehydratase DdahA (a.k.a. WebK), a C3 epimerase DdahB (a.k.a. Cjj1430) and a C4 reductase DdahC (a.k.a. Cjj1427) on GDP-\(\text{d-glycero-d-manno-heptose}\) (McCallum et al., 2011; McCallum et al., 2012). This pathway is under post-translational regulation by the activity of WcaG, a C4 reductase encoded by the CPS cluster itself that reduces the DdahA product, thereby diverting it off the \(\text{altro-heptose}\) synthesis pathway. We also showed additional regulation of the biosynthesis pathway via interactions between WcaG and DdahC. Using this knowledge, we demonstrated the C3, C5 epimerase activity of MlghB (encoded by *mlghB*, a.k.a. *cj1430c*) and the C4 reductase activity of MlghC (encoded by *mlghC*, a.k.a. *cj1428c*) of *C. jejuni* ATCC 700819 (Fig 1B) (McCallum et al., 2013). This was achieved by using a hybrid pathway that combined MlghB and MlghC from *C. jejuni* ATCC 700819 with the DdahA dehydratase from *C. jejuni* 81-176 (Fig 2) since the putative oxidase MlghA necessary to initiate the pathway in *C. jejuni* ATCC 700819 is unknown. We also showed a C4 reductase activity on the DdahA product for the WcaG enzyme encoded by *wcaG* (a.k.a. *cj1427c*) in strain ATCC 700819.
The proposed 6-O-methyl-D-glycero-α-L-gluco-heptose (called thereafter 6OMe-Hep) synthesis pathway is depicted in Fig. 2. Our biochemical work suggests that WcaG, MlghB, and MglhC are required for CPS heptose modification. This agrees with data showing that homologues of wcaG, mlghB, and mlghC are only found in CPS biosynthesis loci of strains whose CPS contains modified heptoses (Karlyshev et al., 2005; St Michael et al., 2002), and with the observation that inactivation of mlghC results in loss of the modified heptose (St Michael et al., 2002).

In this study, we investigated the role of wcaG, mlghB, and mlghC genes from strain ATCC 700819 in CPS synthesis and function. Using a panel of defined mutants, we determined the contribution of each gene to CPS composition and to phenotypes associated with pathogenesis including protection against bile salts, detergents and serum, and bacterial motility. We also tested the contribution of these genes to C. jejuni’s adhesion and invasion of intestinal epithelial cells, survival within macrophages, and colonization of the chicken intestine. Our results demonstrate that wcaG, mlghB, and mlghC are required for CPS heptose modification and indicate that the modified heptoses contribute to the pathogenicity of C. jejuni ATCC 700819.

RESULTS

Genetic characterization of the capsular heptose biosynthesis mutants

Insertional mutants in wcaG, mlghB, mlghC, and kpsM genes were constructed as described under Experimental Procedures. PCR and Southern blot analyses indicated that each mutant contained the disrupted targeted gene without compromising the surrounding
genes (data not shown). One of the \textit{wcaG::cat} mutants, named \textit{wcaG::catΔ}, also had a 6.1-kb deletion removing genes \textit{cj1421c} to \textit{cj1426c}. This mutant was included in our studies for the following reasons. First, the deletion removes \textit{cj1425c-cj1423c}, which are involved in the synthesis of the heptose precursor (GDP-\textit{glycero-manno}-heptose, Fig.1B) (Karlyshev et al., 2005; Kneidinger et al., 2001; Parkhill et al., 2000; Valvano et al., 2002), suggesting that \textit{wcaG::catΔ} should lack heptose in its CPS. Second, the deletion also eliminates the putative heptose methyltransferase \textit{cj1426c} (Fig.1B) (Sternberg et al., 2013), thereby ensuring lack of methylation. Third, \textit{cj1422c} and \textit{cj1421c}, which are also deleted, encode enzymes for the transfer of MeOPN to \textit{d-\alpha-L-glucoHepp} and \textit{\beta-d-GalfNAc}, respectively (Fig.1B) (Karlyshev et al., 2005; McNally et al., 2007). While MeOPN synthesis genes (\textit{cj1415c-cj1418c}) are intact, the attachment of MeOPN to the CPS should not occur in this mutant. Therefore, \textit{wcaG::catΔ} should produce a CPS backbone devoid of modifications (no heptose, no methylation and no MeOPN), thereby serving as a valuable control in our study. The \textit{kpsM} mutant provided a non-capsular, negative control since KpsM is a critical component of the ABC transporter for CPS export across the cytoplasmic membrane (Silver et al., 2001). Complemented strains were constructed by re-introducing the original genes in the chromosome between the 16S and 23S rRNA genes and using the constitutive OmpE promoter as described previously (Karlyshev and Wren, 2005).

For all phenotypic analyses, the strains were revived under appropriate antibiotic selection, but the final sub-culture prior to phenotypic analysis was performed in the absence of antibiotic selection so that all strains were grown under the exact same conditions. Bacteria were harvested and suspensions normalized to the same OD$_{600nm}$ to
alleviate potential variation arising from different growth rates. CFU measurements performed on bacterial suspensions used as inoculum for phenotypic assays indicated similar viability of all strains used as measured after 24 h of growth (data not shown).

*Mutants in the heptose modification pathway produce high molecular weight CPS*

The effect of inactivation of heptose modification genes on CPS synthesis was investigated by SDS-PAGE and silver staining of CPS obtained by hot water/phenol extraction (Westphal and Jann, 1965) and ultracentrifugation. The wild type had high and low molecular weight bands (Fig. 3A) corresponding to CPS and co-extracted LOS, respectively (Karlyshev and Wren, 2001). As expected, the *kpsM* mutant lacked high molecular weight bands while production of LOS was not affected (Fig. 3A). In contrast, all heptose modification mutants formed CPS but *mlghB::cat* apparently produced less CPS than the others (Fig. 3A). Western blot analysis (with anti HS:2 Penner serotyping antibodies) of CPS samples obtained by SDS solubilization of total cells and proteinase K digestion of proteins (Hitchcock and Brown, 1983) also showed that all mutants tested produced CPS (Fig. 3B) and the amount produced by *mlghB::cat* was on par with all other strains. The differences in relative amounts seen for *mlghB::cat* by silver staining and Western blotting could relate to slight variations in CPS composition that could affect silver staining (Szymanski et al., 2003) and CPS solubility and recovery in the hot water/phenol extraction method, but compositional data below exclude this possibility.

The differences probably rather relate to additional modifications of surface properties in this mutant, which may in turn affect extractability of the CPS by the hot water/phenol
method. Together, these results indicate that the absence of heptose or modified heptose does not prevent production of high molecular weight CPS. Slight upwards shifts of CPS bands of the mutants were observed depending on loading amounts and gel composition. Because wild type C. jejuni CPS is anchored to the outer membrane via a phospholipid (Corcoran et al., 2006), the band shifts could reflect CPS anchoring to a different lipid carrier, such as lipid A, as seen in E. coli K_{LPS} (Jann et al., 1992). To test this possibility, CPS samples were treated with phospholipase prior to SDS-PAGE analysis (Karlyshev et al., 2000). This led to disappearance of CPS bands in all strains tested (data not shown), demonstrating that CPS was phospholipid-bound. Also, in contrast to LOS bands, wild type and mutant CPS bands did not react with anti-lipid A antibody (data not shown), confirming that CPS was not covalently linked to lipid A. We conclude that the band shifts represent subtle changes in CPS composition affecting not only the size of CPS units but also their hydrophobicity and ability to bind SDS.

The CPS of heptose modification pathway mutants does not contain methylated heptose

The composition of hot water/phenol extracted CPS was determined using a sugar analyzer after complete acid hydrolysis, and also using one- and two-dimensional NMR spectroscopy (Tables 1 and 2, Figs. S1 and S2). The data obtained, combined with data reported for C. jejuni NCTC 11168 CPS (McNally et al., 2007; St Michael et al., 2002; Szymanski et al., 2003), enabled inferring the CPS structures of wild type and mutant strains (Fig. 4). Sugar analysis revealed the three CPS backbone constituents, Rib,
GalNAc (detected as GalN) and GlcA in all strains. The higher than expected Rib/GalN ratios (expected equimolar) are likely due to RNA contamination of the samples. GlcA was not quantitated because it was amidated with EtN or GroN and was poorly released by hydrolysis but NMR spectroscopy analyses confirmed its presence by the characteristic signals for H-1 and C-1 in all strains (Table 2). Without authentic D-glycero-L-gluco-heptose as standard, the presence or absence of heptose was inferred from signals for H-1 at δ 5.58 and C-1 at δ 98.3, which were observed in ¹H and ¹³C NMR spectra of wild type CPS only (Table 2). Characteristic signals were also detected for 3-O-Me and 6-O-Me groups on heptose in wild type only (Fig S2), confirming that heptose was present and 3,6-di-O-methylated in wild type CPS while it was absent in the CPS from the mutants.

NMR spectroscopy did not reveal MeOPN modification in wild type CPS, but MeOPN was readily apparent on GalNAc in wcaG::cat and mlghB::cat (Table 2) and traces of MeOPN were found in mlghC::cat. Consistent with the deletion of MeOPN transfer genes in wcaG::catΔ, no MeOPN was detected in its CPS despite the presence of the GalNAc acceptor. Also, while the GlcA residue carried only the EtN substituent in wild type CPS, both EtN and GroN were found in the mutants (Table 1). These differences between wild type and heptose modification mutants could represent a compensatory mechanism whereby amidation of GlcA by GroN and/or MeOPN addition on GalNAc is enhanced when the production of D-glycero-L-gluco-heptose is impaired.

No O-methyl groups were present in the complemented wcaG and mlghC mutants by NMR spectroscopy, suggesting that incorporation of wild type-like modified heptose was
not restored in these strains. The complemented \textit{mlghB} strain was not tested by NMR spectroscopy for lack of sufficient CPS material.

Inactivating heptose modification genes causes drastic changes in transcription within the CPS gene cluster

The compensatory mechanisms inferred from NMR spectroscopy analyses in our mutants and lack of complementation of modified heptose incorporation in the CPS could result from polarity effects or from transcriptional regulation within the CPS cluster. We used quantitative real-time PCR (qRT-PCR) to demonstrate lack of polarity on expression of genes located downstream of the chloramphenicol (\textit{cat}) and kanamycin (\textit{kan}) resistance cassettes used for gene inactivation. Expression of the gene immediately downstream of \textit{kpsM} in \textit{kpsM::kan} or downstream of \textit{wcaG} and \textit{mlghC} in \textit{wcaG::cat} and \textit{mlghC::cat}, respectively was not affected (Fig. 5), indicating that insertion of the \textit{cat} and \textit{kan} cassettes was non-polar. However, in \textit{mlghB::cat}, transcription of \textit{cj1429c} directly downstream of \textit{mlghB} was upregulated ~187-fold. Since the \textit{cat} cassette causes no polarity, we concluded that the upregulation of \textit{cj1429c} transcription is related to inactivation of \textit{mlghB} via a regulatory effect and not a mutagenesis artifact. Such transcriptional regulation implies the existence of promoters within the CPS cluster.

\textit{C. jejuni} promoters are different from \textit{E. coli} promoters (Wosten \textit{et al.}, 1998) and difficult to predict. To test for their existence, we measured the transcription levels of genes involved in CPS synthesis and modification by qRT-PCR. By doing so, we could also assess whether inactivation of one step during D-manno- to L-gluco- heptose
conversion had any feedback regulatory effects on other steps or on other CPS modifications (e.g. MeOPN addition, amidation of GlcA, heptose methylation).

Measurements were relative to housekeeping gene *cj1537c* (acetyl-CoA synthase) and accounted for primer efficiencies.

Expression levels varied considerably among the genes tested, with some too low to be quantitated accurately (e.g. *kpsM*), others on par with the housekeeping control, and others ~15-fold greater than control (Fig. 5A). The various transcription patterns observed indicate that numerous promoters exist within the CPS cluster. To further assess potential feedback regulatory effects of inactivation of one gene on surrounding genes, we analyzed the data as expression ratios between each mutant and the wild type (Pfaffl, 2001) (Fig. 5B). This comparison indicated that inhibition of CPS transport by *kpsM* inactivation only had minor effects on heptose modification genes and no effects on the remaining CPS cluster genes tested, and that inactivation of biosynthesis/modification genes had little or no impact on transport functions. However, inactivation of *mlghB* or *mlghC* (responsible for heptose ring configuration switch from D-manno to L-gluco) led to upregulation of other genes involved in heptose synthesis and modification, including the O-methyl-transferase gene *cj1426c* (2.8- to 9.9-fold). Inactivation of *mlghB* or *mlghC* also strongly upregulated the transcription of *cj1429c* (186.7- and 18.1-fold, respectively), a gene of unknown function. Inactivation of *wcaG* produced different effects, with modest upregulation of heptose modification genes (2.9- to 4.5-fold), no effect on heptose synthesis and 60% reduction of transcription of *cj1429c*. These differences could be due to the previously established regulatory role of WcaG on heptose modification by substrate scavenging and interaction with MLghC (McCallum *et al*.
Together, the transcriptional data suggest that inactivation of wcaG, mlghB, or mlghC or the absence of their products exert regulatory effects on other CPS modification genes, which may influence the functional properties of CPS.

We next assessed whether these regulatory effects were abrogated in our complemented strains, focusing on the mlghC and mlghB mutants that showed the strongest regulatory effects above. Reintroduction of mlghC into the mlghC mutant led to 60±1.5 fold up-regulation of mlghC compared to wild type, mirrored by 67±3.8 fold up-regulation of mlghB upon its reintroduction into the mlghB mutant. While such high transcription levels had no significant effects on transcription of other CPS genes such as wcaG and mlghB in the complemented mlghC strain (with 1.9±0.3 and 0.4±0.1 fold compared to wild type, respectively), wcaG and mlghC were upregulated 5.4±0.3 and 8.5±0.4 fold compared with wild type, respectively, in the complemented mlghB strain, which may affect CPS composition and function. Overall, this analysis indicates that the strong OmpE promoter and internal promoters in the CPS cluster result in significant transcriptional differences in complemented strains, which together with enzymatic regulatory loops (McCallum et al., 2013) may explain the lack of functional complementation of the mutants observed by NMR. Others have also reported previously similar difficulties with complementation upon perturbation of regulatory networks or improper stoichiometry of enzymes involved in polysaccharide synthesis (van Sorge et al., 2014). Therefore, in view of these difficulties and since qRT-PCR data demonstrated lack of polarity of the mutations, we did not pursue the characterization of the “complemented” strains.
Disruption of heptose modification pathway affects growth rate and decreases motility but does not affect autoagglutination

When measuring growth rates of wild type and mutants under microaerobic conditions, we observed that the heptose modification mutants grew consistently faster than wild type. The \textit{wcaG::catΔ} mutant, which not only lacks heptose in its CPS but also lacks MeOPN on GalNAc (Fig. 6A), reached the highest final cell density. This suggests that implementation of the heptose modification pathway (configuration switch, and methylation) and of the MeOPN addition pathway imposes an energetic cost. The \textit{kpsM::kan} mutant exhibited a longer lag phase before entering exponential phase, suggesting that the accumulation of CPS units or CPS precursors inferred from the qRT-PCR analysis above may be slightly toxic to the bacterium, as observed in comparable mutants of other species (Kroll \textit{et al.}, 1988; Pavelka \textit{et al.}, 1994).

We also investigated if alteration of CPS amount or composition in the mutants could affect autoagglutination, which was measured as the decrease of turbidity over time in the upper level of static bacterial suspensions. Autoagglutination occurred in all strains and there was no significant difference between wild type and the heptose modification mutants (Fig. 6B). In contrast, \textit{kpsM::kan} showed increased autoagglutination (Fig. 6B) and microscopy revealed that this mutant formed clumps of cells (Fig. 6C). Motility was assessed in soft agar to determine if impaired motility contributed to the strong autoagglutination of \textit{kpsM::kan}. This mutant was nonmotile while the heptose modification mutants were motile, albeit at a statistically significantly reduced rate.
compared to wild type (Table 3). Electron microscopy revealed that the majority of
*kpsM::kan* cells produced flagella similar to the wild type strain (Fig. 6D), suggesting that
loss of motility was due to a defect in flagellar function. Overall, the total lack of motility
of *kpsM::kan* may contribute to its autoagglutination.

Disruptions of heptose modification pathway alters CPS barrier function

CPS contributes to resistance to bile salts in many bacteria (Begley *et al.*, 2002; Hsieh *et al.*, 2003; Pace *et al.*, 1997). We tested whether CPS and its modified heptose contribute
to resistance to bile salts for *C. jejuni*. Wild type and mutant strains were exposed to
increasing concentrations of a mixture of cholic and deoxycholic acids, two abundant bile
salts in humans. Low concentrations (0-0.25 g/l) of bile salts had little effect on all strains
(Fig. 7A). However, higher concentrations (0.5-2.0 g/l) resulted in 80-90% killing in the
wild type strain. Interestingly, *kpsM::kan* was as susceptible to bile salt killing as wild
type, indicating that CPS as a whole and in its wild type structure and composition does
not contribute to resistance. Likewise, *wcaG::catΔ* and *wcaG::cat* had wild type like bile
salts susceptibility while *mlghC::cat* and *mlghB::cat* were more resistant (p<0.001) than
wild type. These differences in bile salts resistance may reflect subtle differences in the
CPS, which may not be apparent in NMR analyses of CPS extracted from the mutants
since the mutants had similar NMR profiles, except for a lower MeOPN content in
*mlghC::cat* and lack of MeOPN in *wcaG::catΔ*. The observed differences for *mlghB::cat*
and *mlghC::cat* were specific to bile salts, as no differences in resistance to SDS were
observed for these mutants or with any of the others.
CPS protects bacteria against killing by serum, including in *C. jejuni* 81-176
(Maue *et al.*, 2013). We investigated whether alterations of CPS composition in our
mutants would affect resistance to serum killing. The wild type exhibited 40% survival
after 90 min in 30% serum, while non-capsular kpsM::kan did not survive in 5% serum
(Fig. 8A), indicating that wild type CPS protects *C. jejuni* against serum killing. The
wcaG::cat and wcaG::catΔ mutants were resistant to up to 5% serum but highly
susceptible to concentrations above 20%, while mlghB::cat and mlghC::cat displayed
intermediate susceptibility, resisting killing up to ~15% of serum, but being killed by
more than 30% serum (Fig. 8A). Time-course experiments were performed using 20%
serum, a concentration where maximal differences were observed between strains (Fig.
8B). The kpsM::kan and wcaG::catΔ mutants were killed very rapidly while wcaG::cat
resisted slightly longer (Fig. 8B). Together, these results demonstrate that heptose in its
3,6-O-Me₂-L-gluco form, as present in wild type, is essential for CPS-mediated protection
against serum killing. In contrast, mlghC::cat showed wild type killing kinetics for the
first 45 min, with a slightly lower survival afterwards (Fig. 8B). Since the only difference
between the CPS of mlghC::cat and wcaG::cat is the lower amount of MeOPN in
mlghC::cat, we conclude that MeOPN is actually deleterious for resistance to serum
within the context of heptose-less mutants. This agrees with the observation that wild
type does not produce MeOPN under our growth conditions. Unexpectedly, mlghB::cat
resisted killing better than all strains including wild type for about 45 min, but plummeted
beyond that time to reach wild type levels at 90 min. Because we could not distinguish
the CPS of mlghB::cat from that of wcaG::cat by NMR spectroscopy or Western blotting,
their different serum resistance may reflect additional differences in surface properties in the mlghB::cat mutant. 

Disruption of heptose modification pathway does not affect interactions with RAW 264.7 macrophages

Several studies have suggested that C. jejuni can survive within murine macrophages for several days (Day et al., 2000; Kiehlbauch et al., 1985; Mixter et al., 2003). To test whether the CPS and its modified heptose protect C. jejuni against intracellular killing, the CPS mutants were assayed for survival in RAW 264.7 macrophages. Intracellular survival decreased drastically within a few hours and there was no statistically significant difference between wild type and any of the mutants whether the data were analyzed as percent of original inoculum (Fig. S3A) or percent of initial bacterial load (Fig. S3B), Likewise, no significant differences were observed between heptose modification mutants and wild type regarding adhesion and phagocytosis rates (Fig. S3C and S3D). These data indicate that the modified heptose does not protect against adhesion, uptake or clearance by macrophages. A slight anti-phagocytic role could nevertheless be attributed to wild type CPS as kpsM::kan was engulfed at higher levels than wild type when interactions were allowed to proceed for at least 2 h (Fig S3D).

The heptose modification pathway is important for invasion of intestinal epithelial cells
Adhesion to intestinal epithelial cells and their invasion are important for C. jejuni pathogenicity (Black et al., 1988; De Melo et al., 1989; Fauchere et al., 1986; Konkel et al., 1992) and CPS is thought to be essential for these processes (Bachtiar et al., 2007; Bacon et al., 2001). We therefore assessed our mutants for adhesion and invasion with Caco-2 intestinal epithelial cells. The heptose modification mutants adhered at wild type levels, indicating no role of heptose modification in adhesion (Fig. 9A). Differences among heptose modification mutants were observed for invasion, with abrogated invasion for mlghB::cat and mlghC::cat, wild type invasion for wcaG::cat, and increased invasion for wcaG::catΔ. Finally, kpsM::kan was more adhesive and invasive than wild type.

Phase contrast microscopy showed that it agglutinated on the surface of Caco-2 cells, which could enhance adhesion, while other mutants did not (data not shown).

The heptose modification pathway is important for colonization and persistence in chicken intestine

C. jejuni wild type and mutants were tested for their ability to colonize the intestine of two day old chicks. All mutants were significantly impaired for colonization and/or persistence in the chicken intestinal tract compared to wild type, but differences were also observed between the mutants (Fig. 10). Specifically, wcaG::catΔ and mlghC::cat demonstrated a median 5.4 log (p<0.0001) and 6.3 log (p<0.0001) reduction in colonization compared to wild type, respectively. In addition, while infection of all inoculated chicks was observed with wild type, wcaG::catΔ and mlghC::cat were only isolated from 6 of 11 (54.5%) and 4 of the 12 (25%) inoculated chicks, respectively. In
contrast, bacteria were isolated from all chicks infected with *mlghB::cat* and *kpsM::kan* and in 12 out of 14 chicks inoculated with *wcaG::cat*. All these mutants also persisted significantly less than wild type and demonstrated medians of 1.9 log (p=0.0001), 1.1 log (p=0.0231) and 1.8 log (p=0.0095) reduction in colonization when compared to wild type, for *mlghB::cat*, *kpsM::kan* and *wcaG::cat* respectively. The data indicate that in *C. jejuni* ATCC 700819, CPS is important but not essential for colonization of the chick intestine. We speculate that underlying adhesins compensate for the lack of CPS. However, when CPS is present, its wild type composition featuring the modified heptose appears optimal for colonization of the chicken intestinal tract.

**DISCUSSION**

To assess the role of the role of heptose and its modification in CPS function, we performed a detailed analysis of *C. jejuni* mutants of the *wcaG*, *mlghB*, and *mlghC* genes, which affect the switch of CPS heptose from a D-manno to a L-gluco form (McCallum *et al.*, 2013). Our results showed that these genes play unexpected roles in transcriptional regulation within the CPS cluster. The *C. jejuni* CPS cluster is similar to group II and III CPS clusters of *E. coli*, whereby conserved CPS transport regions 1 and 3 flank the sugar synthesis region 2 (Karlyshev *et al.*, 1999; Whitfield and Roberts, 1999). Region 3 in the *E. coli* K5 CPS cluster has a σ70 promoter (upstream of *kpsM* included in this region) and RfaH-dependent read-through transcription from this promoter into region 2 is essential for CPS production (Rowe *et al.*, 2000; Stevens *et al.*, 1997). If this also applied to *C. jejuni*, genes from regions 2 and 3 would be transcribed at similar levels or with
decreasing levels as their distance from the region 3 promoter increases, without
differential regulation of gene expression within region 2. However, we observed
differential transcription of CPS modification genes in the wild type strain, which is
likely important to fine tune the CPS composition as \textit{C. jejuni} passes from one host to
another or is exposed to the environment, as the modified heptose, MeOPN and
methylation may each enhance resistance to different adverse conditions. The qRT-PCR
data imply the existence of internal promoters within regions 2 and 3, which agrees with
a recent RNA-seq study (Dugar \textit{et al.}, 2013). Transcriptional start sites were identified by
RNA-seq upstream of \textit{cj1445c}, \textit{cj1444c}, and \textit{cj1425c} to \textit{cj1429c}, which was consistent
with our qRT-PCR findings. This RNA-seq study identified a start site for \textit{cj1447c} within
\textit{kpsM} in two strains but not in the strain NCTC 11168 used in our study. We show that
transcription of \textit{kpsM} can vary without affecting that of \textit{cj1447c}, indicating that the start
site for \textit{cj1447c} is also present in strain NCTC 11168.

\textit{Implications of heptose modification pathway disruption for CPS composition}

While it had already been shown that a \textit{mlghC::cat} mutant produces heptoseless CPS (St
Michael \textit{et al.}, 2002), as we also observed in our study, the CPS composition in
\textit{wcaG::cat\Delta}, \textit{wcaG::cat} and \textit{mlghB::cat} mutants had to be determined. We found no
heptose in \textit{wcaG::cat\Delta} by NMR spectroscopy analysis, as expected from deletion of its
heptose biosynthesis genes. Like for \textit{mlghC::cat}, we also found no modified heptose in
\textit{wcaG::cat} and \textit{mlghB::cat}. The lack of even an unmodified heptose in these mutants
despite their ability to synthesize GDP-D-glycero-D-manno-heptose is consistent with the generally high specificity of glycosyltransferases involved in CPS assembly. SDS-PAGE analysis indicated that except for kpsM::kan, CPS production was not abrogated in the mutants, and lack of heptose did not prevent CPS polymerization. Further, all mutants produced comparable amounts of CPS, although lower hot water/phenol extractability of the CPS produced by mlghB::cat was observed. This difference in CPS extractability along with its enhanced serum resistance despite equal CPS composition and production suggest additional differences in surface properties in this mutant. It is possible that such additional differences could be mediated by the striking ~187 fold upregulation of cj1429c that is observed in this mutant only. The upregulation of the putative heptose methyl-transferase gene in all mutants shown by qRT-PCR did not result in incorporation of methyl heptose in the CPS, as shown by NMR spectroscopy. This could indicate that either methylation occurs after the heptose configuration switch or that methylated manno-heptose is not recognized as a substrate by glycosyltransferases for incorporation into CPS. NMR spectroscopy analysis also showed that the MeOPN modification was strongly upregulated in heptose biosynthesis mutants, which may affect the biological function of their CPS.

Role of modified heptose on barrier function of CPS

C. jejuni can resist physiological levels of bile salts (0.1-21 mM) (Lin et al., 2003; Lin et al., 2005) and has been isolated from the gall bladder and bile (Gerritsen van der Hoop and Veringa, 1993; Udayakumar and Sanaullah, 2009). In Listeria monocytogenes and
Vibrio parahaemolyticus, upregulation of CPS genes upon exposure to bile salts suggests a role of CPS in bile resistance (Begley et al., 2002; Pace et al., 1997). Therefore, we determined whether CPS as a whole, or its modified heptose, contributes to resistance of C. jejuni to bile salts. The concentrations tested (0.25 to 2 g/l) amount to ~ 0.6 to 4.8 mM and fall within the physiological ranges previously reported (Campbell et al., 2004; Lin et al., 2003; Perez de la Cruz Moreno et al., 2006). The wild type-like susceptibility of kpsM::kan suggests that wild type CPS does not provide resistance against bile salts, and the enhanced resistance of the mlghB and mlghC mutants showed that heptose and its modification as present in wild type CPS actually rendered the strain more susceptible to bile salts. Therefore, the cumulative effects of lack of heptose and methylation, and variations in MeOPN, GroN and EtN contents observed in the mutants, could alter the bacterial surface hydrophobicity and confer slight protective function to CPS via enhanced repulsion of bile salts.

Serum complement is an essential innate immune defense against pathogens and the sensitivity of C. jejuni strain 81-176 to serum is mitigated by its CPS (Maue et al., 2013) as also reported for Salmonella typhi, Klebsiella pneumoniae, and B. pseudomallei (Cortes et al., 2002; Hashimoto et al., 1993; Reckseidler-Zenteno et al., 2005). Our kpsM::kan mutant confirmed an essential role of CPS in protection against serum in our strain, and the heptose modification mutants showed that the modified heptose in its wild type form is essential for protection. Killing of C. jejuni by serum involves activation of the classical complement pathway (van Alphen et al., 2014) but we do not know if C. jejuni CPS and modified heptose interfere with deposition of critical C3 complement component as observed in other pathogens (Vogel et al., 1997; Woodman et al., 2012).
As mentioned above, the slower kinetics of killing of *mlghB::cat* at low serum concentration may be due to additional modifications in surface properties since no obvious differences were seen in its CPS. Also, we showed a slightly deleterious effect of MeOPN, which increased serum susceptibility in the absence of heptose. Thus the role of MeOPN in serum resistance appears to depend on other CPS components, which may explain prior conflicting results (Maue *et al.*, 2013; van Alphen *et al.*, 2014). Finally, the protective function of CPS against serum killing may depend on other surface components such as LOS since a LOS mutant lacking sialic acid is serum sensitive despite the presence of CPS in strain 81-176 (Guerry *et al.*, 2000; Guerry *et al.*, 2002).

All our mutants produce LOS and the serum sensitivity of *kpsM::kan* (that produces LOS but no CPS) shows that LOS does not confer protection against serum killing in strain ATCC 700819. This is consistent with prior studies indicating no role of LOS in serum resistance (Bacon *et al.*, 2001; Keo *et al.*, 2011).

Role of CPS and modified heptose on interactions with macrophages and epithelial cells

In contrast to prior reports (Day *et al.*, 2000; Kiehlbauch *et al.*, 1985; Mixter *et al.*, 2003), we did not observe prolonged survival of *C. jejuni* in murine RAW 267.4 macrophages and wild type capsule production did not affect intracellular survival or initial adhesion but decreased phagocytosis as determined by comparing wild type to non-capsular *kpsM::kan*. The sharp increase in phagocytosis of *kpsM::kan* coincided with its agglutination and likely resulted from phagocytosis of clumps of bacteria. It could also be due to exposure of adhesins that are masked by the CPS layer in wild type.
The heptose-modification mutants showed that heptose modification and MeOPN addition (that also varies in these mutants) played no role in macrophage / bacteria interactions. Thus, the true biological role of CPS modified heptose is not resistance to clearance by murine macrophages. Different effects may be observed with human or avian macrophages, and may explain the host-dependent pathogenic versus commensal character of *C. jejuni*.

We showed that *C. jejuni* ATCC 700819 adhered to and invaded Caco-2 cells at a very low rate, consistently with prior reports (Ashgar *et al.*, 2007; Carrillo *et al.*, 2004; Everest *et al.*, 1992; Ganan *et al.*, 2010; Szymanski *et al.*, 1995; Vijayakumar *et al.*, 2006). In contrast to what was observed in strain ATCC 81-176 (Bacon *et al.*, 2001), our non-capsular *kpsM::kan* mutant showed increased adhesion and invasion of Caco-2 cells (Fig. 9). Unmasking of adhesins and autoagglutination may each contribute to this phenomenon. The presence of CPS, which limits adhesion to low levels, may prevent overt tissue damage that could lead to faster bacterial clearance.

Although heptose is essential for adhesion of pathogenic *E. coli* to HeLa cells (Benz and Schmidt, 2001), our data indicate that *C. jejuni* CPS heptose is not important for adhesion to Caco-2 cells. Variable levels of invasion were observed for the heptose modification mutants but did not correlate directly with NMR structural data concerning heptose and MeOPN contents. For example, abrogated invasion for *mlghB::cat* and *mlghC::cat* could suggest a role for modified heptose in cell invasion, but the wild type-like and enhanced invasion of heptoseless *wcaG::cat* and *wcaG::catΔ*, respectively, does not support this. Likewise MeOPN presence or abundance could not be correlated with invasion, although MeOPN contributes to epithelial cell invasion in strain 81-176 (van...
Alphen et al., 2014). The variations of invasion however correlated well with the levels of transcription of *cj1429c* in the mutants, and may be due to additional surface differences mediated by *cj1429c*. The increased invasion of *wcaG::catΔ* despite its lack of heptose and MeOPN also suggests that additional components contribute to the process. The data nevertheless indicate that interferences with heptose modification affect invasion. Since invasion can promote tissue damage, transepithelial transport and protection against clearance, our data suggest that the heptose modification pathway is important for host colonization and pathogenicity.

**Role of CPS and modified heptose on colonization of chicken intestinal tract**

The chick intestinal colonization data with *kpsM::kan* showed that CPS of strain 700819 is not essential to establish an infection since all chicks were colonized. This agrees with data obtained with a CPS export mutant of strain ATCC 81116 (Bachtiar et al., 2007). These data do not negate a role for CPS in colonization but may reflect the fact that unmasked adhesins could compensate for lack of CPS. In addition, our data with *kpsM::kan* showed that CPS was important for persistence since a 1.6 log reduction of caecum load was observed. This attenuation differs from another study which showed that a *kpsM* mutant could not persist at all in the chicken intestine (Jones et al., 2004). The discrepancy could be due to the use of a hypermotile strain (NCTC 11168H) and of 2-week-old chickens that present a more mature gut microflora.

Flagella-mediated motility enhances intestinal colonization by *C. jejuni* (Biswa}
et al., 1993) as confirmed by colonization of all chicks tested by our non-motile kpsM::kan. The flagellar apparatus also serves as a secretion system for C. jejuni invasion antigens (Cia), which facilitate colonization and persistence (Konkel et al., 1999; Konkel et al., 2004). The kpsM::kan mutant assembled flagella, indicating that it has the apparatus required for Cia secretion and should thus be able to colonize and persist within the intestinal tract as observed. Also, the increased exposure of adhesins in the absence of CPS may compensate for the lack of motility of this mutant.

The data obtained for our heptose modification mutants show a role of modified heptose in colonization and persistence. Indeed wcaG::catΔ and mlghC::cat were impaired both in colonization (less chicks colonized than wild type) and persistence (lower load than wild type), while wcaG::cat and mlghB::cat showed mostly defects in persistence (most chicks colonized but at lower levels) (Fig. 10). We assume that the effects are due to the modified heptose independently of MeOPN since a MeOPN transferase mutant of strain 81F176 showed wild type-like chicken colonization (van Alphen et al., 2014), although strain-specific differences cannot be excluded. While all heptose modification mutants were less motile than wild type, we exclude that their decreased colonization was due to decreased motility since the kpsM::kan data indicated that the contribution of motility to colonization was limited in this model. Also, the bacterial suspensions used for inoculation were adjusted to the same OD to alleviate interferences from different growth rates, and the highest bacterial load was actually recovered with the slowest growing strain (kpsM::kan). Thus factors other than growth and motility were critical for gut colonization and persistence in our heptose mutants.
Overall, our data indicate that CPS and its heptose affect the efficiency of chicken gut colonization and persistence. It is likely that \textit{C. jejuni} modulates CPS expression and composition \textit{in vivo} at different stages of colonization as seen in other intestinal pathogens such as, for example, the Vi-antigen of \textit{S. typhi} (Jones \textit{et al.}, 2004). This is plausible for \textit{C. jejuni} as expression of CPS is phase variable (Bacon \textit{et al.}, 2001) and co-culture of \textit{C. jejuni} with epithelial cells reduces surface CPS expression, thereby highlighting the dynamic role of CPS in interactions with host cells (Corcionivoschi \textit{et al.}, 2009). Our data suggest that suppressed CPS expression during infection exposes surface adhesins that lead to increased agglutination of \textit{C. jejuni}, facilitating adhesion in clumps and increasing invasion. Resumed CPS production and fine-tuning of its composition may favor persistence at other stages of infection, affecting differentially its barrier functions and its effects on intracellular survival. Our discovery of internal promoters that likely allow transcriptional optimization of CPS composition in response to environmental stimuli is in line with this hypothesis.

Collectively, the data presented in this study indicate a role of \textit{wcaG}, \textit{mlghB}, and \textit{mlghC} in determining CPS composition and biological function. The mutants demonstrate very different behaviors in terms of CPS barrier functions, interactions with different cell types and motility, which culminate in different outcomes concerning colonization and persistence in the chicken intestinal tract. Overall, fine tuning of CPS composition via modified heptose incorporation and other modifications that seem to be interdependent with heptose modification, allows reaching an optimal configuration that contributes to survival of the bacterium when confronted with various host defenses along the gastrointestinal tract (bile salts, serum and phagocytic cells) and also
contributes to persistence of the bacterial population via invasion of intestinal cells. This investigation illustrates the impact that altering CPS composition can have on CPS function and on the virulence of encapsulated bacteria and suggests that the enzymes responsible for the biosynthesis of CPS components such as the modified heptose could be suitable targets for future therapeutic research.

EXPERIMENTAL PROCEDURES

**Bacterial culture conditions**

All experiments were carried out with strain NCTC 11168 / ATCC 700819 (HS: 2 Penner serotype). *C. jejuni* was grown in a microaerobic atmosphere (85% N$_2$, 10% CO$_2$, and 5% O$_2$) at 37˚C on Trypticase Soy Agar (TSA) supplemented with 5% sheep blood and 10 µg/ml vancomycin and 5 µg/ml trimethoprim as background antibiotics. Where appropriate, the medium was supplemented with 15 µg/ml chloramphenicol or 30 µg/ml kanamycin. Unless stated otherwise, *C. jejuni* was grown overnight from freezer stock on TSA containing appropriate antibiotics, followed by a further growth on TSA containing only the background antibiotics for 20-24 hours. The cells were harvested and normalized to the same OD$_{600\text{nm}}$ before use for phenotypic analyses. Viability of the bacterial suspensions used as inoculum for phenotypic assays was assessed by CFU measurements. For transformation, *C. jejuni* was grown on Mueller Hinton (MH) agar (BD, Canada), containing 10 µg/ml vancomycin, 5 µg/ml trimethoprim, 0.05% pyruvate, and 5% heat inactivated Fetal Bovine Serum (Sigma Aldrich). *E. coli* strain DH5α was used for
cloning and was grown in Luria Bertani medium. When necessary, 100 µg/ml ampicillin, 30 µg/ml kanamycin, or 34 µg/ml chloramphenicol were added.

Preparation of knockout constructs

The wcaG (a.k.a. cj1427c), mlghC (a.k.a. cj1428c), mlghB (a.k.a. cj1430c) and kpsM (a.k.a. cj1448c) genes were amplified via Polymerase Chain Reaction (PCR) from chromosomal DNA of C. jejuni strain ATCC 700819 using primers cj1427c P2/P3, cj1428c P2/P3, cj1430c P2/P3, and kpsM P2/P3 (Table 4). The PCR was performed using Expand Long Range DNA polymerase (Roche) according to Manufacturer’s instructions. For wcaG, mlghB and mlghC, the PCR products were cut with BamHI and NcoI and were ligated to a pET23 vector derivative (Newton and Mangroo, 1999) that had been cut with the same enzymes. The kpsM gene was cloned into the EcoRV site of pBluescript KS(+), following blunting of the PCR product by T4 DNA Polymerase (Roche, Canada). After transformation of ligation reactions into E. coli DH5α and selection on ampicillin, the resulting plasmids (pET/wcaG, pET/mlghC, pET/mlghB and pBluescriptKS/kpsM) were extracted and checked by DNA sequencing (Robarts Research Institute, London, Ontario).

Disruption constructs were generated by performing inverse PCR on pET/wcaG, pET/mlghC, pET/mlghB using primers cj1427c P4/P5, cj1428c P4/P5, cj1430c P4/P5, which contain KpnI and ApaI sites. The chloramphenicol resistance cassette (cat) was amplified from plasmid pRY111 (kindly provided by P. Guerry, Naval Medical Research Center, MD, USA) using primers Catcoli P2 and CatColi P3 which contained ApaI and
KpnI sites, respectively. The amplicon was subsequently ligated into the inverse PCR
reaction products following ApaI and KpnI digestion. The constructs were introduced
into *E. coli* DH5α and transformants were selected on ampicillin and chloramphenicol.
The resulting pET/wcaG::cat, pET/mlghC::cat, and pET/mlghB::cat, constructs were
extracted and checked by DNA sequencing. For the disruption of *kpsM*, inverse PCR was
used to amplify pBluescriptKS/*kpsM* with the primers *kpsM* P4/P6 that contain BglII and
NcoI sites, respectively. The kanamycin resistance cassette (*kan*) was amplified from
plasmid pHel3 (Heuermann and Haas, 1998) using Aph3P1 and Aph3P2, which also
contained BglII and NcoI restriction sites. The *kan* cassette was subsequently ligated into
the pBluescriptKS/*kpsM* inverse PCR reaction product after BglII/NcoI digestion.
Following *E. coli* DH5α transformation, transformants were selected on ampicillin and
kanamycin. The resulting pBluescriptKS/*kpsM::kan* construct was checked by DNA
sequencing.

*Generation of knockout mutants in C. jejuni ATCC 700819*

The *wcaG::cat, mlghB::cat, mlghC::cat*, and *kpsM::kan* fragments were amplified using
gene specific primers P2 and P3 (Table 4) containing NcoI and BamHI restriction sites
respectively. *C. jejuni* chromosomal DNA digested with the same restriction enzymes
was ligated to either end of the PCR fragments. The DNA was introduced into *C. jejuni*
via natural transformation using 0.03% saponin (Nuijten *et al.*, 1989; Vijayakumar *et al.*,
2006). Potential transformants were selected on MH agar containing 15 µg/ml
chloramphenicol or 30 µg/ml kanamycin, The transformants were checked by PCR using
gene specific and antibiotic cassette specific primers, as well as by Southern blotting using digoxigenin (Roche) labeled DNA probes.

As an alternative to obtain the *wcaG* mutant, the pET/*wcaG::cat* was methylated *in vitro* as described by others (Donahue *et al.*, 2000). Ten µg of plasmid DNA were treated with a cell-free extract of *C. jejuni* (containing 300-400 µg of proteins) in the presence of 200 nM S-adenosyl methionine (Sigma Aldrich). Methylation was carried out at 37°C for 1 hour in “methylation” buffer (20 mM Tris-acetate (pH 7.9), 50 mM potassium acetate, 5 mM Na₂EDTA, 1 mM dithiothreitol (DTT)) in a total volume of 200 µl. To obtain a cell-free extract, wild type *C. jejuni* was harvested from five TSA plates and resuspended in 4 ml of “methylation” buffer supplemented with protease inhibitor cocktail (Roche). This was passed through a French pressure cell press (Thermo Scientific) five times. The amount of protein in the cell-free extract was quantitated by Bradford Assay (Bradford, 1976). Following methylation, phenol:chloroform:isoamyl alcohol (in a 25:24:1 v:v:v ratio) was used to purify the DNA which was concentrated by sodium acetate/ethanol precipitation. The plasmid was introduced in *C. jejuni* by natural transformation as above, using 70 µl of cells resuspended at 10E9 cells/ml and 2 µg of DNA in a total volume of 80 µl, with recovery of ~ 8-10 h prior to selection on chloramphenicol.

**Preparation of complemented strains**

Complementation was performed by chromosomal integration in the 16S - 23S rRNA region as reported previously (Karlyshev and Wren, 2005). All primers used are listed in
Supplementary Table 1. The 16S – 23S rRNA region was amplified from genomic DNA using primers 16SrRNATop and 23SrRNABottom and was inserted into the KpnI/NotI sites of pBluescript KS (+). Clones were obtained using *E. coli* DH5α and selection with ampicillin. Separately, the primer overlap extension method (Heckman and Pease, 2007) was used to fuse each gene of interest to the *ompE* promoter and to a *kan* resistance cassette. The promoter was amplified using primer ompEFor combined with ompERev1427, ompERev1428, or ompERev1430. The genes to be complemented were amplified using primer pairs 1427ForOmpE / 1427RevKan, 1428ForOmpE / 1428RevKan, or 1430ForOmpE / 1430RevKan. The *kan* cassette was amplified using primer AphP3 combined with KanFor1427, KanFor1428 or KanFor1430. All fragments were fused together by PCR using standard conditions. The fusions were then inserted into the XbaI site of the 16S–23SrRNA-containing vector from above to generate the final complementation constructs. Clones were selected with ampicillin and kanamycin and sequenced (Robarts Sequencing Facility, London, Ontario). The constructs were transformed into their respective mutants following *in vitro* methylation as reported above. Clones were selected on ampicillin and kanamycin and analysed by PCR to check integration of the constructs.

Real-time PCR analyses

Messenger RNA was extracted from *C. jejuni* using the GE-Healthcare mRNA midiprep kit, and cDNA synthesis was performed using the Biorad cDNA biosynthesis kit and random hexanucleotides following Manufacturer’s instructions. Real-time PCR was performed on a Rotor-Gene 6000 (Corbett Life Science, Canada) using SYBR green.
Supermix (Biorad) and gene-specific primers (Table 4). The optimal annealing
temperature and primer concentrations were determined for each gene. The primer
efficiencies were determined from standard curves established using serial dilutions of
genomic DNA under optimal annealing temperature and primer concentrations. Negative
controls for the reverse transcription did not contain the reverse transcriptase, while
negative controls for the real time PCR did not contain template cDNA. The relative gene
expression for each gene was calculated using the Pfaffl equation (Pfaffl, 2001):

$$\text{Ratio} = \left( \frac{E_{\text{target}}^{\Delta C_{\text{target}}(\text{WT-mutant})}}{E_{\text{reference}}^{\Delta C_{\text{ref}}(\text{WT-mutant})}} \right).$$

In this equation, target refers to the gene being studied and the reference is the
housekeeping cij537c gene, which encodes acetyl-CoA synthase (Parkhill et al., 2000). E
is the primer efficiency, and $C_T$ corresponds to the number of PCR cycles necessary to
observe a fluorescence signal above a set threshold.

SDS-PAGE and Western blotting analysis of CPS

Total surface carbohydrates (CPS and LOS) were extracted via SDS solubilization of C.
jejuni cells (Hitchcock and Brown, 1983), followed by digestion of proteins by proteinase K treatment. They were separated on a 15% SDS-PAGE 5 cm mini gel and analyzed by
Western blotting using Penner serotyping antibody HS:2 (kindly provided by Dr. M.
Karmali, Laboratory for Foodborne Zoonoses, Public Health Agency of Canada, Guelph,
Ontario) since strain ATCC 700819 belongs to the HS:2 Penner serotype (Karmali et al.,
1983; Penner et al., 1983) and CPS contributes to serotype specificity (Karlyshev et al.,
2000). Detection was performed with a fluorescently labeled anti-rabbit secondary
antibody (IRDye 680 Goat Anti-Rabbit, Licor Biosciences) on an Odyssey Infrared Imaging system (Licor Biosciences). Alternatively, CPS was extracted by hot water phenol (see below), ran on a 13 cm long gel and detection was performed by silver staining (Fomsgaard et al., 1990).

CPS isolation by the hot water phenol method

C. jejuni ATCC 700819 wild type and mutants were grown on one hundred TSA plates for 24 hours and harvested in saline. The cells were then inoculated into 10 L of Brucella broth, containing 7.5% heat inactivated horse serum and 25 mM sodium pyruvate to an OD$_{600nm}$ of approximately 0.05. After 24 hours of growth (OD$_{600nm}$ approximately 0.3), the bacteria were spun down at 4200 $\times$ g (Avanti J-25I, Beckman-Coulter) for 30 min and the pellets were lyophilized. Purification of CPS was performed by hot water/phenol extraction (Westphal and Jann, 1965). Briefly, 2 g of dry cell pellet were re-suspended in 20 ml of MilliQ water pre-heated to 68°C. An equal amount of phenol (Fisher) preheated to 68°C was added to the pellet and sealed in a 50 ml conical tube. The samples were incubated at 68°C for 10 min with rapid stirring. They were allowed to cool to 10°C on ice and centrifuged for 30 min at 6300 $\times$ g (Eppendorf 5810R) and 10°C. The aqueous (top) phase was collected, and an equal amount of water was added to the remaining organic phase. The procedure was repeated three times and the aqueous phases were pooled. The aqueous phases were dialyzed (molecular weight cut off 12-14000 Da) against running water for 2-3 days until no phenol remained. The samples were lyophilized and re-suspended in double distilled water. Ultracentrifugation of the samples
for 30 hours at 4°C and 110000 × g (Optima Max-XP Ultracentrifuge, Beckman-Coulter) pelleted most of the LOS, while the CPS remained in the supernatant. The samples were lyophilized and re-suspended in 500 µl double distilled water. Treatment with 200 mg of Proteinase K was carried out for 2 hours at 60°C to degrade any remaining proteins. The CPS samples were stored at -20°C until further required.

Sugar analysis

CPS samples (0.2 mg each) were hydrolyzed with 2 M CF$_3$CO$_2$H (120 °C, 2 h), and the monosaccharides were identified using a Biotronik LC-2000 sugar analyzer (Germany) on a column (15 × 0.4 cm) of a Dionex A×8-11 anion-exchange resin and Ostion LC AN B cation-exchange resin (7.5 cm column each). Sugars were eluted with a stepwise gradient of 0.17 M (20 min) and 0.3 M sodium borate buffer pH 8.0 at 0.5 ml min$^{-1}$ and detected with the bicinchoninate reagent.

Nuclear magnetic resonance spectroscopy

Samples were deuterium-exchanged by freeze-drying twice from 99.9% D$_2$O and then examined as solutions in 99.95% D$_2$O at 30° C on NMR spectra were recorded on an Avance II 600 spectrometer (Bruker, Germany) using internal sodium 3-(trimethylsilyl)propanoate-2,2,3,3-d$_4$ (δ$_H$ 0, δ$_C$ -1.6) or 85% H$_3$PO$_4$ (δ$_P$ 0.0) as references for calibration. The $^1$H and $^{13}$C NMR spectra were assigned partially using two-dimensional $^1$H-$^1$H correlation spectroscopy (COSY), total correlation spectroscopy (TOCSY), rotating-frame nuclear Overhauser enhancement spectroscopy (ROESY),
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For Peer Review

1H, 13C heteronuclear single-quantum coherence (HSQC), and 1H, 31P heteronuclear multiple-bond correlation (HMBC) experiments, which were performed using standard Bruker software. A mixing time of 100 ms was used in the TOCSY and ROESY experiments, and a 65-ms delay was used for evolution of long-range coupling in the 1H, 31P HMBC experiment. TopSpin 2.1 (Bruker) program was used to acquire and process the NMR data.

Growth curves assays

A 100 ml sidearm flask containing 20 ml MH broth and background antibiotics (pre-saturated with 85% N2, 10% CO2, and 5% O2) was inoculated with C. jejuni cells grown on TSA at a starting OD600nm of 0.075. The flask was sealed and incubated with shaking (120 rpm) at 37˚C for up to 48 h. Growth was monitored over time using a Klett Summerson photocolimeter.

Motility assays

C. jejuni was harvested in MH broth and adjusted to OD600nm of 1.0 or 2.0. Motility plates (0.3% agar in MH) were stabbed in triplicate with the wild type or mutants and incubated for 24 h under microaerobic conditions at 37˚C. The diameter of the motility halo was monitored over time.

Bile salts susceptibility assay
Following growth on TSA as described above, *C. jejuni* was harvested and washed once in saline and re-suspended in saline to an $OD_{600nm}$ of 0.1. Bile salts (50% cholate and 50% deoxycholate, Sigma Aldrich) were diluted to the appropriate concentrations (0-2 g/l) and 90 µl were aliquoted into the wells of a 96 well plate. Ten µl of the bacterial suspension were added to each well and incubated in microaerobic conditions at 37°C for 15 minutes. The samples were washed once in TSB media and serially diluted for CFU counts.

**SDS susceptibility assays**

For SDS sensitivity assays, different concentrations (0.002 to 0.03%) of SDS were prepared in TSB (supplemented with vancomycin and trimethoprim). A volume of 170 µL of each SDS concentration was added to the wells of a 96 well plate. *C. jejuni* wild type and mutants were grown as previously described and re-suspended in TSB to an $OD_{600nm}$ 1.0. To each well, 30 µl of bacterial suspension was added, and control wells were set up which contained no SDS. The plates were incubated at 37°C with shaking at 180 rpm in microaerobic conditions for 15 h, at which point the $OD_{600nm}$ was read. The data were normalized to controls which did not receive any SDS treatment.

**Serum susceptibility**
Fresh rabbit blood obtained from two rabbits was allowed to clot at room temperature. The serum was separated from the clot and centrifuged for 15 minutes at 10,000 rpm at 4°C to remove remaining blood cells. Half of the serum was inactivated by incubation at 56°C for 1 hr. Bacteria grown for 16-20 h on TSA were washed in saline and re-suspended to an OD$_{600 nm}$ of 0.1. Serum (inactivated or not) was re-suspended in saline to the appropriate concentration (0% - 100%) and 90 µl were aliquoted into the wells of a 96 well plate. To the wells, 10 µl of bacteria were added. The plates were then incubated with shaking (100 rpm) for 1.5 h in microaerobic conditions at 37°C. Following incubation, 100 µl TSB was added to the wells and the samples were serially diluted and plated for CFU counts. For time course experiments, bacterial samples were exposed to 20% pooled rabbit serum over 1.5 h.

Phagocytosis and survival within macrophages

RAW 267.4 murine macrophages (obtained from ATCC) were grown in Dulbeco’s Modified Eagles Medium (DMEM) containing 10% heat inactivated FBS, and passaged every 3-4 days to a maximum of 5 passages. Macrophages were seeded at ~2*10$^5$ cells per well in 6-well plates, and incubated overnight in DMEM (containing 10% inactivated FBS). They were counted (final counts about 10$^6$ per well after incubation) and C. jejuni bacteria that had been resuspended in tryptic soy (TS) broth and adjusted at the appropriate OD were added at a multiplicity of infection (MOI) of 1:100. After addition of the bacteria, the media composition was 97% (DMEM with 10% FBS) and 3% TS broth. The plates were centrifuged for 1 min at 300 x g to synchronize bacteria /
macrophage interaction. For adhesion experiments, the plates were incubated at 4°C for
30 minutes to promote adhesion in the absence of phagocytosis (Peterson et al., 1977),

drawn with cold PBS five times and lysed in water. Control experiments showed that all
strains resisted the water treatment (data not shown). The bacteria were then diluted and plated for CFU counts. For the time course of intracellular survival, the
macrophages were exposed to the bacteria for 2 h at 37°C in a CO2 incubator. The cells
were then washed three times with PBS and incubated with DMEM containing 225 µg/ml
gentamicin for 1 h to kill extracellular bacteria. The macrophages were then washed and
incubated in DMEM for up to 3 h. At each time point, the macrophages were washed
three times with PBS and lysed in water (20 min). The samples were serially diluted and
plated for CFU counts. For infection time course experiments, the macrophages were
exposed to the bacteria for various lengths of time. The macrophages were washed in
PBS, treated with gentamicin, and lysed in water, as described above. The surviving
bacteria were enumerated by CFU counting.

Adhesion and invasion of wild type and mutants to Caco-2 cells

Caco-2 cells (obtained from ATCC) were grown for 3 days in DMEM containing 25 mM
glucose and supplemented with 1.5 g/l sodium bicarbonate, 0.1 mM non-essential amino
acids, 1 mM sodium pyruvate, 100 U/ml penicillin, and 100 µg/ml streptomycin until
they formed a confluent monolayer (approximately 650,000 cells per well in 24-well
plates) and were fully differentiated. The differentiation state of the cells was determined
by measuring the hydrolysis of p-nitrophenyl phosphate in a standard colorimetric assay
(detection at 405 nm) which reflects the production of alkaline phosphatase and is a hallmark of differentiation (Ferruzza et al., 2012). The cells were infected for 5 h with C. jejuni at an MOI of 1:100. The bacteria were prepared as indicated for the macrophage experiments. The plates were centrifuged briefly (500 $\times$ g for 5 min at room temperature) to maximize contact between the bacteria and the cell monolayer. To determine total bacterial cell association (adhering and internalized bacteria), Caco-2 cell monolayers were washed 3 times, lysed with 0.1 % Triton X-100 for 10 min and CFUs were determined by plating serial dilutions. To determine the number of internalized bacteria, the infected monolayers were treated with 200 $\mu$g/ml gentamicin for 2 h to kill extracellular bacteria. The cells were then washed and treated as above to determine bacterial viable counts.

**Autoagglutination assay**

The autoagglutination assay was performed as previously described (Misawa and Blaser, 2000). Briefly, 2 ml of sterile PBS were inoculated with C. jejuni at an OD$_{600\text{nm}}$ of 1.0. At time points 0, 1 and 2 h, the top 1 ml from each tube was carefully removed and the optical density was read at 600 nm. Live images were acquired using an Axioscope 2 (Carl Zeiss) microscope with a 100$\times$ oil immersion objective coupled to a Qimaging (Burnaby) cooled charged-coupled device camera.

**Electron microscopy (EM)**
EM was performed at the EM facility of the department of Microbiology and Immunology led by Dr. S. Koval with uranyl acetate staining as previously described (Merkx-Jacques et al., 2004).

Chicken colonization assays

Chicken colonization assays were performed as previously described (Vijayakumar et al., 2006). *C. jejuni* was grown on TSA agar containing 5% sheep blood under microaerobic conditions at 42°C for 24 hours. The bacteria were re-suspended in PBS pH 7.4, and adjusted to an OD$_{600nm}$ of 0.35 (approx. 10E9 CFU/ml) and diluted 1:10 in PBS. Two-day-old white-leghorn specific pathogen-free chicks were orally administered 100 µl (10E7 CFU) of either the *C. jejuni* wild type or one of the mutants. Five days later, the chicks were euthanized, the caeca and their contents were harvested, weighed and homogenized. Viable counts were obtained from serial dilutions of samples that were plated on Campylobacter selective medium (CSM) plates (Quélab Inc., Montreal) for 48 hours.

**ACKNOWLEDGEMENTS**

We thank former lab members J. Griffin, A. Merkx-Jacques and Dr. D. Ratnayake for advice on genetic manipulation of *C. jejuni* and on tissue culture, X. T. Bui for help with cloning and strain construction, N. Zebian for discussions on CPS purification and statistics, Dr. A. S. Shashkov (Zelinsky Institute, Russia) for help with NMR spectroscopy, Dr. P. Guerry (Naval Medical Research Center) for providing the pRYIII
vector, A. Nazli, J. Lu (McMaster University, Canada) and S. Kim (University of Western Ontario, Canada) for providing Caco-2 cells and advice for tissue culture experiments, Dr. M. Karmali (Laboratory for Foodborne Zoonoses Health Canada) for providing the *C. jejuni* serotype specific antibody, and Dr. J. Lam (Guelph University) for providing the anti lipid A antibody.

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Dr. Creuzenet was the recipient of a University Faculty Award from NSERC and a Premier's Research Excellence Award (Ontario, Canada). Dr. C.M. Dozois was supported by funds from the Canada Research Chair in Bacterial Infectious Diseases. Dr Valvano was a Canada Research Chair in Infectious Diseases and Microbial Pathogenesis.
REFERENCES:


Pei, Z., and Blaser, M.J. (1993) PEB1, the major cell-binding factor of Campylobacter jejuni, is a homolog of the binding component in gram-negative nutrient transport systems. J Biol Chem 268: 18717-18725.


polysaccharide of *Burkholderia pseudomallei* as a major virulence determinant. *Infect Immun* **69**: 34-44.


Yuki, N., Taki, T., Takahashi, M., Saito, K., Yoshino, H., Tai, T., Handa, S., and Miyatake, T. (1994) Molecular mimicry between GQ1b ganglioside and
**Table 1: Sugar and NMR spectroscopy analyses of hot water / phenol extracted CPS from the wild type *C. jejuni* and its isogenic mutants.**

Monosaccharide analysis was conducted with a sugar analyzer after full acid hydrolysis. Numbers in the columns under “Sugar analysis data” represent the amounts of various sugars present, after normalization to GalN. A plus (+) or minus (-) in the NMR spectroscopy data columns represent either the presence or the absence of the specified component, respectively. GalN = galactosamine (from GalNAc), Rib = ribose, Gal = galactose (probably from the lipooligosaccharide), GlcA = glucuronic acid, Hep = heptose, Me = methyl, MeOPN = O-methyl phosphoramidate, EtN = ethanolamine, GroN = 2-amino-2-deoxyglycerol.

<table>
<thead>
<tr>
<th></th>
<th>Sugar analysis data</th>
<th>NMR spectroscopy data</th>
</tr>
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<tr>
<td></td>
<td>GalN</td>
<td>Rib</td>
</tr>
<tr>
<td>Wild type</td>
<td>1.0</td>
<td>2.6</td>
</tr>
<tr>
<td><em>wcaG::cat</em></td>
<td>1.2</td>
<td>trace</td>
</tr>
<tr>
<td><em>mlghC::cat</em></td>
<td>1.4</td>
<td>3.6</td>
</tr>
<tr>
<td><em>mlghB::cat</em></td>
<td>1.0</td>
<td>1.8</td>
</tr>
<tr>
<td><em>wcaG::catΔ</em></td>
<td>0.9</td>
<td>trace</td>
</tr>
<tr>
<td><em>kpsM::kan</em></td>
<td>1.0</td>
<td>2.7</td>
</tr>
</tbody>
</table>
Table 2: \(^1\)H and \(^{13}\)C NMR data for the CPS isolated from *C. jejuni* wild type and isogenic mutants *wcaG::cat, mlghB::cat, mlghC::cat* and *wcaG::cat\(\Delta\).*

\(^{a}\): Data from this study.

\(^{b}\): The mutant *mlghC::cat* had essentially the same chemical shifts.

\(^{c}\): The mutant *wcaG::cat* had essentially the same chemical shifts.

\(^{d}\): Published data (McNally *et al.*, 2007).

\(^{e}\): Values without/with the MeOPN modification at position 3.

<table>
<thead>
<tr>
<th>Sugar residue</th>
<th>Atom or position</th>
<th>Type</th>
<th>Chemical shift (ppm)</th>
<th>Wild type (^{a})</th>
<th>Mutants (^{a,b})</th>
<th>Mutants (^{a,c})</th>
<th>NCTC 11168 (^{d})</th>
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<td>Rib</td>
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<td>5.38</td>
<td>5.36</td>
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<tr>
<td></td>
<td></td>
<td>δ(_C)</td>
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<td>105.9</td>
<td>106.0</td>
<td>106.1</td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td>δ(_C)</td>
<td>106.1</td>
<td>106.7</td>
<td>106.9</td>
<td>105.1/104.3(^e)</td>
<td>105.1/104.3(^e)</td>
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<td></td>
<td>3 CH</td>
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<td>4.93/4.23(^e)</td>
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<td>78.8/73.9(^e)</td>
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<tr>
<td></td>
<td>3 MeOPN</td>
<td>δ(_H)</td>
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<td>none</td>
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<td>99.0</td>
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<td>Hep</td>
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<td>none</td>
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<td></td>
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<td>none</td>
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<tr>
<td></td>
<td>6 MeO</td>
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<tr>
<td></td>
<td></td>
<td>δ(_C)</td>
<td>60.8</td>
<td>none</td>
<td>none</td>
<td>59.3</td>
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</tr>
</tbody>
</table>
Table 3. Comparison of motility for wild type and mutant strains.

The motility of the wild type and mutant strains were measured and compared quantitatively after stabbing into 0.3% agar and incubation for 48 hours under microaerobic conditions. The values shown are for the diameters of the motility halos, measured in centimeters. The mean and standard errors (SE) of three independent experiments are shown for each strain. In addition, the p value, as determined by one-way ANOVA, is shown. Compared to the wild type, all mutant strains were significantly reduced in motility.

<table>
<thead>
<tr>
<th>C. jejuni strain</th>
<th>Diameter of halo (cm) ± SE</th>
<th>p value</th>
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<tr>
<td>wild type</td>
<td>3.09 ± 0.09</td>
<td>N/A</td>
</tr>
<tr>
<td>wcaG::cat</td>
<td>2.35 ± 0.08</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>mlghC::cat</td>
<td>2.77 ± 0.06</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>mlghB::cat</td>
<td>2.73 ± 0.06</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>wcaG::catΔ</td>
<td>2.38 ± 0.10</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>kpsM::kan</td>
<td>0.00 ± 0.00</td>
<td>&lt; 0.01</td>
</tr>
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**Table 4: List of primers used to construct mutants and perform qRT-PCR analyses.**

When applicable, the restriction sites are indicated in bold letters.

<table>
<thead>
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<th>Primer name</th>
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<tr>
<td>Aph3 P1</td>
<td>GAAGATCTGATAAACCCAGCGAACA</td>
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<tr>
<td>Aph3 P2</td>
<td>AGGGTCCATGGGACATCTAAATCTAGGTC</td>
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<td>CatColi P2</td>
<td>GTGGTGATACCTTTATTTTCAGCAAGTCCTT</td>
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<td>CatColi P3</td>
<td>GTCATCGGGGCCCTTCTTTTCAAGTTAATTGCG</td>
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<tr>
<td>cj1427c P2</td>
<td>AGGGTCCATGGGACATCTAAATCTAGGTC</td>
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<td>GTGGTGATACCTTTATTTTCAGCAAGTCCTT</td>
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<td>kpsM P2</td>
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<td>RT1426R</td>
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<tr>
<td>RT1427F</td>
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<tr>
<td>RTAcCoAR</td>
<td>TAGCCCCAATCTTGGCACAAGCT</td>
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</table>
FIGURE LEGENDS:

**Fig. 1:** Schematic representation of the CPS from *C. jejuni* ATCC 700819 and organization of its CPS gene cluster. **Panel A:** The CPS unit comprises 4 sugars, including a 3-sugar linear backbone (sugars 1-3) that is attached to a phospholipid (PL) for anchorage in the membrane and a modified heptose (H) branch. The exact structure is also indicated and denotes additional modifications such as O-methyl phosphoramidate (MeOPN on GalNAc and heptose) and addition of ethanolamine (EtN) or 2-amino-2-deoxyglycerol (GroN) on GlcA (Karlyshev et al., 2005; McNally et al., 2007; St Michael et al., 2002). **Panel B:** Global organization of the CPS gene cluster (Karlyshev et al., 2005; Parkhill et al., 2000) showing the tripartite organization of CPS genes as well as the genes relevant to this study. Diagram not to scale.

**Fig. 2:** Simplified biochemical pathway highlighting the role of enzymes encoded by *wcaG, mlghB* and *mlghC* in the synthesis of *L*-gluco-heptose. Intricacies of this pathway were described earlier (McCallum et al., 2011; McCallum et al., 2012; McCallum et al., 2013). This figure only highlights the linear pathway from the manno-heptose precursor to the final product (additional intermediates excluded) as well as the side branch mediated by WcaG that decreases product formation via substrate scavenging. R represents OH or OMe. It is not known when methylation by *cj1426c* occurs along this pathway (as denoted by ?).

**Fig. 3:** SDS-PAGE analysis of the CPS produced by wild type and mutants. **Panel A:** CPS extracted by hot water/phenol method was analyzed on a 13 cm long gel with
detection by silver staining. Panel B: CPS obtained by SDS solubilization of total cells and proteinase K digestion of all proteins was analysed on a 5 cm gel. Detection was performed with anti-HS:2 Penner serotyping antibody (kindly supplied by Dr M. Karmali). The wcaG::cat mutant is not represented on panel B as no antibody was available anymore when the proper mutant was obtained.

Fig. 4: CPS structures of the wild type strain and the mutants. The structures are based on the data presented in Tables 1 and 2 and in supplementary Figures S1 and S2, and also take into account previously published data for the wild type strain (McNally et al., 2007; St Michael et al., 2002; Szymanski et al., 2003).

Fig. 5: qRT-PCR analysis of expression of capsular genes in the wild type and mutants. Panel A: Intra-strain comparison where the level of transcription of each gene is expressed relatively to housekeeping gene acetyl-CoA synthase in the same strain. Panel B: Inter-strain comparison where data from panel A are expressed relatively to wild type (Pfaffl, 2001). Cat and Kan denote the antibiotic resistance cassettes used for gene inactivation. Crosses for wcaG::catΔ denote deleted genes. Additional genes deleted in this mutant are not shown as their levels of transcription were not investigated. Small arrows indicate promoters inferred from differential transcription of neighboring genes in each individual data set. The +/- refers to standard error obtained from 2 independent experiments each including triplicate. Darker and darker shades indicate more and more deviation from housekeeping levels (Panel A) or from wild type levels (Panel B), red being for reduced levels and green for higher levels. ND: none detected. NA: not
applicable, used for kpsM in wcaG::catΔ and mlghC::cat where data could not be
calculated since levels were too low in the wild type reference but colors nevertheless
indicate higher transcription than in wild type in both strains, with a 10-fold difference
between wcaG::catΔ and mlghC::cat as per Panel A.

Fig. 6: Effect of mutations on growth rates, auto-agglutination and flagellum
production. Panel A: Growth curves in broth under microaerobic atmosphere
determined using Klett’s flasks over 24 h. Error bars represent SEM (standard error of the
mean) for 3 independent experiments with 1 reading/flask at each time point. Panel B:
Auto-agglutination quantitated by measuring the OD_{600nm} of the top layer of a static
bacterial suspension over time. Error bars represent SEM for 3 independent experiments
each including 3 replicates. The same color scheme applies as in panel A. *: p<0.01 by
one-way ANOVA (with Dunnett’s post test). Panel C: Phase contrast microscopic
examination of auto-agglutination for kpsM::kan compared with wild type (100x
magnification). Panel D: Electron microscopy analysis of flagella production in wild
type and kpsM::kan strains with uranyl acetate staining.

Fig. 7: Effect of mutations on resistance to bile salts and SDS. Panel A: Resistance to
various concentrations of bile salts. The bacteria were exposed to bile for 15 min under
microaerobic atmosphere at 37°C and serially diluted for enumeration of viable cells by
CFU counting. Panel B: Resistance to various concentrations of SDS. The cells were
exposed to SDS for 15 h and cell lysis was assessed by measuring the OD_{600nm}. The
legend is the same in both panels and is shown within panel B. Error bars represent SEM
for three independent experiments, each carried out with triplicates. Data for each replica were obtained from 2 CFU spots Panel A and 1 OD$_{600nm}$ read for Panel B.

**Fig. 8: Effect of mutations on resistance to serum. Panel A:** Resistance to various concentrations of serum for 1.5 h under microaerobic atmosphere at 37°C. **Panel B:** Time course of resistance to 20% serum. For both panels, viability was assessed by CFU counting. The legend is the same in both panels and is shown within panel A. Error bars represent SEM. Experiments performed 3 times independently with triplicates within each experiment and determination of CFU from 2 spots for each replica.

**Fig. 9: Effect of mutations on interactions with epithelial cells.** The bacteria were centrifuged onto cell monolayers to account for motility defects. **Panel A:** Adherence to Caco-2 cells measured after 5h incubation, with elimination of unbound bacteria by washing and CFU counting of bound bacteria. **Panel B:** Invasion of Caco-2 cells measured after 5 h incubation and after elimination of externally bound bacteria via gentamicin treatment. Live intracellular bacteria were enumerated via CFU counting after lysis of epithelial cells with Triton X-100. ND: none detected. Error bars represent SEM. *: p<0.05. **: p<0.01 by one-way ANOVA. Experiments performed 3 times with duplicates within each experiment and determinations from 2 CFU spots for each replica.

**Fig. 10: Effect of the mutations on colonization and persistence in chicken intestine.** Two day old chicks were orally gavaged with $10^7$ CFU and their caecal content in *C. jejuni* was determined after 5 days by CFU counting of plated caecal homogenate. **Panel**
A: Test of wild type and four mutants. **Panel B:** Test of wild type and one additional mutant. While experiments were performed following the same procedure, a slightly lower level of colonization and wider distribution of colonization levels were obtained for wild type in panel B compared with panel A, therefore, the data for the last mutant tested are displayed separately. For both panels, each data point represents an individual chick. The numbers at the top of the graphs are the number of chicks from which *C. jejuni* was isolated over the total number of chicks inoculated for each strain tested. The lower limit of detection for colonization was ~ 1.5 log CFU/g. Horizontal bars represent the median of each group. Significant differences (**** p< 0.0001; *** p<0.001; ** p<0.01; * p< 0.05) in colonization compared to wild type as determined by the Mann-Whitney test are indicated. A second experiment was performed with an inoculation dose of 10^6 and similar data were obtained (data not shown).
CPS composition and CPS cluster

Figure 1: Wong et al.
Figure 2: Wong et al.

Heptose modification pathway
99x99mm (300 x 300 DPI)
CPS gels
199x199mm (300 x 300 DPI)
WILD-TYPE

\[ 3,6-O-\text{Me}_2-D-\alpha-L-\text{glucoHepp}-(1-3) \]
\[ -2)-\beta-D-\text{Ribf}-(1-5)-\beta-D-\text{GalNAc}-(1-4)-\alpha-D-\text{GlcP}-A-(1- \]
\[ \text{EtN-6} \]

\textit{wcaG::cat, mlghB::cat, mlghC::cat} (trace)

\[ -2)-\beta-D-\text{Ribf}-(1-5)-\beta-D-\text{GalNAc}-(1-4)-\alpha-D-\text{GlcP}-A-(1- \]
\[ \text{MeOPN-3} \]
\[ \text{GroN/EtN-6} \]

\textit{wcaG::catΔ, mlghC::cat} (major)

\[ -2)-\beta-D-\text{Ribf}-(1-5)-\beta-D-\text{GalNAc}-(1-4)-\alpha-D-\text{GlcP}-A-(1- \]
\[ \text{GroN/EtN-6} \]
qRT-PCR analysis of CPS cluster
240x384mm (300 x 300 DPI)

Figure 5 Wong et al
Growth, agglutination and microscopy

Wong et al Figure 6

A

Growth (Klett units)

Time (h)

0 5 10 15 20 25

wild type
wspG:cat
wspH:cat
wspG::cat
wspH::cat
epsG:eps1
epsH:eps1

B

Turbidity of top layer (OD_{600})

Time (h)

0 1 2

WT kpsM::kan

C

WT kpsM::kan

D

WT kpsM::kan

0.6 μm

199x199mm (300 x 300 DPI)
Barrier function towards bile and SDS

Figure 7 Wong et al
Resistance to serum

Figure 8 Wong et al

Resistance to serum

278x360mm (300 x 300 DPI)
Figure 9 Wong et al

Interactions with epithelial cells

278x360mm (300 x 300 DPI)
Chicken colonization experiments
199x199mm (300 x 300 DPI)
chicken data and CPS structure for graphical abstract
59x39mm (300 x 300 DPI)
Graphical abstract for Wong et al 2015

80 words.

*Campylobacter jejuni* ATCC 700819 produces a capsule that is important for virulence and contains a modified heptose. Inactivation of any of the genes *wcaG, mlghB*, and *mlghC* involved in heptose modification leads to capsule lacking modified heptose and presenting altered MeOPN, EtN and NGro contents. This alters capsule barrier functions and interactions with intestinal cells and decreases colonization and/or persistence in the chicken gut. This demonstrates that these genes contribute to bacterial resistance against host defenses in the gastrointestinal tract.

**Legend for figure:**

Chicken caecum colonization by heptose modification mutants and schematic representation of their capsule composition.
Supplementary Table 1: List of primers used to construct complementation strains.

When applicable, the restriction sites are indicated in bold letters.

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<thead>
<tr>
<th>Primer name</th>
<th>Sequence (5’ – 3’)</th>
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<tr>
<td>KanFor1427</td>
<td>TAAATCGCTTTGCAAAATTTAATTAAGAAACCCAGC GAACCATTGG</td>
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<tr>
<td>23SrRNA.Bottom</td>
<td>ATAAGAATGCGGCGCGTCTTTGCACATTGCAGTCTTA</td>
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</table>
Legends to supplementary figures:

**Supplementary Fig. S1:** Parts of two-dimensional $^1$H, $^{31}$P HMBC spectra of CPS of the wild type strain and the mutants. One-dimensional $^1$H and $^{31}$P NMR spectra are shown along the horizontal and vertical axes, respectively.

**Supplementary Fig. S2:** Parts of two-dimensional $^1$H, $^{13}$C HSQC spectra of CPS of the wild type strain and the mutants. One-dimensional $^1$H NMR spectra are shown along the horizontal axis.

**Supplementary Fig. S3: Effect of mutations on interactions with RAW 267.4 murine macrophages. Panels A and B:** Time course of intracellular bacterial survival performed by CFU counting after elimination of extracellular bacteria by gentamicin treatment and lysis of macrophages by water. The data are expressed as % of original inoculum (panel A) or as a function of the initial bacterial load at time zero after gentamicin (GM) treatment (Panel B). Panel C: adherence to macrophages. Incubation was performed at 4°C to inhibit phagocytosis. Panel D: Time course of invasion of macrophages before gentamicin treatment. Error bars represent SEM. *: p<0.05 between wild type and kpsM::kan by one way ANOVA. Experiments performed 3 times independently with triplicates within each experiment and data acquisition from 2 CFU spots for each replica. For all panels, the bacteria were centrifuged onto the macrophages to account for motility defects and the legend is the same as in panel A.
Fig S1
Supplementary Figure S3 Wong et al

A

Survival (% of inoculum) vs Time after Gm (h)

B

Survival (% of time zero after Gm) vs Time after Gm (h)

C

Adhesion (% of inoculum) vs Wild-type, wcaG::cat, mlghC::cat, mlghB::cat, wcaG::catΔ, kpsM::kan

D

Uptake (% of inoculum) vs Time before Gm (h)