

## MINIREVIEW

# Microbial Adherence to and Invasion through Proteoglycans

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### INTRODUCTION

A large array of glycoproteins, glycolipids, and proteoglycans decorate the surfaces of animal cells. These glycoconjugates mediate many fundamental cellular processes, including cell-cell and cell-matrix adhesion, motility, growth, and signaling (28, 110). Over time, many pathogenic microorganisms have learned to exploit cell surface glycoconjugates as receptors for attachment, a process which ultimately facilitates tissue colonization and invasion. The interaction of specific proteins on the surface of microorganisms (adhesins) with carbohydrate chains on the glycoconjugate (receptors) enables the microbes to take their first step towards establishing an infection.

This review concentrates on proteoglycans as adhesion receptors for bacteria, viruses, and parasites. Microbial binding to glycolipids and glycoproteins also occurs and has been discussed elsewhere (27, 40, 61–63, 85, 94). Proteoglycans are ubiquitous among animal cells, and as discussed below, their carbohydrate chains (glycosaminoglycans) bind many different protein ligands. Different experimental criteria have been used to establish a role for proteoglycans in attachment and invasion of host cells, including direct binding measurements, identification of microbial carbohydrate-binding proteins, competition studies with defined polysaccharides, loss of adhesion upon enzymatic removal of host glycans, and altered adherence to animal cell mutants with defective glycosaminoglycan biosynthesis. Overall, the experimental evidence for microbial adhesion to host cell proteoglycans is compelling, and future molecular studies may provide a basis for designing therapeutic strategies based on these interactions.

### PROTEOGLYCAN STRUCTURE

Proteoglycans consist of a protein core and one or more covalently attached glycosaminoglycan chains (Fig. 1). Their assembly initiates in the endoplasmic reticulum and ends in the Golgi apparatus, where the various glycosyltransferases and sulfotransferases reside. Proteoglycans are present in intracellular secretion granules (67), in the extracellular matrix (55), and on the cell surface (12). Many membrane proteoglycans have a single membrane-spanning segment in a type I orientation (66). The prototypical membrane proteoglycan in this class is syndecan-1, which belongs to a family of structurally related proteoglycans with four members (syndecan-1, fibroglycan, *N*-syndecan, and ryudocan) (Table 1). Each member has conserved attachment sites for three to five glycosaminoglycan chains (12). The syndecans exemplify hybrid proteoglycans since they contain mixtures of the two major types of

glycosaminoglycan chains found in animal cells, heparan sulfate and chondroitin sulfate (Fig. 1). Other cell surface proteoglycans include the hybrid molecules betaglycan and a splice variant of CD44 (epican) and the pure chondroitin sulfate proteoglycans NG2 and thrombomodulin. The other major family of membrane proteoglycans are called glypicans since they contain glycosylphosphatidylinositol anchors instead of a membrane-spanning segment (glypican-1, OCI-5, K-glypican, and cerebroglycan). In contrast to the syndecans, the glypicans appear to contain only heparan sulfate chains (26). In general, the expression of these proteoglycans occurs in a tissue-specific and temporally regulated manner during development, although their expression overlaps in some cell types (12, 66) (Table 1). Their localization to apical and basolateral membranes of polarized cells varies as well (26).

Much of the chemistry of proteoglycans is dominated by the glycosaminoglycan chains, which consist of alternating residues of an amino sugar and an uronic acid (Fig. 1). Chondroitin sulfate is based on the disaccharide repeat (GlcUA $\beta$ 1-3GalNAc $\beta$ 1-4)<sub>*n*</sub>, and heparan sulfate is based on the disaccharide (GlcUA $\beta$ 1-4GlcNAc $\alpha$ 1-4)<sub>*n*</sub>. As the chains polymerize, they undergo various sulfation and epimerization reactions, which result in the addition of sulfate groups to different sugars and conversion of a portion of the D-glucuronic acid (D-GlcUA) residues to L-iduronic acid (L-IdUA). Proteoglycans exhibit tremendous structural heterogeneity due to substoichiometric glycosylation, variation in the lengths of the glycosaminoglycan chains, and variation in the extent and pattern of sulfation and epimerization. Thus, a preparation of proteoglycans really consists of hundreds of thousands of distinct molecular species, or glycoforms. Determining if specific glycoforms have unique biological properties is a major goal for structural biologists in the field.

One way to fractionate proteoglycans is based on the charge characteristics of the glycosaminoglycan chains. Chondroitin sulfates usually contain one sulfate residue per disaccharide unit, attached to the hydroxyls at C-4 (chondroitin sulfate A) or C-6 (chondroitin sulfate C) of GalNAc residues (Fig. 1). A third type of chondroitin sulfate (B, or dermatan sulfate) contains IdUA and somewhat more sulfate, with groups attached to hydroxyls at C-4 or C-6 of GalNAc residues and to C-2 of IdUA residues. Typical dermatan sulfate preparations from porcine skin contain ~1.1 sulfate groups per disaccharide and as much as 80% IdUA (82). Heparan sulfate chains vary in sulfate content from 0.8 to 1.4 sulfate groups per disaccharide (79, 81). Heparin, which is found in intracellular granules of mast cells, is the most highly sulfated glycosaminoglycan. Commercial preparations have been prefractionated by charge and contain, on average, ~2.4 sulfate groups per disaccharide (38). In heparan sulfate and heparin, the sulfate residues occur at the amino groups and the C-6 hydroxyl groups of glucosamine

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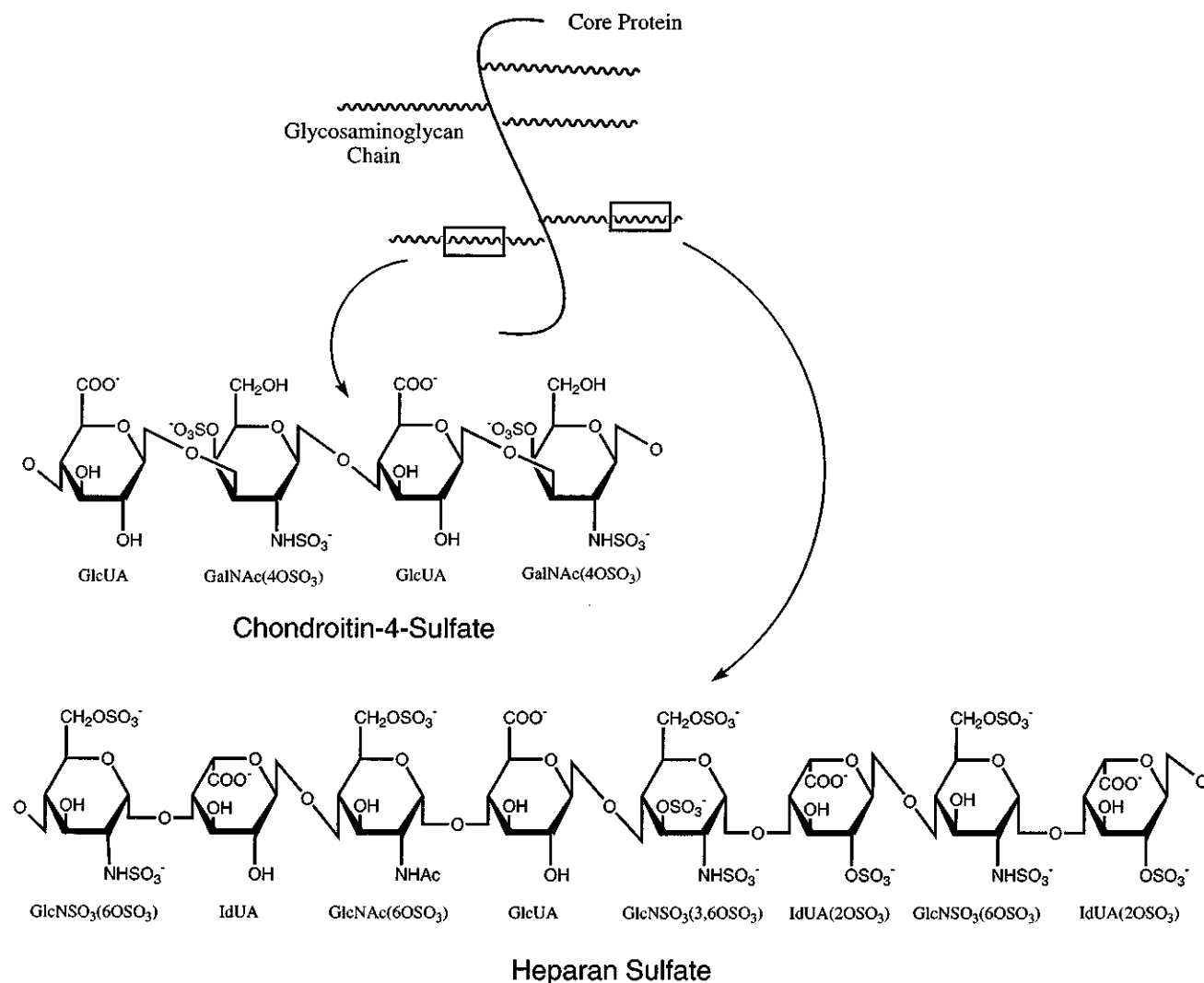


FIG. 1. Partial structure of a membrane proteoglycan.

residues, at C-2 of IdUA and GlcUA residues, and occasionally at the C-3 hydroxyl of glucosamine residues (Fig. 1). The various modifications (epimerization and sulfation) occur to a greater extent in heparin than in heparan sulfate. Thus, 80 to 85% of the glucosamine residues in heparin are N sulfated, compared to 40 to 60% in heparan sulfate. The content of IdUA and the degree of O sulfation are also much greater in heparin.

The enzymes involved in heparan sulfate and heparin biosynthesis are coordinated, resulting in regions rich in IdUA and sulfated sugars, interspersed among unmodified sections of the chain (79, 81). The reactions tend to be incomplete, giving rise to structural heterogeneity within the modified regions of the chains. These domains can have a very high charge density due to the clustering of sulfate groups, which can result in nonspecific binding of proteins, such as a cation-exchange resin. However, several examples exist in which unique sequences of sugars in the glycosaminoglycan chain define a binding site for a ligand. For example, different subpopulations of heparin bind to fibronectin, type I collagen, and laminin (98); different heparin oligosaccharides bind to acidic fibroblast growth factor and basic fibroblast growth factor (43, 80);

TABLE 1. Cell surface proteoglycans

Proteoglycan	Glycosaminoglycan(s)	Cell type(s)
Syndecan family Syndecan 1 Fibroglycan <i>N</i> -syndecan Ryudocan	Chondroitin sulfate, heparan sulfate	Epithelial cells, endothelial cells, fibroblasts
Glypican family Glypican OCI-5 K-glypican Cerebroglycan	Heparan sulfate	Epithelial cells, endothelial cells, fibroblasts
Betaglycan	Chondroitin sulfate, heparan sulfate	Fibroblasts
Thrombomodulin	Chondroitin sulfate	Endothelial cells
NG2	Chondroitin sulfate	Melanocytes
CD44	Chondroitin sulfate	Lymphocytes

TABLE 2. Methods for producing modified heparin

Modification	Reference
GlcNSO <sub>3</sub> N desulfation .....	54
GlcN re-N sulfation .....	75
GlcNAc N deacetylation .....	100
GlcN re-N acetylation.....	95
Iduronic acid/glucuronic acid 2-O desulfation .....	74
Glucosamine 3-O desulfation .....	
Glucosamine 6-O desulfation .....	86
Carboxyl reduction (GlcUA and IdUA).....	106
Periodate oxidized, borohydride reduced (nonsulfated GlcUA and IdUA residues) .....	47
Aminomethylsulfonic acid addition (carboxyl groups).....	25

and a distinct pentasaccharide with a uniquely positioned 3-O-sulfated glucosamine residue binds with high affinity to anti-thrombin III (13, 66). Binding sequences often consist of combinations of modified and unmodified residues (Fig. 1). A major goal is to establish if microbial binding depends on specific types of proteoglycans and if unique arrangements of sugar residues in the glycosaminoglycan chains play a role.

### METHODOLOGICAL CONSIDERATIONS

In order to study microbial adhesion *in vitro*, adherence assays have been developed for many microorganisms with the use of cultured cells, tissue sections, or plastic surfaces coated with proteoglycans or glycosaminoglycans. Inhibition of adherence by the addition of glycosaminoglycans is usually the first indication that receptors on the mammalian cells might be proteoglycans. If heparin inhibits adhesion and other glycosaminoglycans (e.g., chondroitin sulfate and dermatan sulfate) do not, then adhesion or binding is generally considered specific for heparan sulfate proteoglycans. However, this interpretation may not be correct since heparin may compete nonspecifically due to its high charge density. To circumvent this problem, one can cleave heparin into fragments of specific length and chemically alter the number and position of sulfate groups (Table 2). These derivatives (heparinoids) can then be used to determine if competition, and, by inference, adhesion,

depends on specific functional groups or a specific sugar sequence(s). Some tissues contain adequate amounts of heparan sulfate to prepare native material for competition studies (e.g., liver contains about 1 mg of glycosaminoglycan/g [dry weight] of tissue). For direct binding measurements, the chains can be radiolabeled by using the techniques described in Table 2. Alternatively, radioactive proteoglycans can be prepared from cultured cells by supplementing the growth medium with radioactive precursors (e.g., [1-<sup>3</sup>H]galactose, [6-<sup>3</sup>H]glucosamine, or <sup>35</sup>SO<sub>4</sub>, [5]).

In addition to competition and binding experiments, one can examine how removal of glycosaminoglycans from target cells affects adhesion. Treatment of cells with bacterial heparin or chondroitin lyases removes cell surface heparan sulfate or chondroitin sulfate, respectively (73). These enzymes are commercially available and are quite reliable. Care should be taken to ensure that the enzymes were effective by measuring the loss of cell surface glycosaminoglycans (e.g., after trypsin treatment).

Another way to modify the expression of proteoglycans is to grow cells in medium containing an inhibitor of glycosaminoglycan formation. One class of useful compounds contains xylose covalently linked to an hydrophobic aglycone ( $\beta$ -D-xylosides). These compounds resemble a natural biosynthetic intermediate and act as primers of free glycosaminoglycan chains, which are then secreted from cells (29). Growth of cells in the presence of a  $\beta$ -D-xyloside inhibits the formation of proteoglycans by diverting assembly of the chains from the core proteins, causing underglycosylated proteoglycans to appear on the cell surface.

Another tactic is to reduce the extent of sulfation of the glycosaminoglycan chains by growing cells in medium deficient in inorganic sulfate and supplemented with sodium chlorate, an inhibitor of sulfation (2). These conditions lead to variable undersulfation of the glycosaminoglycan chains, depending on the concentration of inhibitor (6, 53). One problem with inhibitors is the lack of specificity.  $\beta$ -D-Xylosides can affect the formation of glycolipids in some cells (34), and chlorate inhibits the addition of sulfate to other glycoconjugates, lipids, and proteins (2). However, when these characteristics are com-

TABLE 3. Mutant CHO cell lines used in microbial adherence studies

Cell line	Biochemical deficiency	Glycoaminoglycan produced	Microorganism(s) studied (reference)
Wild type	None	Heparan sulfate, chondroitin-4-sulfate	
pgsA-745	Xylosyltransferase	None	<i>Bordetella pertussis</i> (45), <i>H. influenzae</i> (89), <i>Borrelia burgdorferii</i> (69), <i>Trypanosoma cruzi</i> (49), HSV (101), CMV (24, 88), <i>Neisseria gonorrhoeae</i> (109)
pgsB-761	Galactosyltransferase I	~5% of wild-type heparan sulfate, chondroitin sulfate	<i>Bordetella pertussis</i> (45), <i>C. trachomatis</i> (114), <i>T. cruzi</i> (49), HSV (101)
pgsB-618	Galactosyltransferase I	~15% of wild-type heparan sulfate, chondroitin sulfate	<i>N. gonorrhoeae</i> (109), <i>H. influenzae</i> (89), <i>Leishmania amazonensi</i> (77)
pgsB-650	Galactosyltransferase I	~30% of wild-type heparan sulfate, chondroitin sulfate	None
pgsD-677	N-Acetylglucosaminyl transferase, glucuronosyltransferase	No heparan sulfate, threefold-higher levels of chondroitin sulfate	<i>H. influenzae</i> (89), <i>Borrelia burgdorferii</i> (69), <i>L. amazonensi</i> (77), <i>T. cruzi</i> (49), HSV (101), CMV (24, 88), <i>N. gonorrhoeae</i> (109)
pgsF-17	2-O-Sulfotransferase	2-O-Sulfate-deficient heparan sulfate, normal levels of chondroitin sulfate	<i>P. falciparum</i> (102a)

TABLE 4. Microorganisms bind proteoglycan receptors on eukaryotic cells

Microbe	Target tissue(s)	Type of cells used or activity assayed in vitro	Reference(s)
<b>Gram-negative bacteria</b>			
<i>Bordetella pertussis</i>	Ciliated epithelium in respiratory tract	HeLa cells, CHO cells	45, 83
<i>Chlamydia trachomatis</i> (obligate intracellular organism)	Eyes, genital tract, lymphoid tissues	HeLa cells, CHO cells, L929 mouse fibroblasts, binding of <sup>125</sup> I-heparan sulfate	17, 65, 114
<i>Helicobacter pylori</i>	Gastric mucosa	Binding of <sup>125</sup> I-heparan sulfate	1, 20, 50
<i>Haemophilus influenzae</i>	Respiratory epithelium	Hep-2, mouse fibroblast, human foreskin fibroblasts, CHO cells	89
<i>Borrelia burgdorferii</i>	Endothelium, epithelium, extracellular matrix	HeLa cells, Vero cells, CHO cells	56, 69
<i>Nisseria gonorrhoeae</i>	Genital tract	Chang cells, CHO cells	19, 109
<b>Gram-positive bacteria</b>			
<i>Staphylococcus aureus</i>	Connective tissues, endothelial cells	Binding of <sup>125</sup> I-heparin to bacteria	70, 71
<i>Streptococcus pyogenes</i>	Cardiac and kidney tissues	Binding of <sup>125</sup> I-heparin to bacteria, binding to heparin-agarose, kidney and cardiac tissue sections	11, 41, 99, 111
<i>Streptococcus mutans</i>	Cardiac and kidney tissues	Binding to heparin-agarose, kidney and cardiac tissue sections	21, 22
<i>Streptococcus gordonii</i>	Cardiac tissue	Human umbilical vein endothelial cells	108
<b>Parasites</b>			
<i>Plasmodium falciparum</i> (CSs)	Hepatocytes, placenta	HepG-2 cells, primary mouse hepatocytes, human placenta, brain capillaries, coated plastic	35, 36, 91, 97
<i>Leishmania amazonensi</i> (amastigotes)	Macrophages, fibroblasts, epithelium	CHO cells, mouse peritoneal macrophages, mouse fibroblasts	77
<i>Leishmania donovani</i> (promastigotes)	Macrophages, fibroblasts, epithelium	Mouse macrophages	14
<i>Trypanosoma cruzi</i>	Heart, tract, nervous system, extracellular matrix	Vero cells, CHO cells	49, 90
<b>Viruses</b>			
HSV	Mucosal surfaces of mouth, eyes, genital tract, respiratory tract; latent in nerve ganglia	Vero, HepG-2, CHO, mouse L cells	42, 78, 101
CMV	Neutrophils, monocytes	Human foreskin fibroblasts, human embryonic lung fibroblasts	24, 88
HIV-1	T lymphocytes	T-cell lines MT-4 and H9	92

bined with the results of the other strategies described above, a clear picture regarding the role of proteoglycans in adhesion emerges.

Many studies have utilized mutant cell lines defective in glycosaminoglycan biosynthesis (Table 3). A large collection of biochemically characterized Chinese hamster ovary (CHO) cell mutants lacking glycosaminoglycans have been reported (3–6, 30, 31, 72). Some lack both heparan and chondroitin sulfate glycosaminoglycans (*pgsA* and *pgsB* mutants). Other strains lack only heparan sulfate (*pgsD*) or chondroitin sulfate (*ldld*) cells when starved for GalNAc. Some are defective in polymer modification reactions, e.g., GlcNAc N deacetylation/N sulfation (*pgsE*) or IdUA 2-O sulfation (*pgsF*). Mutant mouse L cells have also been described previously (7, 8, 42). These strains provide the opportunity for studying microbial adhesion to living cells with defined alterations in proteoglycan expression.

#### HEPARAN SULFATE MEDIATES ADHESION

An impressive body of literature documents that many bacteria, parasites, and viruses exploit proteoglycans as adhesion receptors (Tables 3 and 4). Most adherent microorganisms apparently bind to heparan sulfate, but as discussed above, this predilection may be nonspecific. The most thoroughly studied example of specific oligosaccharides that appear to be involved

in microbial adherence is the binding of herpes simplex virus (HSV) glycoproteins gpB and gpC. Studies that involved competition experiments, lyases, and CHO cell mutants have shown that HSV depends on cell surface heparan sulfate for adherence and penetration (101, 102, 113). HSV binding to host cells is inhibited by heparin fragments composed of five disaccharide units and containing at least 1.5 sulfates per disaccharide (78). Using chemically modified heparin with a defined structure, Herold et al. (47) demonstrated that both gpC and gpB promote adherence by binding to heparan sulfate but that the individual glycoproteins interact with different structural motifs within the chain. Sulfate groups at C-2 of the uronic acids and the carboxyl groups were critical for gpB binding to heparin, but they were not required for gpC binding. If these studies can be extended to natural heparan sulfate chains on cells, then the differential expression of sequences rich in 2-O-sulfated uronic acids on various cells could partly explain the tissue tropism of HSV-1 and HSV-2 (39, 46). This issue is controversial since the results of other studies suggest that chondroitin sulfate receptors may exist as well (7, 8, 42).

*Plasmodium falciparum* sporozoites bind to heparin and heparan sulfate in a tissue-specific manner (35), with preferred binding to the basolateral surface of hepatocytes and the basement membrane of kidney tubules. Binding is mediated by the circumsporozoite (CS) protein that covers the sporozoite cell surface, but the heparan sulfate proteoglycans that interact

TABLE 5. Microbial heparin-binding proteins

Microorganism	Protein	Binding domain(s)	Reference
<i>Plasmodium falciparum</i>	CS protein	C-terminal region II+ (PCSVTCGNGIQVRIK)	103
HIV	gp120	V3 loop (NNTRKSIRIQRGPRAEVTIGKIG), C4 region	96
<i>Trypanosoma cruzi</i>	Penetrin	Unknown	49
HSV	gpC	Region SP-1 (RxxxRCFRxxxR), region SP-4	107
<i>Bordetella pertussis</i>	Filamentous hemagglutinin	C-terminal region	76

with CS have not been identified. It is known that hepatocytes produce a heparan sulfate highly enriched in N-sulfated glucosamine residues and 2-O-sulfated uronic acids, with most of the modifications clustered in three heparin-like domains at the nonreducing ends of the chains (79). Perhaps this structure facilitates the selective binding of CS protein by hepatocytes (16). Recent studies indicate that binding also depends on the charge imparted by the carboxyl groups of the uronic acids (102a), consistent with the idea that the CS protein binds mostly through electrostatic interactions with highly charged regions of the chains. Subpopulations of *Plasmodium* also bind to chondroitin sulfate A, but the identity of the chondroitin receptor has not yet been established (36, 97).

Recent studies of *Chlamydia trachomatis* indicate a complex mode of adhesion. In this organism, heparan sulfate acts as a bridge, binding both host cell receptors and *Chlamydia trachomatis* (18, 114). At minimum, a decasaccharide is needed, and based on competition studies with chemically modified heparin, the binding sequences for host and microbial receptors apparently differ (18). This situation is reminiscent of the coreceptor activity of heparan sulfate in binding basic fibroblast growth factor and its high-affinity signal-transducing receptor (60). Interestingly, *Chlamydia* produces its own sulfated heparin-like molecule (114), which may provide the opportunity to infect cells with low levels of endogenous heparan sulfate or with heparan sulfate that lacks appropriate binding sequences.

### HEPARIN-BINDING ADHESINS

Information regarding the adhesins expressed on microbial cells that bind to glycosaminoglycans is accumulating. The heparin-binding adhesins associated with intracellular pathogens are probably the best-studied proteins. These include the filamentous hemagglutinin (FHA) of *Bordetella pertussis*, the CS surface protein of *Plasmodium falciparum*, gp120 from human immunodeficiency virus (HIV), gpB and gpC of HSV, and the trypanosome adhesin penetrin (Table 5). Several high-molecular-weight proteins on *Haemophilus influenzae* show significant homology to FHA and bind to the epithelium through heparan sulfate proteoglycans (89). A common motif has emerged from studying the primary sequence of these adhesins. Their binding domains generally include a region rich in basic amino acids flanked by hydrophobic residues (Table 5). In some cases two distant regions of primary sequence may be brought together by a secondary structure to form the binding site (96).

In malarial sporozoites, the CS protein interacts with heparan sulfate proteoglycans on hepatocytes (15) through a cluster of positively charged amino acids and adjoining hydrophobic residues at the C-terminal end of the protein (91, 103). A synthetic peptide that inhibits adherence to cells and CS protein clearance by the liver in mice has been constructed (103). The sequence is also present in thrombospondin, a glycosaminoglycan-binding protein present in the extracellular matrix, and several other heparin-binding proteins (52, 103). Evidence

indicates that this region may interact preferentially with heparan sulfate and with lower affinity to chondroitin sulfate (84).

A number of viruses utilize cell surface proteoglycans as receptors, including HIV, HSV, and cytomegalovirus (CMV) (Tables 3 and 4). The glycoproteins involved in HSV binding to heparan sulfate have been well studied (105, 107), and protein sequences involved in this interaction are conserved and functional in other alphaherpesvirus glycoproteins (104). CD4 constitutes the primary receptor on T cells for the HIV-1 envelope glycoprotein gp120. However, attachment of the virus also appears to involve heparan sulfate (92). The V3 and C4 domains of gp120 contain positively charged regions that interact with heparin. These regions may be brought together in oligomeric gp120 to form a binding site for heparan sulfate (96).

*C. trachomatis* (114) and promastigotes of *Leishmania donovani* (14) appear to utilize heparan sulfate in a unique way, as a bridging molecule between heparan sulfate-binding proteins on their surfaces and on host cells. Thus, the addition of heparan sulfate at low concentrations enhances the attachment of chlamydiae to CHO cells deficient in heparan sulfate, but at high concentrations it inhibits attachment, presumably by increasing the formation of binary complexes instead of ternary complexes (114). This is an open area for research since the heparin-binding proteins have not yet been described in any detail (77). Host cell proteins that bind heparan sulfate also have been detected (68, 93), but their role in infection has not been established. Heparin-binding proteins may be interesting targets for developing antibody-based inhibitors of adhesion.

### INVASION

Although it is clear that cell surface proteoglycans act as adhesion receptors, their role in invasion is unclear. The abilities of heparin to block the initial interaction of microbes with cells and to displace freshly bound organisms suggest that proteoglycans mediate an early, probably initial, stage in adhesion and that the initial interaction is relatively weak. Adherence can become irreversible with time, suggesting that additional interactions may occur, possibly with non-heparan sulfate receptors. Some heparan sulfate-binding adhesins appear to be multifunctional. For example, in addition to a heparan sulfate-binding site, the FHA of *Bordetella pertussis* contains an RGD binding sequence that interacts with the  $\beta_2$  integrin CR3 on macrophages (76). Binding to proteoglycan receptors may also result in host cell responses that lead to internalization of adherent microbes (32, 33, 57). Thus, it may be more appropriate to refer to the proteoglycans as coreceptors, where binding initiates a series of interactions that lead to tight adherence, subsequent internalization, and possibly downstream inflammatory responses characteristic of infections (51).

Recent evidence suggests a role for proteoglycans in viral invasion. Studies of HSV show that heparan sulfate is involved in fusion of the viral envelope with the host cell plasma membrane (101). The viral glycoprotein gpC appears to be primar-

ily an adhesin that promotes adherence and is not required for penetration of the cell. In contrast, gpB binds heparan sulfate and promotes both adherence and virus-cell fusion (48). gpB binding to heparan sulfate also leads to syncytium formation (102). The mechanism by which heparan sulfate facilitates membrane fusion is unknown, but perhaps it acts like a template facilitating the association of fusogenic membrane proteins.

### SUMMARY AND FUTURE STUDIES

Although many microorganisms bind to cell surface heparan sulfate (Tables 3 and 4), questions about the nature of these interactions remain unanswered. Are specific oligosaccharide sequences required for binding? Do microbes bind to subsets of proteoglycans that differ in protein or glycosaminoglycan composition (64)? Does binding to the core protein as well as to the carbohydrate chains occur (44)? What is the amino acid sequence in the carbohydrate binding domains of adhesins? What is the role of heparin-binding proteins on host cells? Recent studies suggest that some proteoglycans reside in focal adhesions (112), where they participate in cell attachment to substrata and intracellular signaling (59). Thus, future studies should focus on whether microbial binding to proteoglycans also results in a signal transduction event that subsequently triggers processes helpful to the microbe (e.g., invasion).

Although the *in vitro* evidence for heparan sulfate-microbial cell interactions is compelling, the role of heparan sulfate in microbial pathogenesis is not well established. Examination of virulent and nonvirulent isolates may reveal a correlation with heparan sulfate-dependent adherence and expression of heparin-binding proteins on the microbial cell surface. Another approach suggested by *in vitro* studies is to administer fragments of heparin or heparan sulfate to infected animals and subsequently determine microbial distribution, tissue colonization, and host survival. The ability of exogenous heparin and related polysaccharides to inhibit viral replication suggests that this approach might lead to polysaccharide-based antiviral pharmaceutical agents (23, 58, 87, 88).

Another approach worth consideration is to inhibit the production of proteoglycans metabolically by using  $\beta$ -D-xylosides (29). Cultured cells take up  $\beta$ -D-xylosides rapidly and use them as primers for the assembly of single glycosaminoglycan chains, which are then secreted (37). Priming also diverts the synthesis of the chains from endogenous proteoglycans, resulting in the expression of underglycosylated proteins on the cell surface. Recent studies show that  $\beta$ -D-xylosides when injected into animals prime glycosaminoglycan chains and that the compounds are apparently well tolerated (9, 10). The secreted glycosaminoglycan chains may block microbial attachment by competition, and the reduction in cell surface receptors should reduce the number of binding sites on the host cells. Thus,  $\beta$ -D-xylosides may be a double-edged sword to fend off infection.

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### REFERENCES

- Ascencio, F., L. Fransson, and T. Wadström. 1993. Affinity of the gastric pathogen *Helicobacter pylori* for the N-sulphated glycosaminoglycan heparan sulphate. *J. Med. Microbiol.* **38**:240–244.
- Bacuerle, P. A., and W. B. Huttner. 1986. Chlorate—a potent inhibitor of protein sulfation in intact cells. *Biochem. Biophys. Res. Commun.* **141**:870–877.
- Bai, X. M., and J. D. Esko. 1996. An animal cell mutant defective in heparan sulfate hexuronic acid 2-O-sulfotransferase. *J. Biol. Chem.*
- Bame, K. J., and J. D. Esko. 1989. Undersulfated heparan sulfate in a Chinese hamster ovary cell mutant defective in heparan sulfate N-sulfotransferase. *J. Biol. Chem.* **264**:8059–8065.
- Bame, K. J., K. Lidholt, U. Lindahl, and J. D. Esko. 1991. Biosynthesis of heparan sulfate. Coordination of polymer-modification reactions in a Chinese hamster ovary cell mutant defective in N-sulfotransferase. *J. Biol. Chem.* **266**:10287–10293.
- Bame, K. J., R. V. Reddy, and J. D. Esko. 1991. Coupling of N-deacetylation and N-sulfation in a Chinese hamster ovary cell mutant defective in heparan sulfate N-sulfotransferase. *J. Biol. Chem.* **266**:12461–12468.
- Banfield, B. W., Y. Leduc, L. Esford, K. Schubert, and F. Tufaro. 1995. Sequential isolation of proteoglycan synthesis mutants by using herpes simplex virus as a selective agent: evidence for a proteoglycan-independent virus entry pathway. *J. Virology* **69**:3290–3298.
- Banfield, B. W., Y. Leduc, L. Esford, R. J. Visalli, C. R. Brandt, and F. Tufaro. 1995. Evidence for an interaction of herpes simplex virus with chondroitin sulfate proteoglycans during infection. *Virology* **208**:531–539.
- Bellamy, F., V. Barberousse, N. Martin, P. Masson, J. Millet, S. Samreth, C. Sepulchre, J. Theveniaux, and D. Horton. 1995. Thioxyloside derivatives as orally active venous antithrombotics. *Eur. J. Med. Chem.* **30**(Suppl.): 101S–115S.
- Bellamy, F., D. Horton, J. Millet, F. Picart, S. Samreth, and J. B. Chazan. 1993. Glycosylated derivatives of benzophenone, benzhydrol, and benzhydrol as potential venous antithrombotic agents. *J. Med. Chem.* **36**:898–903.
- Bergey, E. J., and M. W. Stinson. 1988. Heparin-inhibitable basement membrane-binding protein of *Streptococcus pyogenes*. *Infect. Immun.* **56**: 1715–1721.
- Bernfield, M., R. Kokenyesi, M. Kato, M. T. Hinkes, J. Spring, R. L. Gallo, and E. J. Lose. 1992. Biology of the syndecans: a family of transmembrane heparan sulfate proteoglycans. *Annu. Rev. Cell Biol.* **8**:365–393.
- Bourin, M. C., and U. Lindahl. 1993. Glycosaminoglycans and the regulation of blood coagulation. *Biochem. J.* **289**:313–330.
- Butcher, B. A., L. A. Sklar, L. C. Seamer, and R. H. Glew. 1992. Heparin enhances the interaction of infective *Leishmania donovani* promastigotes with mouse peritoneal macrophages: a fluorescence flow cytometric analysis. *J. Immunol.* **148**:2879–2886.
- Cerami, C., U. Frevert, P. Sinnis, B. Takacs, P. Clavijo, M. J. Santos, and V. Nussenzweig. 1992. The basolateral domain of the hepatocyte plasma membrane bears receptors for the circumsporozoite protein of *Plasmodium falciparum* sporozoites. *Cell* **70**:1021–1033.
- Cerami, C., U. Frevert, P. Sinnis, B. Takacs, and V. Nussenzweig. 1994. Rapid clearance of malaria circumsporozoite protein (CS) by hepatocytes. *J. Exp. Med.* **179**:695–701.
- Chen, J. C. R., and R. S. Stephens. 1994. Trachoma and LGV biovars of *Chlamydia trachomatis* share the same glycosaminoglycan-dependent mechanism for infection of eukaryotic cells. *Mol. Microbiol.* **11**:501–507.
- Chen, J. C. R., J. P. Zhang, and R. S. Stephens. 1996. Structural requirements of heparin binding to *Chlamydia trachomatis*. *J. Biol. Chem.* **271**: 11134–11140.
- Chen, T., R. J. Belland, J. Wilson, and J. Swanson. 1995. Adherence of pilus<sup>+</sup> Opa<sup>+</sup> gonococci to epithelial cells *in vitro* involves heparan sulfate. *J. Exp. Med.* **182**:511–517.
- Chmiela, M., B. Paziak-Domanska, W. Rudnicka, and T. Wadström. 1995. The role of heparan sulfate-binding activity of *Helicobacter pylori* bacteria in their adhesion to murine macrophages. *APMIS* **103**:469–474.
- Choi, S. H., and M. W. Stinson. 1989. Purification of a *Streptococcus mutans* protein that binds to heart tissue and glycosaminoglycans. *Infect. Immun.* **57**:3834–3840.
- Choi, S. H., and M. W. Stinson. 1991. Binding of a *Streptococcus mutans* cationic protein to kidney *in vitro*. *Infect. Immun.* **59**:537–543.
- Clayette, P., E. Moczar, A. Mabondzo, M. Martin, B. Toutain, D. Marcé, and D. Dormont. 1996. Inhibition of human immunodeficiency virus infection by heparin derivatives. *AIDS Res. Hum. Retroviruses* **12**:63–69.
- Compton, T., D. M. Nowlin, and N. R. Cooper. 1993. Initiation of human cytomegalovirus infection requires initial interaction with cell surface heparan sulfate. *Virology* **193**:834–841.
- Danishefsky, I., and E. Siskovic. 1971. Conversion of carboxyl groups of mucopolysaccharides into amides of amino acid esters. *Carbohydr. Res.* **16**:199–205.
- David, G. 1993. Integral membrane heparan sulfate proteoglycans. *FASEB J.* **7**:1023–1030.
- Do Carmo Ciavaglia, M., T. U. De Carvalho, and W. De Souza. 1993. Interaction of *Trypanosoma cruzi* with cells with altered glycosylation patterns. *Biochem. Biophys. Res. Commun.* **193**:718–721.
- Esko, J. D. 1991. Genetic analysis of proteoglycan structure, function and metabolism. *Curr. Opin. Cell Biol.* **3**:805–816.
- Esko, J. D., and R. I. Montgomery. 1995. Synthetic glycosides as primers of oligosaccharide biosynthesis and inhibitors of glycoprotein and proteoglycan assembly, p. 17.11.1–17.11.6. *In* F. M. Ausubel, R. Brent, R. Kingston, D. D. Moore, J. G. Seidman, J. A. Smith, K. Struhl, A. Varki, and J. Coligan (ed.), *Current protocols in molecular biology*. Greene Publishing and Wiley-Interscience, New York.

30. Esko, J. D., T. E. Stewart, and W. H. Taylor. 1985. Animal cell mutants defective in glycosaminoglycan biosynthesis. *Proc. Natl. Acad. Sci. USA* **82**:3197–3201.
31. Esko, J. D., J. L. Weinke, W. H. Taylor, G. Ekborg, L. Rodén, G. Anantharamaiah, and A. Gawish. 1987. Inhibition of chondroitin and heparan sulfate biosynthesis in Chinese hamster ovary cell mutants defective in galactosyltransferase I. *J. Biol. Chem.* **262**:12189–12195.
32. Falkow, S. 1991. Bacterial entry into eukaryotic cells. *Cell* **65**:1099–1102.
33. Falkow, S., R. R. Isberg, and D. A. Portnoy. 1992. The interaction of bacteria with mammalian cells. *Annu. Rev. Cell Biol.* **8**:333–363.
34. Freeze, H. H., D. Sampath, and A. Varki. 1993.  $\alpha$ - and  $\beta$ -Xylosidases alter glycolipid synthesis in human melanoma and Chinese hamster ovary cells. *J. Biol. Chem.* **268**:1618–1627.
35. Frevert, U., P. Sinnis, C. Cerami, W. Shreffler, B. Takacs, and V. Nussen-zweig. 1993. Malaria circumsporozoite protein binds to heparan sulfate proteoglycans associated with the surface membrane of hepatocytes. *J. Exp. Med.* **177**:1287–1298.
36. Fried, M., and P. E. Duffy. 1996. Adherence of *Plasmodium falciparum* to chondroitin sulfate A in the human placenta. *Science* **272**:1502–1504.
37. Fritz, T. A., F. N. Lugenwa, A. K. Sarkar, and J. D. Esko. 1994. Biosynthesis of heparan sulfate on beta-D-xylosides depends on aglycone structure. *J. Biol. Chem.* **269**:300–307.
38. Gallagher, J. T., and M. Lyon. 1989. Molecular organization and functions of heparan sulphate, p. 135–158. *In* D. A. Lane and U. Lindahl (ed.), *Heparin, chemical and biological properties: clinical applications*. Edward Arnold Ltd., London.
39. Gerber, S. I., B. J. Belval, and B. C. Herold. 1995. Differences in the role of glycoprotein C of HSV-1 and HSV-2 in viral binding may contribute to serotype differences in cell tropism. *Virology* **214**:29–39.
40. Gillette-Castro, B. L., A. Prakobphol, A. L. Burlingame, H. Leffler, and S. J. Fisher. 1991. Structure and bacterial receptor activity of a human salivary proline-rich glycoprotein. *J. Biol. Chem.* **266**:17358–17368.
41. Glurich, I., B. Winters, B. Albini, and M. Stinson. 1991. Identification of *Streptococcus pyogenes* proteins that bind to rabbit kidney *in vitro* and *in vivo*. *Microb. Pathog.* **10**:209–220.
42. Gruenheid, S., L. Gatzke, H. Meadows, and F. Tufaro. 1993. Herpes simplex virus infection and propagation in a mouse L cell mutant lacking heparan sulfate proteoglycans. *J. Virol.* **67**:93–100.
43. Guimond, S., M. Maccarana, B. B. Olwin, U. Lindahl, and A. C. Rapraeger. 1993. Activating and inhibitory heparin sequences for FGF-2 (basic FGF): distinct requirements for FGF-1, FGF-2, and FGF-4. *J. Biol. Chem.* **268**:23906–23914.
44. Guo, B. P., S. J. Norris, L. C. Rosenberg, and M. Höök. 1995. Adherence of *Borrelia burgdorferi* to the proteoglycan decorin. *Infect. Immun.* **63**:3467–3472.
45. Hannah, J. H., F. D. Menozzi, G. Renaud, C. Locht, and M. J. Brennan. 1994. Sulfated glycoconjugate receptors for the *Bordetella pertussis* adhesin filamentous haemagglutinin (FHA) and mapping of the heparin-binding domain on FHA. *Infect. Immun.* **62**:5010–5019.
46. Herold, B. C., S. I. Gerber, B. J. Belval, A. M. Siston, and N. Shulman. 1996. Differences in the susceptibility of herpes simplex virus types 1 and 2 to modified heparin compounds suggest serotype differences in viral entry. *J. Virol.* **70**:3461–3469.
47. Herold, B. C., S. I. Gerber, T. Polonsky, B. J. Belval, P. N. Shaklee, and K. Holme. 1995. Identification of structural features of heparin required for inhibition of herpes simplex virus type 1 binding. *Virology* **206**:1108–1116.
48. Herold, B. C., R. J. Visalli, N. Susmarski, C. R. Brandt, and P. G. Spear. 1994. Glycoprotein C (gC)-independent binding of herpes simplex virus to cells requires cell surface heparan sulfate and virion glycoprotein B (gB). *J. Gen. Virol.* **75**:1211–1222.
49. Herrera, E. M., M. Ming, E. Ortega-Barria, and M. E. A. Pereira. 1994. Mediation of *Trypanosoma cruzi* invasion by heparan sulfate receptors on host cells and penetrin counter-receptors on the trypanosomes. *Mol. Biochem. Parasitol.* **65**:73–83.
50. Hirno, S., M. Utt, M. Ringner, and T. Wadström. 1995. Inhibition of heparan sulphate and other glycosaminoglycans binding to *Helicobacter pylori* by various polysulphated carbohydrates. *FEMS Immunol. Med. Microbiol.* **10**:301–306.
51. Hoepelman, A. I. M., and E. I. Tuomanen. 1992. Consequences of microbial attachment: directing host cell functions with adhesins. *Infect. Immun.* **60**:1729–1733.
52. Holt, G. D., H. C. Krivan, G. J. Gasic, and V. Ginsburg. 1989. Antistatin, an inhibitor of coagulation and metastasis, binds to sulfatide (Gal(3-SO<sub>4</sub>) beta 1-1Cer) and has a sequence homology with other proteins that bind sulfated glycoconjugates. *J. Biol. Chem.* **264**:12138–12140.
53. Humphries, D. E., and J. E. Silbert. 1988. Chlorate: a reversible inhibitor of proteoglycan sulfation. *Biochem. Biophys. Res. Commun.* **154**:365–371.
54. Inoue, Y., and K. Nagasawa. 1976. Selective N-desulfation of heparin with dimethyl sulfoxide containing water or methanol. *Carbohydr. Res.* **46**:87–95.
55. Iozzo, R. V., and A. D. Murdoch. 1996. Proteoglycans of the extracellular environment: clues from the gene and protein side offer novel perspectives in molecular diversity and function. *FASEB J.* **10**:598–614.
56. Isaacs, R. D. 1994. *Borrelia burgdorferi* bind to epithelial cell proteoglycans. *J. Clin. Invest.* **93**:809–819.
57. Isberg, R. R. 1991. Discrimination between intracellular uptake and surface adhesion of bacterial pathogens. *Science* **252**:934–938.
58. Ito, M., M. Baba, A. Sato, R. Pauwels, E. De Clercq, and S. Shigeta. 1987. Inhibitory effect of dextran sulfate and heparin on the replication of human immunodeficiency virus (HIV) *in vitro*. *Antiviral Res.* **7**:361–367.
59. Jockusch, B. M., P. Bubeck, K. Giehl, M. Kroemker, J. Moschner, M. Rothkegel, M. Rüdiger, K. Schlüter, G. Stanke, and J. Winkler. 1995. The molecular architecture of focal adhesions. *Annu. Rev. Cell Biol.* **11**:379–416.
60. Kan, M., F. Wang, J. Xu, J. W. Crabb, J. Hou, and W. L. McKeehan. 1993. An essential heparin-binding domain in the fibroblast growth factor receptor kinase. *Science* **259**:1918–1921.
61. Karlsson, A., M. Markfjäll, H. Lundqvist, N. Strömberg, and C. Dahlgren. 1995. Detection of glycoprotein receptors on blotting membranes by binding of live bacteria and amplification by growth. *Anal. Biochem.* **224**:390–394.
62. Karlsson, K.-A. 1989. Animal glycosphingolipids as membrane attachment sites for bacteria. *Annu. Rev. Biochem.* **58**:309–350.
63. Karlsson, K. A. 1995. Microbial recognition of target-cell glycoconjugates. *Curr. Opin. Struct. Biol.* **5**:622–635.
64. Kato, M., H. Wang, M. Bernfield, J. T. Gallagher, and J. E. Turnbull. 1994. Cell surface syndecan-1 on distinct cell types differs in fine structure and ligand binding of its heparan sulfate chains. *J. Biol. Chem.* **269**:18881–18890.
65. Kihlström, E., M. Majeed, B. Rozalska, and T. Wadström. 1992. Binding of *Chlamydia trachomatis* serovar L2 to collagen types I and IV, fibronectin, heparan sulphate, laminin, and vitronectin. *Zentralb. Bakteriell.* **277**:329–333.
66. Kjellén, L., and U. Lindahl. 1991. Proteoglycans: structures and interactions. *Annu. Rev. Biochem.* **60**:443–475.
67. Kolset, S. O., and J. T. Gallagher. 1990. Proteoglycans in haemopoietic cells. *Biochim. Biophys. Acta* **1032**:191–211.
68. Lankes, W., A. Griesmacher, J. Grünwald, R. Schwartz-Albiez, and R. Keller. 1988. A heparin-binding protein involved in inhibition of smooth-muscle cell proliferation. *Biochem. J.* **251**:831–842.
69. Leong, J. M., P. E. Morrissey, E. Ortega-Barria, M. E. A. Pereira, and J. Coburn. 1995. Hemagglutination and proteoglycan binding by the Lyme disease spirochete, *Borrelia burgdorferi*. *Infect. Immun.* **63**:874–883.
70. Liang, O. D., F. Ascencio, L.-Fransson, and T. Wadström. 1992. Binding of heparan sulfate to *Staphylococcus aureus*. *Infect. Immun.* **60**:899–906.
71. Liang, O. D., F. Ascencio, R. Vazquez-Juarez, and T. Wadström. 1993. Binding of collagen, fibronectin, lactoferrin, laminin, vitronectin, and heparan sulphate to *Staphylococcus aureus* strain V8 at various growth phases and under nutrient stress conditions. *Zentralb. Bakteriell.* **279**:180–190.
72. Lidholt, K., J. L. Weinke, C. S. Kiser, F. N. Lugenwa, K. J. Bame, S. Cheifetz, J. Massagué, U. Lindahl, and J. D. Esko. 1992. A single mutation affects both N-acetylglucosaminyltransferase and glucuronosyltransferase activities in a Chinese hamster ovary cell mutant defective in heparan sulfate biosynthesis. *Proc. Natl. Acad. Sci. USA* **89**:2267–2271.
73. Linhardt, R. J. 1995. Analysis of glycosaminoglycans with polysaccharide lyases, p. 17.13.17–17.13.32. *In* F. M. Ausubel, R. Brent, R. Kingston, D. D. Moore, J. G. Seidman, J. A. Smith, K. Struhl, A. Varki, and J. Coligan (ed.), *Current protocols in molecular biology*. Greene Publishing and Wiley Interscience, New York.
74. Liu, Z., and A. S. Perlin. 1992. Regioselectivity in the sulfation of some chemically-modified heparins, and observations on their cation-binding characteristics. *Carbohydr. Res.* **236**:121–133.
75. Lloyd, A. G., G. Embery, and L. J. Fowler. 1971. Studies on heparin degradation. I. Preparation of 35S sulphamate derivatives for studies on heparin degrading enzymes of mammalian origin. *Biochem. Pharmacol.* **20**:637–648.
76. Locht, C., P. Bertin, F. D. Menozzi, and G. Renaud. 1993. The filamentous haemagglutinin, a multifaceted adhesin produced by virulent *Bordetella* spp. *Mol. Microbiol.* **9**:653–660.
77. Love, D. C., J. D. Esko, and D. M. Mosser. 1993. A heparin-binding activity on leishmania amastigotes which mediates adhesion to cellular proteoglycans. *J. Cell Biol.* **123**:759–766.
78. Lycke, E., M. Johansson, B. Svennerholm, and U. Lindahl. 1991. Binding of herpes simplex virus to cellular heparan sulphate, an initial step in the adsorption process. *J. Gen. Virol.* **72**:1131–1137.
79. Lyon, M., J. A. Deakin, and J. T. Gallagher. 1994. Liver heparan sulfate structure: a novel molecular design. *J. Biol. Chem.* **269**:11208–11215.
80. Maccarana, M., B. Casu, and U. Lindahl. 1993. Minimal sequence in heparin/heparan sulfate required for binding of basic fibroblast growth factor. *J. Biol. Chem.* **268**:23898–23905.
81. Maccarana, M., Y. Sakura, A. Tawada, K. Yoshida, and U. Lindahl. 1996. Domain structure of heparan sulfates from bovine organs. *J. Biol. Chem.* **271**:17804–17810.
82. Mascellani, G., L. Liverani, P. Bianchini, B. Parma, G. Torri, A. Bisio, M.

- Guerrini, and B. Casu.** 1993. Structure and contribution to the heparin cofactor II-mediated inhibition of thrombin of naturally oversulphated sequences of dermatan sulphate. *Biochem. J.* **296**:639–648.
83. **Menozi, F. D., R. Mutombo, G. Renaud, C. Gantiez, J. H. Hannah, E. Leininger, M. J. Brennan, and C. Loch.** 1994. Heparin-inhibitable lectin activity of the filamentous hemagglutinin adhesin of *Bordetella pertussis*. *Infect. Immun.* **62**:769–778.
84. **Murphy-Ullrich, J. E., L. G. Westrick, J. D. Esko, and D. F. Mosher.** 1988. Altered metabolism of thrombospondin by Chinese hamster ovary cells defective in glycosaminoglycan synthesis. *J. Biol. Chem.* **263**:6400–6406.
85. **Murray, P. A., A. Prakobphol, T. Lee, C. I. Hoover, and S. J. Fisher.** 1992. Adherence of oral streptococci to salivary glycoproteins. *Infect. Immun.* **60**:31–38.
86. **Nagasawa, K., Y. Inoue, and T. Kamata.** 1977. Solvolytic desulfation of glycosaminoglycuronan sulfates with dimethyl sulfoxide containing water or methanol. *Carbohydr. Res.* **58**:47–55.
87. **Neyts, J., and E. De Clercq.** 1995. Effect of polyanionic compounds on intracutaneous and intravaginal herpesvirus infection in mice: impact on the search for vaginal microbicides with anti-HIV activity. *J. Acquired Immune Defic. Syndr.* **3**:1–5.
88. **Neyts, J., R. Snoeck, D. Schols, J. Balzarini, J. D. Esko, A. Van Schepdael, and E. De Clercq.** 1992. Sulfated polymers inhibit the interaction of human cytomegalovirus with cell surface heparan sulfate. *Virology* **189**:48–58.
89. **Noel, G. J., D. C. Love, and D. M. Mosser.** 1994. High-molecular-weight proteins of nontypeable *Haemophilus influenzae* mediate bacterial adhesion to cellular proteoglycans. *Infect. Immun.* **62**:4028–4033.
90. **Ortega-Barria, E., and M. E. Pereira.** 1991. A novel T. cruzi heparin-binding protein promotes fibroblast adhesion and penetration of engineered bacteria and trypanosomes into mammalian cells. *Cell* **67**:411–421.
91. **Pancake, S. J., G. D. Holt, S. Mellouk, and S. L. Hoffman.** 1992. Malaria sporozoites and circumsporozoite proteins bind specifically to sulfated glycoconjugates. *J. Cell Biol.* **117**:1351–1357.
92. **Patel, M., M. Yanagishita, G. Roderiquez, D. C. Bou-Habib, T. Oravecz, V. C. Hascall, and M. A. Norcross.** 1993. Cell-surface heparan sulfate proteoglycan mediates HIV-1 infection of T-cell lines. *AIDS Res. Hum. Retroviruses* **9**:167–174.
93. **Patton, W. A., C. A. Granzow, L. A. Getts, S. C. Thomas, L. M. Zotter, K. A. Gunzel, and L. J. Lowe-Krentz.** 1995. Identification of a heparin-binding protein using monoclonal antibodies that block heparin binding to porcine aortic endothelial cells. *Biochem. J.* **311**:461–469.
94. **Prakobphol, A., P. A. Murray, and S. J. Fisher.** 1987. Bacterial adherence on replicas of sodium dodecyl sulfate-polyacrylamide gels. *Anal. Biochem.* **164**:5–11.
95. **Rej, R. N., K. G. Ludwig-Baxter, and A. S. Perlin.** 1991. Sulfation of some chemically-modified heparins: formation of a 3-sulfate analog of heparin. *Carbohydr. Res.* **210**:299–310.
96. **Roderiquez, G., T. Oravecz, M. Yanagishita, D. C. Bou-Habib, H. Mostowski, and M. A. Norcross.** 1995. Mediation of human immunodeficiency virus type 1 binding by interaction of cell surface heparan sulfate proteoglycans with the V3 region of envelope gp120-gp41. *J. Virol.* **69**:2233–2239.
97. **Rogerson, S. J., S. C. Chaiyaroj, K. Ng, J. C. Reeder, and G. V. Brown.** 1995. Chondroitin sulfate A is a cell surface receptor for *Plasmodium falciparum*-infected erythrocytes. *J. Exp. Med.* **182**:15–20.
98. **San Antonio, J. D., J. Slover, J. Lawler, M. J. Karnovsky, and A. D. Lander.** 1993. Specificity in the interactions of extracellular matrix proteins with subpopulations of the glycosaminoglycan heparin. *Biochemistry* **32**:4746–4755.
99. **Schmidt, K.-H., F. Ascencio, L. Fransson, W. Köhler, and T. Wadström.** 1993. Studies on binding of glycosaminoglycans to *Streptococcus pyogenes* by using <sup>125</sup>I-heparan sulphate as a probe. *Zentralb. Bacteriol.* **279**:472–483.
100. **Shaklee, P. N., and H. E. Conrad.** 1986. The disaccharides formed by deaminative cleavage of N-deacetylated glycosaminoglycans. *Biochem. J.* **235**:225–236.
101. **Shieh, M.-T., D. WuDunn, R. I. Montgomery, J. D. Esko, and P. G. Spear.** 1992. Cell surface receptors for herpes simplex virus are heparan sulfate proteoglycans. *J. Cell Biol.* **116**:1273–1281.
102. **Shieh, M. T., and P. G. Spear.** 1994. Herpesvirus-induced cell fusion that is dependent on cell surface heparan sulfate or soluble heparin. *J. Virol.* **68**:1224–1228.
- 102a. **Sinnis, P.** Personal communication.
103. **Sinnis, P., P. Clavijo, D. Fenyo, B. T. Chait, C. Cerami, and V. Nussenzweig.** 1994. Structural and functional properties of region II-plus of the malaria circumsporozoite protein. *J. Exp. Med.* **180**:297–306.
104. **Spear, P. G.** 1993. Entry of alphaherpesviruses into cells. *Virology* **4**:167–180.
105. **Spear, P. G., M.-T. Shieh, B. C. Herold, D. WuDunn, and T. I. Koshy.** 1992. Heparan sulfate glycosaminoglycans as primary cell surface receptors for herpes simplex virus, p. 341–351. *In* D. A. Lane and U. Lindahl (ed.), *Heparin and related polysaccharides*. Plenum Press, New York.
106. **Taylor, R. L., J. E. Shively, and H. E. Conrad.** 1976. Stoichiometric reduction of uronic acid carboxyl groups in polysaccharides. *Methods Carbohydr. Chem.* **7**:149–151.
107. **Trybala, E., T. Bergström, B. Svennerholm, S. Jeansson, J. C. Glorioso, and S. Olofsson.** 1994. Localization of a functional site on herpes simplex virus type 1 glycoprotein C involved in binding to cell surface heparan sulphate. *J. Gen. Virol.* **75**:743–752.
108. **Vacca-Smith, A. M., C. A. Jones, M. J. Levine, and M. W. Stinson.** 1994. Glucosyltransferase mediates adhesion of *Streptococcus gordonii* to human endothelial cells in vitro. *Infect. Immun.* **62**:2187–2194.
109. **Van Putten, J. P. M., and S. M. Paul.** 1995. Binding of syndecan-like cell surface proteoglycan receptors is required for *Neisseria gonorrhoeae* entry into human mucosal cells. *EMBO J.* **14**:101–111.
110. **Varki, A.** 1993. Biological roles of oligosaccharides: all of the theories are correct. *Glycobiology* **3**:97–130.
111. **Winters, B. D., N. Ramasubbu, and M. W. Stinson.** 1993. Isolation and characterization of a *Streptococcus pyogenes* protein that binds to basal laminae of human cardiac muscle. *Infect. Immun.* **61**:3259–3264.
112. **Woods, A., and J. R. Couchman.** 1994. Syndecan 4 heparan sulfate proteoglycan is a selectively enriched and widespread focal adhesion component. *Mol. Biol. Cell* **5**:183–192.
113. **WuDunn, D., and P. G. Spear.** 1989. Initial interaction of herpes simplex virus with cells is binding to heparan sulfate. *J. Virol.* **63**:52–58.
114. **Zhang, J. P., and R. S. Stephens.** 1992. Mechanism of *C. trachomatis* attachment to eukaryotic host cells. *Cell* **69**:861–869.

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