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Molecular Characterization of the viaB Locus Encoding the Biosynthetic Machinery for Vi Capsule Formation in Salmonella Typhi

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Abstract

The Vi capsular polysaccharide (CPS) of Salmonella enterica serovar Typhi, the cause of human typhoid fever, is an important virulence factor. The Vi biosynthetic machinery is encoded within the viaB locus composed of 10 genes involved in regulation of expression (tviA), polymer synthesis (tviB-tviE), and cell surface localization of the CPS (vexA-vexE). We cloned the viaB locus from S. Typhi and transposon insertion mutants of individual viaB genes were characterized in Escherichia coli DH5α. Phenotype analysis of viaB mutants revealed that tviB, tviC, tviD and tviE are involved in Vi polymer synthesis. Furthermore, expression of tviB-tviE in E. coli DH5α directed the synthesis of cytoplasmic Vi antigen. Mutants of the ABC transporter genes vexBC and the polysaccharide copolymerase gene vexD accumulated the Vi polymer within the cytoplasm and productivity in these mutants was greatly reduced. In contrast, de novo synthesis of Vi polymer in the export deficient vexA mutant was comparable to wild-type cells, with drastic effects on cell stability. VexE mutant cells exported the Vi, but the CPS was not retained at the cell surface. The secreted polymer of a vexE mutant had different physical characteristics compared to the wild-type Vi.

Introduction

The causative agent of the human systemic infection typhoid fever, Salmonella enterica subspecies I serotype Typhi (S. Typhi), expresses a capsular polysaccharide (CPS) known as Vi antigen (Vi). The Vi capsule provides S. Typhi with mechanisms to avoid host defenses [1,2] and it is important in enhancing infectivity and virulence [3,4,5]. Besides being an important virulence factor, the Vi is also a protective antigen and a vaccine based on purified Vi polysaccharide has been developed and licensed for use as a parenteral vaccine against typhoid fever [6].

Vi is a linear, acidic homopolymer of α-1,4-linked N-acetylglactosaminuronate (D-GalNAcA), variably O-acetylated at C-3. The O-acetyl groups make up most of the surface and the immunogenicity of Vi is closely related to the degree of O acetylation [7,8]. Key proteins involved in Vi capsule formation are encoded within a cluster of genes, known historically as the viaB locus [9], a region located on a 134 kb DNA island, termed Salmonella pathogenicity island 7 (SPI-7) within S. Typhi [10]. The S. Typhi viaB locus constitutes 10 genes involved in regulation of expression (tviA), biosynthesis (tviB to tviE), and cell surface localization of the Vi polysaccharide (vexA to vexE) (Figure 1A). Analysis of the bioinformatics signature of viaB highlighted the presence of a putative ATP-binding cassette (ABC) transporter and the absence of a homologue of wzy/wzx respectively. Therefore, biosynthesis of Vi is thought to be similar to E. coli group 2 CPS [11].

Vi expression in S. Typhi is under control of the ResB-ResC and OmpR-EnvZ two-component regulator systems [12,13,14] and when the complete viaB operon is expressed in Escherichia coli K12 a similar pattern of regulation can also be observed [15]. ResB-ResC and OmpR-EnvZ likely interact with TviA and regions upstream of the tviA promoter thereby linking Vi expression to environmental signatures such as osmolarity [16], TviA is an activator of the viaB operon and deletion of the tviA gene strongly decreases expression of the Vi capsule [17].

Biosynthesis of the Vi polysaccharide takes place in the cytoplasm and requires functional TviB, TviC, TviD and TviE proteins [17] (Figure 1B). TviB and TviC are involved in catalyzing the conversion of UDP-N-acetylgalactosamine (UDP-GlcNAc) to UDP-N-acetylgalactosaminuronate (UDP-GalNAcA), which serves as the building block for the assembly of the Vi polymer [18]. Assembly of the Vi polymer is dependent on functional expression of tviD and tviE [17]. The enzyme responsible for O-acetylation of the Vi polysaccharide has not yet been identified.

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Competing Interests: The authors have read the journal’s policy and have the following conflicts: M. Wetter, MK and M. Wacker are all GlycoVaxyn AG employees. M. Wetter, MK and M. Wacker own shares/stock options from GlycoVaxyn AG, and GlycoVaxyn AG was the funder for this study. This does not alter the authors’ adherence to all the PLOS ONE policies on sharing data and materials, as detailed online in the guide for authors.
Cell surface localization of the Vi polymer is dependent on functional expression of vexA, vexB, vexC, vexD and vexE (Figure 1B). The predicted lipoprotein VexA belongs to group B of the outer membrane polysaccharide export (OPX) proteins [19]. OPX proteins for which high-resolution structures have been solved include Wza [20], a protein essential for group 1 CPS expression on the surface of E. coli and the E. coli group 4 capsule protein GfcC [21]. The Wza protein forms an octameric structure that spans the outer membrane and protrudes into the periplasm, thereby forming a water-filled channel. One of the most extensively studied bacterial group 2 capsules is the K1 serotype of E. coli. The E. coli K1 capsular gene cluster encodes KpsD, which is the functional homologue of VexA. VexBC belong to the large family of ABC transporters whose members have been implicated in the transport of substrates across membranes. The E. coli K1 ABC transporter KpsMT is a close homologue of VexBC [22]. KpsM is a hydrophobic, integral inner membrane protein with six transmembrane domains whereas KpsT is a hydrophilic, peripheral inner membrane protein containing an ATP-binding domain. The functional transporter is proposed to consist of two subunits each of KpsM and KpsT. VexD and its homologous protein KpsE of E. coli K1 belong to a family called the polysaccharide copolymerases subfamily 3 (PCP-3) [19]. There is no structural information yet available about this subfamily but all PCP proteins have a characteristic membrane topology in which a large periplasmic loop is flanked by two transmembrane regions localized in the inner membrane. PCP-3 proteins might provide a periplasmic scaffold for linking the ABC transporter in the inner membrane with the OPX protein in the outer membrane therefore assembling the complete polysaccharide translocation machinery. VexE seems to be responsible for anchoring the Vi to the cell surface.

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Figure 1. Overview of the viaB operon and Vi capsular polysaccharide biosynthesis pathway. (A) Schematic diagram of the S. Typhi viaB operon. (B) The Vi antigen is a linear polymer of α-1,4-linked N-acetylgalactosaminuronate, nonstoichiometrically esterified with acetyl groups at the C-3. A TviB-catalyzed oxidation of UDP-N-acetylglucosamine (UDP-GlcNAc) followed by the TviC-catalyzed epimerization at the C-4 of UDP-N-acetylglucosaminuronate (UDP-GlcNAcA) results in the formation of UDP-N-acetylgalactosaminuronate (UDP-GalNAcA), the building block for Vi polymer formation. The Vi polymer is synthesized in the cytoplasm and assembly is dependent on TviD and TviE. The enzyme catalyzing the O-acetylation of the capsular polysaccharide has not yet been identified. Subsequent translocation of the polysaccharide to the cell surface follows an ATP-binding cassette (ABC) transporter-dependent process. The transporter consists of VexA, VexB, VexC and VexD. The precise function of VexE is equivocal although it might be involved in anchoring the Vi to the cell surface.
ization of viaB single gene mutants and their effect on biosynthesis and cell surface expression of the Vi CPS is reported here.

Results

Expression of the Vi capsule in E. coli DH5α

The low copy plasmid pGVXN158 was constructed using a 14.9 kb DNA fragment of S. Typhi BRD948 that harbors the 10 open reading frames of the viaB operon with around 900 bp upstream of the first gene tviA. Therefore the viaB operon contains the natural regulatory sequences and expression is not controlled by elements encoded on the plasmid backbone. E. coli DH5α was transformed with pGVXN158 whereupon the transformants changed colony morphology towards a smooth colony appearance, indicating the expression of a capsule. These cells could be agglutinated using a Vi specific antibody. Furthermore, these encapsulated cells were tested for susceptibility to infection by well characterized Vi phages that are part of the classical typing set [23,24,25,26,27]. All 7 Vi phage types were able to infect E. coli DH5α(pGVXN158) but not the plasmid free controls. Thus, using these simple methodologies the Vi produced by E. coli was indistinguishable from Vi expressed by the parenteral S. Typhi. Therefore, this Vi expression system harbored in E. coli DH5α was used for further analysis of the biosynthetic machinery assembling the Vi capsule.

Quantification and localization of the Vi in E. coli DH5α(pGVXN158) harboring single gene transposon insertions within viaB genes

Next the role of the individual genes of the viaB operon in Vi capsule expression was analyzed. For this purpose single genes within the viaB operon encoded on pGVXN158 were inactivated
by Tn5-mediated transposon insertion mutagenesis. To this end, *viaB* single gene insertion mutants in all of the genes except the regulator *viaA* were selected and the insertion site was mapped (Table 1). Washed cell pellets and the corresponding supernatants of overnight cultures from individual transposon insertion mutants were spotted onto nitrocellulose membranes and the presence of the Vi CPS was detected by immunoblotting using a monoclonal Vi specific antibody. To exclude polar effects on downstream genes, *viaD*:Tn5, *viaC*:Tn5, *viaB*:Tn5, *viaE*:Tn5, *viaC*:Tn5, *viaE*:Tn5, *viaD*:Tn5, *viaC*:Tn5, *viaE*:Tn5 transposon insertion mutants were complemented with the corresponding gene cloned and Vi expression was restored (data not shown). Detection of Vi polysaccharide in the individual *E. coli* DH5α(pGVXN158) transposon mutant derivatives revealed three distinguishable phenotypes (Figure 2A): i) a strong signal was detected with cell cultures from *E. coli* DH5α(pGVXN158) and *E. coli* DH5α(pGVXN158) harboring vex:A::Tn5 (pGVXN158 into:VexA), ii) an intermediate staining was associated with vex:B::Tn5 (pGVXN158 into:xvB), vex:C::Tn5 (pGVXN158 into:xvC), and vex:D::Tn5 (pGVXN158 into:xvD), whereas iii) no Vi was detected in cell cultures of *E. coli* DH5α carrying the empty plasmid control pGVXN157 or *E. coli* DH5α(pGVXN158) harboring tvi:B::Tn5 (pGVXN158 into:tviB), tvi:C::Tn5 (pGVXN158 into:tviC), tvi:D::Tn5 (pGVXN158 into:tviD), tvi:E::Tn5 (pGVXN158 into:tviE) or vex:E::Tn5 (pGVXN158 into:vexE). To determine if the detection of Vi observed in the vex:A::Tn5, vex:B::Tn5, vex:C::Tn5 or vex:D::Tn5 transposon insertion mutants was associated with surface expression of capsular Vi, slide agglutination and Vi phage infections were performed (Table 1). None of the cells harboring these transposon insertion mutants could be agglutinated with a Vi specific antibody and none of the tested mutants could be infected with either one of the seven Vi phages. Taken together these results indicate that Vi polysaccharide is still produced in cells expressing the *viaB* locus with a transposon insertion in *viaA*, *viaB*, *viaC* and *viaD* but this is not cell surface associated.

To generate a more detailed view about the quantities and the localization of the Vi polysaccharide produced in the different *viaB* insertion mutants, a sandwich ELISA was developed. With this method Vi polysaccharide contents were measured in the cell culture supernatant (extracellular Vi), in a suspension of washed cells that were fixed with paraformaldehyde (cell associated Vi), and in cell lysates. Intracellular Vi was defined using the difference in Vi measured in cell lysates and fixed cells (Figure 2B).

Table 1. Overview of transposon insertion mutants analyzed in this study.

<table>
<thead>
<tr>
<th>Plasmid</th>
<th>Tn5 insertion site</th>
<th>Immunoblotting</th>
<th>Agglutination</th>
<th>Phage infection**</th>
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</table>

*bp of insertion site from 3’ end of the gene/total length of gene.

**nd: not determined.
analyzed by transmission electron microscopy (TEM) and immunogold labeling of the Vi polysaccharide using the monoclonal anti-Vi antibody P2B1G2/A9 [28]. The specificity of the antibody was tested by immunogold labeling of DH5α cells carrying the empty plasmid pGVXN157 (Figure 3E). These cells do not express the Vi polysaccharide and practically no staining was observed. Figure 3A shows the normal cellular distribution of the Vi antigen in DH5α(pGVXN158). The images show encapsulated bacteria where the polysaccharide is mainly localized at the cell surface, but Vi antigen is also detectable in the periplasmic space and inside inclusion-like bodies within the cytoplasm.

As expected, the Vi polysaccharide was differently distributed within the cells carrying viaB transposon insertion mutant plasmids. In cells harboring vexA::Tn5 encoding a nonfunctional outer membrane polysaccharide export (OPX) protein, the Vi was mainly stained within large inclusion-like bodies and sometimes clustered at the inside of the inner membrane (Figure 3B). Vi accumulation at the cytoplasmic membrane might indicate the site of Vi translocation over the inner membrane or an accumulation due at a blocked pore complex. Very occasional labeling of filamentous Vi erupting externally from the cell surface was observed.

In cells expressing a nonfunctional ABC transporter ATP-binding protein VexC, DH5α(pGVXN158vexC::Tn5), the Vi was labeled in large inclusion-like bodies inside the cells (Figure 3C). Disruption of the transport motor in this mutant appears to completely block Vi translocation through the pore complex.

Cells harboring the vexE::Tn5 plasmid display a similar phenotype as seen in the vexC::Tn5 insertion mutant (Figure 3D). Vi was mainly stained within inclusion-like bodies inside the cells. The extracellular Vi detected by ELISA was not visualized in the extracellular spaces.

Defect of the outer membrane polysaccharide export (OPX) protein VexA results in cell instability

It was unexpected to detect large amounts of Vi in the cell culture supernatant and on the cell surface of E. coli harboring the vexA::Tn5 mutant derivative. In TEM very often only exceptionally cell surface associated Vi could be detected (Figure 3B) whereas using ELISA and immunoblotting (Figure 2) nearly wild-type levels of surface exposed capsular sugar were detected. One hypothesis to explain these observations would be, that cells have a functional transporter in the inner membrane but lack the outer membrane pore might show potential leakiness, therefore releasing the Vi due at a blocked pore complex. Very occasional labeling of filamentous Vi erupting externally from the cell surface was observed.

The Vi has been labeled with the immunogold technique by using an anti-Vi antibody. (A) E. coli DH5α cells expressing the wild-type viaB operon (pGVXN158) are shown. The Vi is mainly localized on the cell surface (CS) but is also stained in the periplasmic space (PP) and inside inclusion-like bodies within the cytoplasm (IB). (B) E. coli DH5α cells containing the viaB operon with a transposon insertion in vexA (pGVXN158vexA::Tn5), the outer membrane polysaccharide export (OPX) protein, are shown. Vi was mainly stained within large inclusion-like bodies (IB) and sometimes clustered at the inside of the inner membrane (CM). Very occasionally, filamentous Vi erupting from the cell surface was labeled. (C) E. coli DH5α cells containing the viaB operon with a transposon insertion in vexC (pGVXN158vexC::Tn5), the ATP-binding protein of the ABC transporter, are shown. The Vi polysaccharide was labeled in large inclusion bodies in the cytoplasm. (D) E. coli DH5α cells containing the viaB operon with a transposon insertion in vexE (pGVXN158vexE::Tn5) are shown. The Vi polysaccharide was labeled in large inclusion bodies in the cytoplasm. (E) As a control E. coli DH5α cells containing the empty plasmid pGVXN157 are shown. doi:10.1371/journal.pone.0045609.g003

agreement with the inability to agglutinate DH5α(pGVXN158vex- A::Tn5) cells, or infect these cells with a Vi phage.

Size exclusion chromatography of exported Vi produced by E. coli DH5α(pGVXN158) and a vexE::Tn5 transposon insertion mutant

The observed inability of Vi expressed by DH5α(pGVXN158vex- A::Tn5) cells to bind to nitrocellulose membranes or form a
capsule once transported to the cell surface lead to the hypothesis, that this polymer might have different physical properties compared to the wild-type polysaccharide. To further characterize these different Vi polymer species we radiolabeled the Vi and separated the purified polymers by size exclusion chromatography. DH5α(pGVXN157), DH5α(pGVXN158) or DH5α(pGVXN158-vexE::Tn5) cells were metabolically labeled with [3H]GlcNAc and Vi polysaccharide was purified from the cell culture supernatants. There was around 600–700 times more incorporation of radioisotopes into samples purified from cell cultures expressing Vi than from cells carrying the empty plasmid, indicating that the Vi polysaccharide has been labeled specifically (Table 2). Subsequently, [3H]Vi was analyzed by size exclusion chromatography using a Sephacryl S-1000 column. The elution profile revealed that the Vi produced by the vexE::Tn5 mutant derivative is clearly distinguishable from the one produced by E. coli DH5α(pGVXN158) (Figure 5). The wild-type Vi appears to have a uniform size distribution and the molecular size of the Vi polysaccharide was estimated to be 2×10⁶ kDa against dextran standards. The Vi polymer secreted by the vexE::Tn5 mutant derivative displayed a tailing of the peak in the earlier elution fractions indicating the presence of either longer polysaccharide chains or the presence of a polymer with a different Stokes radius.

**O-acetyl content of the Vi polysaccharide**

The ability of a Vi phage to infect a cell is dependent on the expression of a Vi capsule that is partially O-acetylated at the C-3 position of the N-acetylgalactosaminuronic acid polymer [29]. The bacterial enzyme responsible for this Vi polysaccharide modification has not yet been identified. PFAM analysis and other bioinformatics interrogations of the proteins encoded in the viaB locus did not identify a potential acetyltransferase gene. This suggests that any acetylase is located outside the viaB operon. The observation that a Vi phage is able to infect DH5α(pGVXN158) cells implies, that it is well O-acetylated. Furthermore, we speculated that the different elution profiles observed in the size exclusion chromatographic analysis of Vi produced by E. coli DH5α(pGVXN158) and a vexE::Tn5 transposon insertion mutant derivative could be due to a different degree of O-acetylation. We therefore determined O-acetyl contents of Vi produced by S. Typhi BRD948, E. coli DH5α(pGVXN158), DH5α(pGVXN158-vexC::Tn5) or DH5α(pGVXN158-vexE::Tn5) Vi polysaccharide of these derivatives was purified either from the cell culture supernatant (in S. Typhi BRD948, DH5α(pGVXN158) and DH5α(pGVXN158-vexC::Tn5)) or from cell lysates (in DH5α(pGVXN158-vexE::Tn5)). The O-acetyl content of the purified Vi preparations was then measured by the alkaline hydroxylamin method of Hestrin [30]. The average values of the O-acetyl content from three separate preparations are presented in Table 3. The O-acetyl content was comparable in all different derivatives, being around 2.5 mmol per gram of dried Vi polysaccharide, which corresponds to a level of O-acetylation of around 60%. These data show that the Vi produced in E. coli has a similar O-acetyl content as the Vi expressed by S. Typhi. The undistinguishable levels of O-acetylation of Vi purified from the cell lysate of DH5α(pGVXN158-vexC::Tn5) indicates that the O-acetylation reaction takes place in the cytosol and that the reaction is independent of polymer translocation. Furthermore, the inability of DH5α(pGVXN158-vexE::Tn5) to form a capsule does not correlate with different levels of O-acetylation of the Vi polymer.

![Figure 4. Detection of the cytosolic protein GroEL in cell culture supernatants of individual vex mutants.](image-url)

Either whole cells (wc) or supernatants (sn) of DH5α cells cultures carrying the indicated plasmids were separated by SDS-PAGE and after transfer to a nitrocellulose membrane, GroEL was detected by western blot using an anti-GroEL antibody. Supernatant samples were normalized by TCA precipitation to the optical density of the cell culture. In DH5α cells expressing the wild-type viaB operon (pGVXN158), GroEL is mainly detected in the cell pellet. In contrast, the supernatant of a vexA transposon insertion mutant (pGVXN158-vexA::Tn5) contains substantial amounts of the cytosolic marker protein, indicating cell instability.

![Figure 5. Size exclusion chromatography of exported Vi produced by wild type and vexE transposon insertion mutant.](image-url)

DH5α(pGVXN158) and DH5α(pGVXN158-vexE::Tn5) cells were metabolically labeled with [3H]GlcNAc and the Vi polysaccharide was purified from the cell culture supernatants. Purified [3H]Vi polysaccharide was analyzed by size exclusion chromatography using a Sephacryl S-1000 column. The elution profiles of the [3H]Vi preparations are shown. The void volume (v₀) and the inclusion volume (vᵢ) of the column are indicated.

**Table 2. Incorporation of [3H] into purified samples (counts/total mg protein).**

<table>
<thead>
<tr>
<th>Strain</th>
<th>Cpm mg⁻¹ protein</th>
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</tr>
<tr>
<td>DH5α(pGVXN158)</td>
<td>325'984.4</td>
</tr>
<tr>
<td>DH5α(pGVXN158-vexE::Tn5)</td>
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</tr>
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</table>

**Table 2.** Incorporation of [3H] into purified samples (counts/total mg protein).
Discussion

Typhoid fever remains a serious public health problem in many developing countries, with, according to conservative WHO estimates, 16 million cases occurring each year, including about 600,000 deaths. The Vi capsule plays an important role in S. Typhi virulence by increasing the infectivity of the pathogen and the severity of the disease. Parenteral vaccines based on purified Vi CPS have been licensed and are widely used. Yet, many aspects of the biosynthesis, export and capsule formation of this important polysaccharide remain unclear. Here, a detailed molecular characterization of the viaB operon, encoding the biosynthetic machinery for Vi capsule formation is reported.

O-acetylation of the Vi

The Vi CPS is a linear, acidic homopolymer of α-1,4-linked N-acetylgalactosaminuronate (D-GalNAcA) 60–90% O-acetylated at the C-3. The bulky nonpolar O-acetyl groups make up most of the surface of the Vi and complete O-deacetylation eliminates the immunogenicity of this CPS [7]. The bacterial enzyme capable of introducing this modification in the Vi has not yet been described. PFAM analysis of the proteins encoded in the viaB operon did not identify an O-acetyltansferase domain, indicating that the gene is located outside the viaB cluster in the S. Typhi genome. This situation has been demonstrated for the phase-variable O-acetylation of the group 2 capsule of E. coli K1. In this bacteria the modification is catalyzed by a prophage encoded O-acetyltransferase that is not linked to the capsular cluster [31].

Clearly the viaB operon can be functionally expressed in E. coli [15,32]. However, the Vi expressed in E. coli has not yet been thoroughly characterized and the presence of O-acetyl modifications was equivocal. We found that the Vi produced in E. coli is recognized by Vi phage types I–VII, thereby converting E. coli into a Vi phage susceptible bacteria. Recognition of Vi polymer by a Vi phage is dependent on the presence of O-acetyl groups at the C-3 position of the N-acetylgalactosaminuronate (GalNAcA) building blocks and it has been shown that phage particles have deacetylating properties [29]. A conserved protein domain carrying an acetyl esterase was found to be associated with at least one tail fiber gene for all Vi phages [33]. This implies that in contrast to the tip enzymes of K1 or K5 phages, that degrade the polysaccharide backbone, the Vi phages specifically target the acetyl modification on the sugar polymer. Besides the observed susceptibility to Vi phage infection, we could show through chemical analysis that the Vi produced in E. coli is substantially O-acetylated. In addition, a similar degree of O-acetylation could be measured in an intracellular Vi preparation produced by a transporter defective mutant (DH5α[pGVXN158 viaC::Tn5]), indicating that O-acetylation is taking place in the cytoplasm and that it is a translocation independent process.

Vi productivity in E. coli DH5α(pGVXN158) is higher compared to S. Typhi BRD948

It was observed that E. coli cells expressing the wild-type viaB operon produce around 6–7 times more Vi than S. Typhi BRD948. This observation could be explained by the presence of the viaB cluster in different copy numbers in the particular expression systems. The pLAFR1 plasmid derivative that contains the viaB cluster is reported to be present in 5–7 copies per cell [34], whereas S. Typhi BRD948 holds a single viaB operon. Furthermore, spontaneous loss of SPI-7 in Vi-negative S. Typhi has been reported in stored isolates [35]. The robust plasmid borne expression of the Vi might additionally account for the difference seen in CPS productivity. The observed high efficiency of wild-type Vi polysaccharide production in E. coli makes this strain a good model system to characterize Vi capsule formation and an interesting Vi production system.

tviBCDE is the minimal set of genes required for Vi polysaccharide synthesis

Our data confirm the results obtained by Virlogeux et al., 1995, that TviB, TviC, TviD and TviE are required for Vi polymer assembly. Firstly, no Vi could be detected in these individual transposon insertion mutants. Secondly, intracellular Vi was identified in E. coli cells carrying a plasmid encoding viaBCDE (results not shown). The latter result indicates that the Vi polymer is assembled in the cytoplasm and that assembly is independent of the translocation machinery. Similar results have been obtained with the well-characterized group 2 capsule of E. coli K1. It has been shown that cells harboring a plasmid encoding the biosynthetic region-2 genes alone can synthesize intracellular polysialic acid [36]. Additionally, synthesis of full-length polymer has been shown to occur in vivo and in a variety of transport-deficient backgrounds in vivo [37,38].

Synthesis and export of the Vi polysaccharide seem to be coupled processes

It appears to be common to group 2-like capsules that biosynthesis of intracellular polymer is independent of the sugar export machinery. However, Vi quantification in the different vexT::Tn5 transposon insertion mutants that encode the CPS transporter (vexA) by ELISA demonstrated different productivity in the individual mutants. Whereas DH5α(pGVXN158 vexA::Tn5) expressed almost wild-type levels of Vi, the CPS productivity in DH5α(pGVXN158 viaB::Tn5), DH5α(pGVXN158 viaC::Tn5) and DH5α(pGVXN158 viaD::Tn5) was greatly reduced. This result indicates that synthesis and export of the Vi are coupled processes. A reduction in endogenous glycosyltransferase activity has also been shown for E. coli K1 cells harboring export defects [22,37]. Moreover, the formation of a hetero-oligomeric complex consisting of both biosynthetic and export machinery has been demonstrated in E. coli K5 [39] and E. coli K1 [40]. It is possible that the predicted inner membrane associated components of the Vi transporter (VexB, VexC and VexD) interact with the cytoplasmic based biosynthetic machinery and that disruption of the transporter indirectly decreases biosynthesis of the Vi polymer by unknown mechanisms. It seems that this observed negative feedback mechanism between a non-functional exporter and the biosynthesis of Vi polymer does not exist when the outer membrane polysaccharide export protein VexA is nonfunctional. These mutant cells produce almost wild-type amounts of CPS. Furthermore, the Vi could sometimes be detected clustered against the inner membrane by transmission electron microscopy in DH5α(pGVXN158 viaA::Tn5) cells, which might indicate the forma-

Table 3. O-acetyl content of Vi.

<table>
<thead>
<tr>
<th>Strain</th>
<th>O-acetyl content (mmol g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. Typhi BRD948</td>
<td>2.4±0.2</td>
</tr>
<tr>
<td>DH5α(pGVXN158)</td>
<td>2.7±0.2</td>
</tr>
<tr>
<td>DH5α(pGVXN158 viaC::Tn5)</td>
<td>2.5±0.3</td>
</tr>
<tr>
<td>DH5α(pGVXN158 viaD::Tn5)</td>
<td>2.4±0.2</td>
</tr>
</tbody>
</table>

doi:10.1371/journal.pone.0045609.t003
tion of a functional complex between inner membrane export and biosynthesis components. Nevertheless, periplasmic accumulations of Vi could not be detected in these mutant cells as it has been described for E. coli K1 and K5 mutations in the homologous gene kpsD [41,42].

DH5α::pGVXN158(vexC::Tn5) cells accumulated the Vi polysaccharide in large intracellular, inclusion-like bodies as seen by transmission electron microscopy. This phenotype has also been described in E. coli K1 [38,43]. However, inactivation of the E. coli K1 ABC transporter protein KpsT, resulted in a slightly different localization of the K1 polymer within the cell, where it accumulated at discrete sites around the periphery of the cells, located against the cytosolic membrane.

High Vi expression and non-functional export machinery results in cell instability

Our data clearly demonstrate that the high levels of Vi produced in DH5α::pGVXN158(vexC::Tn5) cells is not cell surface exposed. These cells can neither be agglutinated using Vi specific antisera nor be infected by a Vi phage. In addition, transmission electron microscopy pictures of these mutant cells do not show a capsule but intracellular accumulations of the Vi polymer. Substantial amounts of the cytosolic protein GroEL could be detected in the cell culture supernatant, indicating that large amounts of Vi produced by this export deficient mutant destabilize the cell. The Vi detected in the cell culture supernatant and in fixed cells by ELISA and immunoblot represents therefore not translocated but rather released polysaccharide from lysed cells. In transporter deficient mutants showing reduced Vi assembly activity (DH5α::pGVXN158(vexB::Tn5)), DH5α::pGVXN158(vexA::Tn5) and DH5α::pGVXN158(vexD::Tn5)) less GroEL was detected in the cell culture supernatant compared to the vexA::Tn5 transposon insertion mutant. It seems that the level of Vi biosynthesis in transporter deficient mutants correlates with cell instability. The observed destabilizing effect of intracellular CPS accumulations on cell integrity also underlines the necessity that assembly and export have to be coupled and coordinated processes. However, the observed phenotype of a vexE mutant might be less pronounced in a S. Typhi where the Vi polysaccharide is not overexpressed.

Retention of the Vi polysaccharide on the cell surface is dependent on VexE

VexE shows no homologies to other proteins encoded in group 2-like capsular gene clusters and it is exclusively found in the viaB operon. PFAM analysis of VexE identified a C-terminal acyltransferase domain also found in HtrB (LpxL), an enzyme involved in Kdo2-Lipid A biosynthesis. Vi quantification by ELISA demonstrated, that Vi production in DH5α::pGVXN158(vexE::Tn5) cells was only slightly decreased compared to E. coli cells expressing the wild-type viaB operon. The Vi polysaccharide produced by a vexE::Tn5 mutant is mainly found in the cell culture supernatant as determined by ELISA. There was no Vi visualized in the extracellular spaces by TEM and immunogold labeling, but this could be lost during sample preparation. Together, these results indicate that the Vi in a vexE::Tn5 mutant is efficiently translocated to the cell surface, but once translocated, the polysaccharide is not retained on the cell surface but is rather secreted. Therefore these mutant cells can neither be agglutinated using Vi specific antisera nor be infected by a Vi phage. Besides the observed inability of this Vi species to form a capsule, the polysaccharide also does not bind to nitrocellulose membranes, indicating that this species has different physical characteristics compared to the wild type Vi. We can rule out that the observed properties are due to a different degree in O-acetylation because in both Vi preparations a similar O-acetyl content was determined. However, these observations might be explained by a lipid modification that is introduced by the acyltransferase-like enzyme VexE. In addition, the polysaccharide produced by a vexE::Tn5 mutant displays a broader size distribution compared to the wild-type Vi on a Sephacryl S-1000 column. This lipid modification might lead to a different stoke radius, explaining the different behavior in size exclusion chromatography. It is equivocal if the observed phenotype of a vexE mutant plays a biological role. It might be possible that S. Typhi can switch between a capsule producing and a Vi secreting state during different stages of pathogenesis by regulating VexE activity. The precise function of VexE in Vi capsule formation should be addressed in future research.

Conclusions

In summary, we conclude that the Vi capsule biosynthesis shows many characteristics that are typical for group 2-like capsules. The Vi is completely assembled in the cytoplasm by the gene products of vexBCDE, and is subsequently transported to the cell surface by an ABC transporter encoded by vexABCD, that closely resembles the transporters of the Haemophilus influenzae type b and Neisseria meningitidis group B CPSs. However, several genes indicative for E. coli group 2 capsular gene clusters, like kpsFU and kpsSC, that are believed to be involved in CMP-Kdo synthesis and the speculative addition of a diacylglycerophosphate-Kdo to the CPS [11], are absent in the viaB operon. In contrast, the viaB operon contains a gene, vexE, uniquely found in this cluster and possibly involved in lipidation of the Vi polysaccharide. Despite sharing the basic mechanism of group 2-like capsule formation, biosynthesis of the Vi capsule displays features uniquely found in this cell surface structure.

Materials and Methods

Strains, plasmids, and culture conditions

All bacterial strains and plasmids used in this study are listed in Table 4. Construction of the plasmids is described below. E. coli DH5α and EC100 were grown in LB medium (10 g tryptone, 5 g yeast extract, and 5 g NaCl per liter) or on LB agar (LB medium with the addition of 15 g agar per liter) at 37°C. S. Typhi BRD948 [44] was grown in LB medium supplemented with 1% v/v Aro mix (40 mg L-phenylalanine, 40 mg L-tryptophan, 10 mg 4-aminobenzoic acid, and 10 mg 2,3-dihydroxybenzoic acid in 10 ml of ddH2O) and 1% v/v Tyrr mix (40 mg L-tyrosine disodium salt in 10 ml ddH2O) at 37°C. If appropriate, the media contained tetracycline (20 μg ml⁻¹), trimethoprim (100 μg ml⁻¹), or kanamycin (50 μg ml⁻¹). Cells containing pEXT22 derivatives were grown in the presence of 1 mM isopropyl β-D-1-thiogalac-toopyranoside (IPTG).

DNA manipulations

Plasmid DNA was isolated using the NucleoSpin Plasmid or NucleoBond Xtra Maxi Plus kit (Macherey-Nagel). Total chromosomal DNA was isolated using NucleoSpin Tissue Kit (Macherey-Nagel). Restriction enzymes (Fermentas), shrimp alkaline phosphatase (Fermentas), T4 DNA ligase (Fermentas), and Phusion High-Fidelity DNA polymerase (Finzyme) were used according to the manufacturer’s instructions. PCR and restriction fragments were purified for cloning using the NucleoSpin Extract II kit (Macherey-Nagel). All DNA sequencing was completed by Synergene Biotech GmbH (Switzerland) and synthetic oligonucleotides were ordered at Microsynth AG (Switzerland).
Membranes were incubated with a monoclonal anti-Vi antibody in 10% milk in PBST for 1 h on a shaker at room temperature (RT). After washing the membrane 3 times with PBST the membranes were incubated with a horseradish peroxidase labeled goat anti-mouse IgG (Sigma, A9824) diluted 1:2000 in 1% milk in PBST. Membranes were developed using 3,3’,5,5’-tetramethylbenzidine (TMB) liquid substrate system for membranes (Sigma). Antibody detection of Vi antigen on washed cells and in cell culture supernatants.

Antibody detection of Vi antigen on washed cells and in cell culture supernatants

After washing the membranes 3× with PBST the membranes were incubated with a horseradish peroxidase labeled goat anti-mouse IgG (Sigma, A9824) diluted 1:2000 in 1% milk in PBST. Membranes were developed using 3,3’,5,5’-tetramethylbenzidine (TMB) liquid substrate system for membranes (Sigma).

Sample preparation for measuring Vi content by ELISA

1 ml of an overnight culture was centrifuged 5 min at 20,000 g using an eppendorf microcentrifuge. The supernatant was separated from the cell pellet and used to measure Vi content. The pellet was washed 3× with PBS and divided into two
Vi quantification by ELISA
Vi polysaccharide content of samples was measured using a sandwich ELISA. Two monoclonal Vi specific mouse antibodies P2B1G2/A9 (IgG1, coating antibody) and P5B2D8/A9 (IgM, primary antibody) were used in the ELISA and are described elsewhere [28]. In order to saturate the binding of the Vi to the ELISA plate, the coating antibody P2B1G2/A9 was partially purified from the hybridoma supernatant using a 5 ml Hitrap Protein A HP column (GE Healthcare). Briefly, 50 ml of P2B1G2/A9 hybridoma supernatant were diluted 1:10 with binding buffer (20 mM sodium phosphate, pH 7.5) and loaded on the Protein A column using a peristaltic pump at a flow rate of 20 ml min \textsuperscript{-1}. The column was eluted with 100 mM citric acid pH 3.25 and 1 ml fractions were collected. The tubes destined to collect the antibody fractions contained 100 µl 1 M Tris-HCl, pH 9.0 to instantly neutralize the sample.

Flat bottom 96 well micro-titer plates (Nunc immuno MaxiSorb) were coated with 50 µl of the partially purified antibody P2B1G2/A9, diluted 1:100 in PBS, at 4°C overnight. The coating solution was poured away and the plate was submerged and vigorously agitated in 4000 ml of wash buffer (1× PBS with 0.05% Triton ×100). This washing step was performed at least 4 times to completely wash out unbound antibody. Subsequently, the plate was dried by spinning upside down in a micro plate rotor. This washing procedure was always applied in further washing steps. Each well was completely filled with 300 µl of blocking buffer (1× PBS with 2.5% BSA (globulin free BSA, Sigma, A7030) and incubated 2 h at RT on a plate shaker. After washing and drying the plate the sample was applied in an appropriate dilution in dilution buffer (1× PBS with 0.5% BSA). As a standard, Vi polysaccharide (Typhim Vi, Sanofi Pasteur MSD) was used in several dilutions in the range from 0–4 ng ml \textsuperscript{-1}. 100 µl of sample and standard were applied in doublucates to the corresponding wells and incubated 1 h at RT on a plate shaker. After washing and drying the plate, 100 µl of the primary antibody (hybridoma supernatant of P5B2D8/A9) diluted 1:100 in dilution buffer was added to the wells and incubated 1 h at RT on a plate shaker. After another washing and drying step the wells were incubated with 100 µl of secondary antibody (goat anti-mouse IgM peroxidase conjugated, Sigma A8786) diluted 1:2000 in dilution buffer for 1 h at RT on a plate shaker. Following washing and drying the reaction was developed with 100 µl of Ultra TMB substrate (3,3',5,5'-tetramethylbenzidine liquid substrate, Pierce) for 15 min and stopped with the addition 100 µl of 2 M sulphuric acid. The bottom surface of the plate was wiped with 70% 2-Propanol and the absorption at 450 nm was measured.

Vi polysaccharide purification
Vi polysaccharide was purified by a modified procedure as described elsewhere [43]. The Vi was either purified from the cell culture supernatant (in strains Δ Typhi BRD948, DH5α[pGVXN158] and DH5α[pGVXN158,::Tn5]) or from sonicated cells that were treated with proteinase K and nucleases (in strain DH5α[pGVXN158,::Tn5]). Vi was precipitated from the supernatant or enzyme treated cell lysate with 0.1% hexadecyltrimethylammonium bromide (CTAB, Sigma, H6269). 20 g l \textsuperscript{-1} cell 543 (Sigma, 20199-U) was added and the mixture was stirred for 1 h at RT in order to allow the formation of a polysaccharide-CTAB complex, which adsorbs onto the cells. The cell was poured into a reservoir of appropriate size (Extract-clean EV SPE Reservoir, Socochim S.A.) equipped with a frit (Socochim S.A.). The column was washed successively by gravity flow with 10 column volumes (CV) of 0.05% CTAB, 10 CV of 20% ethanol, 50 mM sodium phosphate buffer pH 6.0, and 15 CV of 45% ethanol to eliminate adsorbed impurities. The Vi polysaccharide was finally eluted with 1.5 CV of 50% ethanol, 0.4 M NaCl. Following elution, the polysaccharide was precipitated by addition of ethanol to a final concentration of 80% and incubation for 20 min at RT. The precipitate was washed twice with 80% ethanol prior to lyophilization. The protein and nucleic acid content of the purified Vi polysaccharide was determined by the bichinchenic acid assay (BCA, Pierce) and UV spectroscopy respectively.

Determination of O-acetyl content in the Vi polysaccharide
The method was used as described elsewhere [30]. Briefly, the O-acetyl groups were released by mild base treatment of the Vi polysaccharide solution. The O-acetyl groups reacted with the added hydroxylamine in alkali to form hydroxamic acid. The formed hydroxamic acid was measured by the formation of a purple-brown complex with Fe\textsuperscript{3+}. Acetylcholine was used as a standard.

Radiolabeling of Vi polysaccharide
Cells were cultured in LB medium supplemented with antibiotics at 37°C in the shaker incubator (180 rpm). Cultures were inoculated from an overflow culture to an A\textsubscript{600} of 0.01. After 4 cell doublings, 1 µCi ml \textsuperscript{-1} \textsuperscript{3}H]GlcNAc (American Radiolaabeled Chemicals, Inc., ART 0142) was added and the culture was incubated 2 h at 37°C in the shaker incubator. After incubation the cells were centrifuged and the cell culture supernatant was used to purify the labeled Vi polysaccharide as described above. After drying of the purified Vi, the polysaccharide was resuspended in 50 mM NaCl. Incorporation of radioactivity in the purified samples was measured and normalized to the protein content measured in the cell pellets.

Size exclusion chromatography
Sephacryl S-1000 (GE Lifescience) gel filtration medium was used in a column with the proportions of 23 cm x 1.7 cm (height x diameter). Chromatography was done by gravity flow using 50 mM NaCl as the mobile phase and 1 ml fractions were collected.

Transmission Electron Microscopy (TEM)
TEM was done as described elsewhere [46].

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Author Contributions
Conceived and designed the experiments: M. Wetter MK CJW GD M. Wacker. Performed the experiments: M. Wetter DG DP. Analyzed the
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data: M. Wetter DG DP CJW GD M. Wacker. Contributed reagents/

References


