MINIREVIEW

The sweet side of the pathogenic Neisseria: the role of glycan interactions in colonisation and disease

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One sentence summary: Glycosylation of the surface of meningococci and gonococci, and interactions with glycan structures of the host, are essential for pathogenic Neisseria colonisation and disease.

ABSTRACT

Glycomics is a rapidly growing field that focuses on the structure and function of carbohydrates (glycans) in biological systems. Glycan interactions play a major role in infectious disease, at all stages of colonisation and disease progression. Neisseria meningitidis, the cause of meningococcal sepsis and meningitis, and Neisseria gonorrhoeae, which causes the sexually transmitted infection gonorrhoea, are responsible for significant morbidity and mortality worldwide. Neisseria meningitidis displays a range of surface glycosylations including capsule polysaccharide, lipooligosaccharide and O-linked glycoproteins. While N. gonorrhoeae does not have a capsule, it does express both lipooligosaccharide and O-linked glycoproteins. Neisseria gonorrhoeae also has the ability to scavenge host sialic acids, while several N. meningitidis serogroups can synthesise sialic acid. Surface expressed sialic acid is key in serum resistance and survival in the host. On the host side, the pathogenic Neisseria protein adhesins such as Opc and NHBA bind to host glycans for adherence and colonisation of host cells. Essentially, from both the bacterial and host perspective, glycan interactions are fundamental in colonisation and disease of pathogenic Neisseria. The key aspects of glycobiology of the pathogenic Neisseria are reviewed herein.

Keywords: Neisseria gonorrhoeae; Neisseria meningitidis; glycomics; carbohydrate; lectin; host–pathogen interactions

INTRODUCTION

Carbohydrates (glycans) and carbohydrate-recognising proteins (lectins) play significant roles in a diverse range of interactions within organisms, as well as between different organisms (Varki and Sharon 2009). Glycans are extremely diverse; there are 10 basic monosaccharide building blocks, and chains of monosaccharides can vary in length, have a range of different linkages and can be linear or branched. These macromolecules are present in all forms of life, and can be found as free oligo- or polysaccharide chains, or as glycoconjugates when attached to proteins or lipids. Protein glycosylation is one of the most common post-translational modifications and enhances the functional diversity of proteins produced by an organism. For example, most mammalian cell surface receptors and almost all serum proteins are glycosylated (Apweiler, Hermjakob and Sharon 1999). Consequently, human cells are covered by a glycocalyx, a rich surface coat of glycans (Varki and Sharon 2009), that is important for mediating interactions with other cells and molecules. Furthermore, glycan interactions between microbes and host cells play a major role in bacterial colonisation and disease (Esko and Sharon 2009).

The pathogenic Neisseria, Neisseria meningitidis and N. gonorrhoeae, display extensive glycosylation of bacterial surfaces...
and structures, and interaction with host glycans is crucial for colonisation and disease. The pathogenic Neisseria are closely related obligate human pathogens that share 80%–100% DNA homology, with conservation of the majority of genes (Klee et al. 2000). Several of the same bacterial surface structures are involved in initial colonisation of mucosal surfaces by these bacteria (Merz and So 2000); however, they cause distinct diseases. Neisseria meningitidis asymptomatically colonises the upper respiratory tract of ∼10%–20% of the population, but also poses a significant health problem due to its ability to cause life-threatening meningitis and septicaemia (Rouphael and Stephens 2012). Despite the availability of effective antibiotics, and vaccines for five serogroups, there are an estimated 1.2 million cases and ∼135 000 deaths attributed to meningococcal disease, each year, worldwide (Rouphael and Stephens 2012). Neisseria gonorrhoeae, the causative agent of the sexually transmitted infection gonorrhoea, is a growing global public health threat. Infection typically results in urethritis in males and cervicitis in females; however, asymptomatic cases are common, and untreated gonorrhoea can lead to serious sequelae, including infertility and increased HIV transmission (reviewed in Edwards et al. 2016). There are estimated to be more than 106 million cases of gonorrhoea worldwide each year (World Health Organization and Research 2012). Furthermore, there is no available vaccine and the continuing emergence of antibiotic-resistant strains raises concerns that gonorrhoea may become untreatable in the near future (Unemo and Shafer 2014).

In terms of glycosylated surface structures, N. meningitidis is a capsulate organism, and both N. meningitidis and N. gonorrhoeae express lipooligosaccharide (LOS) and glycosylate some of their proteins (Fig. 1). Several of these structures mediate host-pathogen interactions and are involved in virulence. In addition, human host microenvironments are highly glycosylated (Varki, Esko and Colley 2009) and the pathogenic Neisseria targets specific host glycan structures for adherence and colonisation of host cells. In this review, the current knowledge regarding the glycans present on the Neisserial surface and the host glycans known to interact with Neisseria is discussed. There is a focus on N. meningitidis, with key points of difference or interest highlighted for N. gonorrhoeae. An overview of the glycan-rich host environments inhabited by the pathogenic Neisseria highlights the potential for additional glycan-based interactions during various stages of colonisation and disease.

GLYCAN STRUCTURES OF THE PATHOGENIC NEISSERIA

Meningococcal polysaccharide capsule

The meningococcal capsule is a high molecular weight polysaccharide, which is linked to the bacterial surface by a glycolipid moiety (Tzeng et al. 2005). Neisseria meningitidis strains can be classified into 13 serogroups, based on structural differences in their capsular polysaccharides (see Table 1). Six serogroups cause the majority of invasive meningococcal disease worldwide (serogroups A, B, C, W135, X and Y) (Rouphael and Stephens 2012). The polysaccharides differ in their individual monomers and/or linkages between these monomers (Harrison et al. 2013) (Table 1). Capsule polysaccharide-based vaccines are available for serogroups A, C, W and Y. However, the α(2–8)-linked sialic acid homopolymer of the N. meningitidis serogroup B capsule is identical to that produced in mammalian cells (Finne, Leinonen and Mäkelä 1983), and due to this molecular mimicry of host glycans, the serogroup B capsule is poorly immunogenic and has not been used in vaccine development.

The polysaccharide capsule is crucial for invasive meningococcal disease (Spinosa et al. 2007), and it is universally expressed by strains isolated from the blood and cerebrospinal fluid (Stephens, Greenwood and Brandtzaeg 2007) The meningococcal capsule increases resistance to the complement-mediated bactericidal activity of human serum, and resistance to oposonophagocytosis (reviewed in Lewis and Ram 2014). Carriage strains isolated from the nasopharynx of healthy individuals may or may not be encapsulated (Corbett et al. 2004). The
Table 1. Structures of meningococcal polysaccharide capsules.

| Serogroup | Glycan repeat unit | Linkage | Description                                                                 | Ref                           |
|-----------|-------------------|---------|------------------------------------------------------------------------------|-------------------------------|
| A         | ManNAc-1-phosphate | α1→6 (phosphodiester) | Homopolymer of α1→6 linked N-acetyl-D-mannosamine-1-phosphate                  | Liu et al. (1971)             |
| B         | Neu5Ac            | α2→8 (glycosidic)    | Homopolymer of α2→8-linked sialic acid                                         | Bhattacharjee et al. (1975)   |
| C         | Neu5Ac            | α2→9 (glycosidic)    | Homopolymer of O-acetylated or non-acetylated α2→9-linked sialic acid          | Bhattacharjee et al. (1975)   |
| D         | Not elucidated    | –       | –                                                                            | –                             |
| E         | GalNAc3 -7KDO     | β2→3 (glycosidic)    | Alternating D-galactosamine (GalN) and 2-keto-3-deoxyoctulosonate (KDO) residues | Bhattacharjee et al. (1978)   |
| H         | Gal1-2 Gro-3-phosphate | Phosphodiester | Partially O-acetylated Galactosyl glycerol-3-phosphate units                    | Van Der Kaaden et al. (1984)  |
| I         | LGulNAcα1-3 ManNAcA | β1→4 (glycosidic) | O-Acetylated alternating N-acetyl-guluronic acid and N-acetyl-mannosaminuronic acid residues | Michon et al. (1985)          |
| K         | ManNAcβ1-4 ManNAcA | β1→3 (glycosidic)    | O-Acetylated N-acetylmannosaminuronic acid disaccharide repeat units            | Van Der Kaaden et al. (1985)  |
| L         | GlcNAcβ1-3GlcNAcβ1-3GlcNAc-1-phosphate | Glycosidic and Phosphodiester | Heteropolymer of a trimeric repeating unit                                    | Jennings et al. (1983); Litschko et al. (2015) |
| W-135     | Galα1-4Neu5Sα     | α2→6 (glycosidic)    | Heteropolymer of alternating sequences of D-galactose and sialic acid         | Bhattacharjee et al. (1976)   |
| X         | GlcNAc-1-phosphate | α1→4 Phosphodiester  | Homopolymer of (α1→4)-linked N-acetylgulosaminuronic acid-phosphate              | Bundle et al. (1974)          |
| Y         | Glcα1-4Neu5Ac     | α2→6 (glycosidic)    | Heteropolymer of alternating sequences of D-glucose and sialic acid            | Bhattacharjee et al. (1976)   |
| Z         | GalNAcα1-1Gro-3-phosphate | Phosphodiester | Monosaccharide glycerol-3-phosphate repeat units                               | Harrison et al. (2013)        |

Absence of capsule can be either due to the complete absence of the capsule production genes, known as the capsule-null (cnl) phenotype (Claus et al. 2002), or due to phase variation (i.e. ON/OFF or graded switching of expression). Two mechanisms of phase variation have been described, slipped strand mispairing of the poly-cytosine tract present within siaD and the insertion/excision of the insertion sequence IS1301 in siaA (Hammerschmidt et al. 1996a,b). In addition, capsule expression is regulated by RNA thermoregulation, with increased temperature up-regulating cssA translation and consequently, capsule expression (Loh et al. 2013). The two-component MisR/MisS system negatively regulates capsule expression, with inactivation of misR and misS resulting in increased capsule expression (Tzeng et al. 2008). The regulation of capsule is reviewed in detail elsewhere (Bartley and Kahler 2014; Tzeng, Thomas and Stephens 2016).

It has been suggested that capsule may block interactions with host cells due to steric hindrance and masking of surface adhesins involved in intimate cellular interactions, as well due to the negative charge of its sialic acid residues (Corbett et al. 2004; Virji 2009). Therefore, phase variation and regulation of capsule expression allows the bacteria to adapt to the different stages of infection, i.e. the expression of the capsule is decreased during colonisation but present during invasive disease (Hammerschmidt et al. 1996b; Stephens, Greenwood and Brandtzaeg 2007).

Meningococcal and gonococcal LOS

LOS makes up ~75% of the outer membrane of Gram-negative bacteria such as the pathogenic Neisseria (Gronow and Brade 2001). Neisserial LOS consists of lipid A that anchors the LOS into the outer membrane, an inner core composed of two 3-deoxy-D-manno-2-octulosonic acid (KDO) and two heptose residues (Hep1 and Hep2 residues), and an outer core of oligosaccharide chains (α, β, γ) attached to the heptose residues (Jennings et al. 1999). The individual sugars in each of the oligosaccharide chains are sequentially added onto the elongating chain by
The interaction between the gonococcal LOS with the asialoglycoprotein receptor (C-type lectin) (Harvey et al. 2001). This interaction is abated in mutants expressing truncated LOS that lack the LNnT structure, and in strains expressing a terminal sialic acid on their LOS (Harvey et al. 2001). Gonococcal LOS sialylation decreases non-opsonic, opacity-associated uptake by neutrophils (Rest and Frangipane 1992) and allows direct interaction of gonococcal LOS with factor H (Ram et al. 1998), thus promoting serum resistance. Interestingly, LOS sialylation also allows interaction of the pathogenic Neisseria with human myeloid cells, via the sialic acid-binding immunoglobulin-like lectins expressed on some phagocytic cells, thereby making the bacteria more susceptible to phagocytosis (Jones, Virji and Crocker 2003).

### Glycosylated proteins

Post-translational modification of proteins with glycan moieties (glycosylation) is ubiquitous in nature and is important for protein function. The PilE subunit of pilin and the nitrite reductase AniA are the best characterised Neisserial glycoproteins. The pathogenic Neisseria express type IV pilin, which are homopolymeric multimers of a 17–21 kDa polypeptide units (pilin/PilE) that can extend several micrometers from the bacterial cell surface. In Neisseria, type IV pilins have been grouped in class I or class II pilin. The class I and II pilin genes are present in different genomic locations (Wormann et al. 2014): class I pilin (but not class II) is recognised by the SM1 antibody (Virji et al. 1989) and class II pilin are restricted to strains from certain clonal complexes (cc1, cc5, cc8, cc11 and cc174) (Wormann et al. 2014). These pilin undergo many post-translational modifications, including glycosylation at serine 63 (Stimson et al. 1998) and glycosylation of up to five sites on class II pilins (Kahler et al. 1991) with human myeloid cells, via the sialic acid-binding immunoglobulin-like lectins expressed on some phagocytic cells, thereby making the bacteria more susceptible to phagocytosis (Jones, Virji and Crocker 2003).

### Table 2. Oligosaccharide structures of meningococcal LOS immunotypes.

| α-chain | β-chain | γ-chain | II PEA | Ref |
|---------|---------|---------|--------|-----|
| L1      | aGal1–4Galβ1–4Glc | – | GlcNAcα1–2 | 3P | Di Fabio et al. (1990), Griffiss et al. (2000) |
| L2      | aGal1–4GlcpNAcα1–3Galβ1–4Glc | Glcp α1–3 | bGlcNAc α1–2 | 6P | Gamian et al. (1992) |
| L3      | aGal1–4GlcpNAcα1–3Galβ1–4Glc | – | GlcNAc α1–2 | 3P | Pavliak et al. (1993) |
| L4      | aGal1–4GlcpNAcα1–3Galβ1–4Glc | – | bGlcNAc α1–2 | 6P | Kogan et al. (1997) |
| L5      | aGal1–4GlcpNAcα1–3Galβ1–4Glc | Glcp α1–3 | bGlcNAc α1–2 | – | Michon et al. (1990) |
| L6      | 4GalNAcα1–3Galβ1–4Glc | – | GlcNAc α1–2 | 6P | Di Fabio et al. (1990) |
| L7      | Galβ1–4GlcNAcα1–3Galβ1–4Glc | – | GlcNAc α1–2 | 6P | Kogan et al. (1997) |
| L8      | Galβ1–4GlcNAcα1–4Glc | – | GlcNAc α1–2 | 3P | Griffiss et al. (2000) |
| L9      | Galβ1–4GlcNAcα1–3Galβ1–4Glc | – | GlcNAc α1–2 | 6P | Choudhury et al. (2008) |
| L10     | Galβ1–4GlcNAcα1–3Galβ1–4Glc | – | GlcNAc α1–2 | 3P/6P | Kim et al. (1994) |
| L11     | Glcβ1–4Glc | – | GlcNAc α1–2 | 3P&6P | Kim et al. (1994), Mästrettta et al. (2010) |

*aTerminal Gal of α-chain is often partially sialylated.

*bPartial O-acetylation of the α-D-GlcNAc (of the γ-chain) observed. Phosphoethanolamine (PEA) substituents at O-3 or O-6 of Hep II = 3P or 6P, respectively.
Gal[α1,3]GlcNAc disaccharide is present in this same position on pili of gonococcal and some meningococcal strains (reviewed in Banerjee and Ghosh 2003; Bartley and Kahler 2014). It has also recently been shown that Gal and GlcNAc residues can be O-acetylated, and O-acetylation impacts oligosaccharide chain length (Anonsen et al. 2017).

Neisserial pili are considered to be the primary adhesins involved in early adherence events in colonisation of epithelial cells (Virji 2009). In N. meningitidis, pilin glycosylation enhances adherence to epithelial cells (Virji et al. 1993), and is required for platelet activating factor receptor-mediated adherence to human airway epithelial cells (Jen et al. 2013). In N. gonorrhoeae, the glycan on the pilus subunit interacts directly with the host complement receptor 3 I-domain that is expressed on the surface of epithelial cells. This interaction facilitates bacterial adherence and promotes intracellular survival (Jennings et al. 2011).

The nitrate reductase, AniA, is a glycoprotein that is expressed by all N. gonorrhoeae and most N. meningitidis strains (Ku et al. 2009; Shewell et al. 2013). AniA is glycosylated at the C-terminus with the tri saccharide digalactosyl 2,4-diacetamido-2,4,6-trideoxyhexose (Ku et al. 2009), which is not required for its nitrite reductase function (Ku et al. 2009). However, the O-linked monosaccharide of the AniA glycoprotein is immunodominant and glycosylation of AniA is suggested to be an immune evasion mechanism in which the glycan moiety acts as a ‘decoy’ to diminish an antibody response against the functional region of the protein (Shewell et al. 2013). A truncated, non-glycosylated, form of AniA induces a non-native immune response against the conserved core region of the protein regardless of the glycosylation state and has been proposed as a vaccine antigen for N. gonorrhoeae (Shewell et al. 2013).

Additional glycoproteins have been reported for the pathogenic Neisseria via highly sensitive mass spectrometry methods (Vik et al. 2009; Anonsen et al. 2012). However, another study has suggested that for some of the additional proteins identified as glycoproteins, the majority of the protein expressed by the bacteria was essentially unglycosylated (Schulz et al. 2013).

**INTERACTIONS OF THE PATHOGENIC NEISSERIA WITH HOST GLYCAN AND GLYCOPROTEINS**

The pathogenic Neisseria express a variety of surface structures that interact with host cells. These include the major outer membrane proteins (e.g. pili, the opacity proteins Opc and Opa, and the major porins PorA and PorB) as well as other minor outer membrane structures and adhesins (Merz and So 2000; Virji, 2009). Studies have shown that some of the Neisserial surface structures bind to host glycans and glycoproteins; however, for the latter it is unclear as to whether these interactions are solely protein based, or are also glycan dependent (summarised in Table 3 and Fig. 1). Since these membrane proteins have often undergone post-translational modification by glycosylation, the binding interactions between these bacterial membrane proteins and the host may be either protein:protein, protein:glycan (Esko and Sharon 2009) or glycan:glycan based (Day et al. 2015). The pathogenic Neisseria are also known to interact with various other host glycans, such as gangliosides and oligosaccharides, although the specific Neisserial surface structures responsible for this binding are unknown (Table 3).

**Opacity proteins (Opc and Opa)**

The opacity proteins, Opc and Opa, are phase variable, integral, β-barrel outer membrane proteins involved in Neisserial adherence and invasion (Carbonnelle et al. 2009; Sa E Cunha, Griffiths and Virji 2010). Opc is not expressed by gonococci (Zhu, Morelli and Achtman 1999) and the opcA gene is absent in several meningococcal strains, including the majority of strains in the ST-11/ET-37 and ST-8/Cluster A4 clonal complexes (Seiler et al. 1996). When present in high levels, Opc aids in meningococcal adhesion and invasion into host cells (Virji et al. 1995). Neisseria meningitidis strains have 3–4 opcA genes, while N. gonorrhoeae strains may express up to 11 opcA genes (Bhat et al. 1991). Phase variation of opcA genes is random and independent, so strains may express any of their repertoire of opcA genes at any given time (Bhat et al. 1991). The structural variability displayed by these proteins has been linked to functional diversity between Opa variants (reviewed in Billker et al. 2000).

Opc and some Opa proteins can bind the glycosaminoglycans heparin and heparan sulfate proteoglycans (HSPGs) (van Putten and Paul 1995; De Vries et al. 1998). Heparin and heparan sulfate are both highly sulphated glycans, with heparan being found primarily in mast cell granules while heparan sulfate is found in plasma, the extracellular matrix and on cell surfaces of most mammalian cells (Rabenstein 2002). Through its interaction with HSPGs, Opc is able to support, but not sustain, meningococcal adhesion and invasion of host endothelial cells (Virji, Makepeace and Moxon 1994). Due to this and the fact that the interactions are of low affinity, this may not be the only ligand for the opacity proteins. Opc and a few of the Opa variants also interact with extracellular matrix glycoproteins such as vitronectin and fibronectin (Sa E Cunha, Griffiths and Virji 2010). These interactions facilitate association with endothelial cells via the endothelial integrins αVβ3-integrin and α5β1-integrin (the fibronectin and vitronectin receptors, respectively) and result in efficient cellular invasion by meningococci (Virji, Makepeace and Moxon 1994; Unkmeir et al. 2002b) and gonococci (Gómez-Duarte et al. 1997). Furthermore, vitronectin binding also increases meningococcal serum survival by inhibiting the insertion of membrane attack complex into the bacterium (Singh, Su and Riesbeck 2010). The interactions between the gonococcal Opa50 protein and vitronectin can be inhibited by heparin in dose-dependent manner, which suggests that this interaction may be glycan based (Gómez-Duarte et al. 1997).

Both Opa and Opc have been reported to bind a range of other carbohydrate structures including galactose and sialic acids (Moore et al. 2005). Sialic acid residues are typically found at the outermost end of glycan chains of all cell types (Varki 2008). They are a common terminal residue on mucins (Linden et al. 2008) and are an integral component of gangliosides which are abundantly expressed in neuronal tissues (Varki 2008). A majority of Opa proteins also recognise one or more members of the human CD66 carcinoembryonic antigen superfamily; a family of heavily glycosylated cell adhesion proteins which includes the carcinoembryonic antigen-related cell adhesion molecule family (Virji et al. 1996; Sadarangani, Pollard and Gray-Owen 2011). This interaction however is glycan independent (Bos et al. 1998).

**Other adhesins that bind glycans**

A range of other Neisserial surface antigens have been shown to bind host glycans or glycoproteins, and these are outlined in Table 3. These include the serogroup B vaccine antigen, the Neisserial heparin binding antigen (NHBA), which binds heparin
Table 3. Interactions of meningococcal and gonococcal structures with host glycans and glycoproteins.

| Outer membrane structure | Species | Host glycan or glycoprotein | Role of interaction | Ref |
|--------------------------|---------|-----------------------------|---------------------|-----|
| Opc                      | Nm      | Fibronectin, vitronectin    | Invasion into brain endothelia | Unkmeir et al. (2002b), Sa E Cunha, Griffiths and Virji (2010) |
|                          |         | Heparin/HSPGs               | Possible adhesin      | De Vries et al. (1998) |
|                          |         | Various oligosaccharides    | Adherence to epithelial cells | Moore et al. (2005) |
|                          |         | including sialic acid       |                     |                 |
| Opa                      | Nm      | Various oligosaccharides    | Adherence to epithelial cells | Moore et al. (2005) |
| Msf                      | Nm      | Vitronectin                 | Serum survival       | Griffiths et al. (2011) |
| NHBA                     | Nm      | Heparin                     | Serum survival       | Serruto et al. (2010) |
| NHBA                     | Nm      | Heparan sulphate            | Adherence to epithelial cells | Vacca et al. (2016) |
| fHBP                     | Nm      | Factor H                    | Serum survival       | Madico et al. (2006), Seib et al. (2009) |
| NhhA                     | Nm      | Laminin                     | ND                   | Scarselli et al. (2006) |
|                          | Nm      | HSPGs                       | ND                   | Scarselli et al. (2006) |
|                          | Nm      | Heparan sulphate            | ND                   | Scarselli et al. (2006) |
| NspA                     | Nm      | Factor H                    | Serum survival       | Lewis et al. (2010) |
| NadA                     | Nm      | Integrins                   | ND                   | Nägele et al. (2011) |
| PorA                     | Nm      | C4Bp                        | Serum survival       | Jarva et al. (2005) |
| PorB                     | Nm      | TLR2-TR1 heterodimer        | Immune evasion       | Massari et al. (2002) |
|                          | Nm      | Factor H                    | Serum survival       | Lewis et al. (2013) |
| Pili                      | Nm      | CD46                        | Unknown              | Gill and Atkinson (2004) |
|                          | Nm      | PAFr                        | Adherence to human airway cells | Jen et al. (2013) |
|                          | Ng      | CR3                         | Adherence to cervical epithelial cells | Jennings et al. (2011) |
| Unknown adhesin          | Nm      | Gangliosides                | Adherence to red blood cells | Rumiantsev et al. (1990) |
|                          | Nm      | ECM components              | ND                   | Eberhard et al. (1998) |

Nm, Neisseria meningitidis; Ng, Neisseria gonorrhoeae; HSPG, heparan sulfate proteoglycans; ECM, extracellular matrix; C4Bp, C4 binding protein; TLR, Toll like receptor; PAFr, platelet activating factor receptor; CR3, complement receptor 3. ND, not determined.

(Serruto et al. 2010) and heparan sulfate proteoglycans (Vacca et al. 2016) via an arginine-rich region. NHBA binding to heparin mediates increased serum resistance (Serruto et al. 2010), potentially via interactions between heparin and factor H or C4b binding protein (Sahu and Pangburn 1993; Serruto et al. 2010). NHBA is also involved in meningococcal adherence to epithelial cells, via binding to heparan sulfate proteoglycans (Vacca et al. 2016). Other minor adhesins such as NadA, Msf, NspA and NhhA also bind host glycans and/or glycoconjugates (see Table 3).

**CONCLUSION**

Understanding the glycobiology of the pathogenic *Neisseria* is important for a better understanding of Neisserial pathogenesis, and may ultimately aid improved therapeutic and vaccine development. Surface glycans of the pathogenic *Neisseria* play a key role in resistance to host immune responses by reducing the efficiency of bacterial recognition and killing by the host, and by immune evasion via phase variation and molecular mimicry. These pathogens also harness the host glyco-lex, which provides opportunities for adherence that are key in colonisation (reviewed in Rouphael and Stephens 2012). The full range of glyco-interactions remains to be discovered. A recent study reports that terminal sugars on bacterial LPS/LOS mediate interactions with host cells via direct binding to host glycans (Day et al. 2015), and this may also be the case in the pathogenic *Neisseria* and is the subject of current investigation in our laboratory.

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