have been classified according to the interaction of the virus with the H, A, B, and Le epitopes (Fig. 1) [6, 7]. HBGAs are important factors for determining host specificity, although it is still unclear whether HBGAs act as the primary receptor or enhance norovirus infectivity. Researchers including ourselves have demonstrated that feline calicivirus (FCV), a member of the genus Vesivirus, infects the upper respiratory tract by attaching to α2-6-linked sialic acids and using junctional adhesion molecule-1 for internalization [8, 9]. It is comparatively easy to study the life cycle of FCV because the virus replicates efficiently in cell culture without specific supplementation, whereas noroviruses are not cultivable in cell culture.

Interaction between Enteric Bacteria and Carbohydrates

Carbohydrates also function as receptors for bacterial attachment at the initial step of infection. Here, we describe the role of carbohydrates in bacterial infections, focusing on *Salmonella enterica* and several assortative bacterial species that produce a variety of fimbrial adhesions (Fig. 2).

Salmonella strains cause disease in diverse mammalian hosts. Some *Salmonella* strains have a narrow host range, such as *Salmonella enterica* serovar Typhi (*S. typhi*) and serovar Paratyphi (*S. paratyphi*), which cause disease only in humans, whereas strains such as *Salmonella enterica* serovar Typhimurium (*S. typhimurium*) and serovar Enteritidis (*S. entertitidis*) cause infection in numerous species including mice, poultry, pigs, sheep, cattle, horses and humans [2].

Infected orally, *Salmonella* reach the intestinal tract and then mainly attach to the M cells of the intestinal epithelium to initiate invasion [10]. After colonization of the intestinal epithelium, Typhoid *Salmonella*, *S. typhi* and *S. paratyphi*, invade M cells. However, *S. typhi* and *S. paratyphi* can also survive being engulfed by macrophages, which then spread throughout the body via the lymphatic and blood systems. Non-typhoidal *Salmonella*, *S. typhimurium* and *S. enteritidis* cannot survive within macrophages (Fig. 3). They cause gastroenteritis in humans and animals by colonizing the intestinal epithelium and then invading and destroying the M cells and enterocytes [2].

Bacterial adherence requires both specific and non-specific interactions. In the case of *Salmonella*, the negative charge produced by sialic acid on the surface of the host cell is required as a non-specific adherence factor [11]. For their specific interactions, *Salmonella* and assortative bacteria possess various adhesion molecules such as a variety of bacterial fimbriae. At the initial infection step, bacterial attachment is mainly controlled by these bacterial fimbriae. Individual fimbria recognize and bind to specific receptors to promote adhesion to the host cell surface [2, 12].

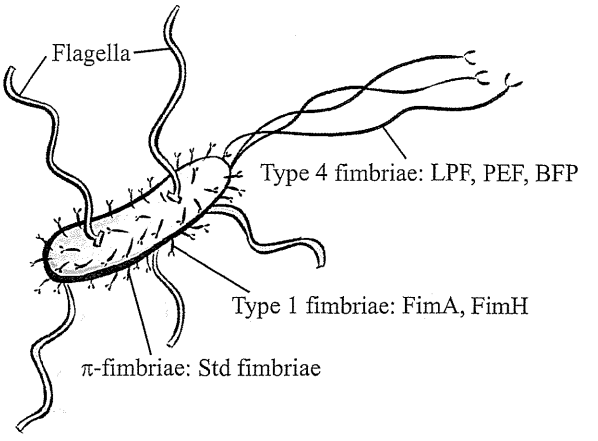

Fig. 2. General structure and localization of bacterial fimbriae and flagella.
Gram-negative bacteria have many kinds of fimbriae (pili) and flagella. Bacterial lectin-like adhesive molecules (adhesins) included in bacterial fimbriae recognize and bind to sugar-containing molecules on the host cell surface. Bacterial fimbriae and adhesins contribute to bacterial attachment, the initial step of bacterial infection. Each bacterial adhesin recognizes a specific structure of its target sugar molecule, and bacterial fimbriae also help to determine the specificity (species, tissue, or cell) of bacterial infection. Two types of representative fimbriae of *Salmonella* and assortative bacteria (Type 1 fimbriae and Type 4 fimbriae) are shown. Type 1 fimbriae are short and highly expressed entirely on the surface of bacteria. Type 4 fimbriae are thin and flexible, expressed at low levels, and are generally located at the polar part of bacteria. FimA and FimH are categorized as Type 1 fimbriae. Long-polar fimbriae (LPF), Plasmid-code fimbriae (PEF) and bundle-forming pili (BFP) are categorized as Type 4 fimbriae. Std fimbriae are categorized as π-fimbriae. Bacterial flagella are the moving apparatus of bacteria, but their components can also contribute to the binding to sugar-containing molecules.

Long polar fimbriae (LPF) and plasmid-code fimbriae (PEF) are categorized as type 4 fimbriae (Fig. 2). Std fimbriae are categorized as π-fimbriae [2, 13–15]. A previous report showed that when one of the fimbriae carried by *Salmonella typhimurium* was deleted, only virulence for mouse was moderately altered, and that multiple fimbrial adhesins were required for full virulence [16]. For *Salmonella* and assortative bacteria, type 1 fimbria is the

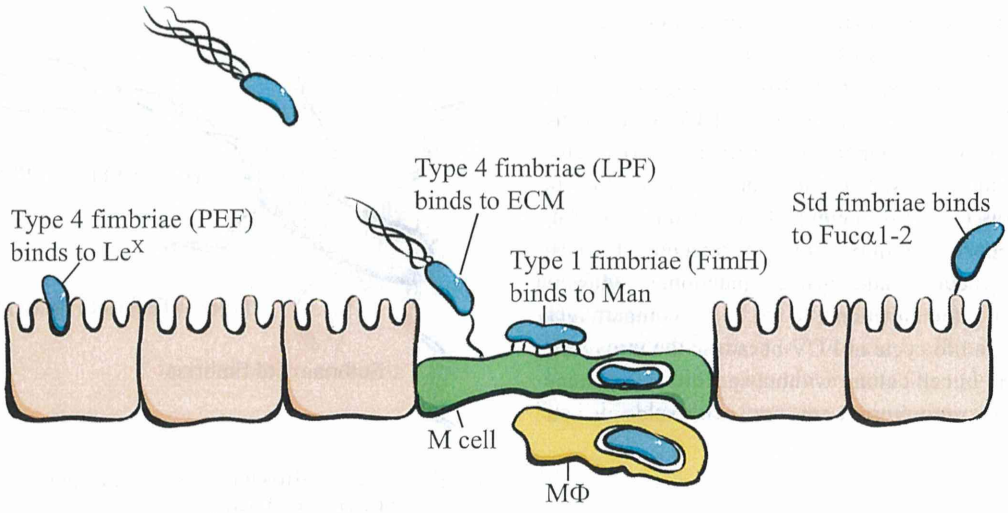

Fig. 3. Various fimbriae of *Salmonella* and assortative bacteria and their sugar-containing receptor molecules.
Salmonella and assortative bacteria express a variety of fimbriae. The minor component of Type 1 fimbriae, FimH, is present at the tip of type 1 fimbriae, mediates binding to D-mannose-containing structures and enables bacteria to colonize various host tissues [18]. Type 1 fimbria is highly expressed on the bacterial surface, allowing large amounts of bacteria to adhere via the FimH-mannose interaction.
The various kinds of type 4 fimbriae play an important role in bacterial infection. Plasmid-encoded fimbria (PEF) is required for bacterial attachment to intestinal epithelial cells. PEF specifically binds to trisaccharide Galβ1-4(Fucα1-3)GlcNAc, also known as the Lewis X (Le^X) blood group antigen [13].
Long polar fimbria (LPF) mediates the adhesion of *S. typhimurium* to murine Peyer's patches [21]. Extracellular matrix proteins (ECMs) may act as receptors for LPF. ECMs are modified with various carbohydrate moieties, and the presence of Mannose inhibits the LPF-ECM interaction. Mannose-containing carbohydrates may participate in bacterial adhesion via LPF [23].
Std fimbriae are categorized as π-fimbriae and are well conserved among *S. enterica* serotypes but absent from other related bacterial species. Std fimbriae recognize and bind the H type 2 histo-blood group oligosaccharide, the terminal Fucα1-2Galβ1 moiety.
S. typhi and *S. paratifi* can survive within the macrophages after they are engulfed by phagocytosis. Non-typhoidal *Salmonella*, *S. typhimurium* and *S. enteritidis*, however, are unable to survive within macrophages.

best characterized [17]. Type 1 fimbriae consist of a major component (FimA) and a minor component (FimH) (Fig. 2). FimH lies at the tip of type 1 fimbriae, where it mediates binding to D-mannose-containing structures and enables the bacteria to colonize various host tissues [18]. Type 1 fimbriae are also produced by other gram-negative bacteria, such as *Escherichia coli* and *Klebsiella pneumoniae* [19]. The FimH protein of enterobacterial species including *Salmonella* recognizes mannose-containing oligosaccharides [18]. In the case of *E. coli*, previous reports have shown that FimH protein has a considerably high affinity for oligosaccharides containing Manα1-3, such as Manα1-3Manβ1-4GlcNAc and Manα1-6(Manα1-3)Manα1-6(Manα1-4)Man, which are constituents of cell surface glycoproteins [19]. The process of bacterial adhesion to the epithelial cell surface mediated by Type 1 fimbriae (FimH) is conservative among enterobacteria. Type 1 fimbriae are highly expressed on the bacterial surface, allowing large quantities of bacteria to adhere via the FimH-Mannose interaction (Fig. 3).

Type 4 fimbriae are thin and flexible, and generally expressed at a lower level than type 1 fimbriae. Some type 4 fimbriae are only present at low levels on the surface of bacteria, and are localized at the bacterial pole. Although their expression level is low, type 4 fimbriae frequently play an important role in bacterial infection. Like type 1 fimbriae, type 4 fimbriae are thought to recognize carbohydrates as specific receptors, but the receptor molecules and precise functions of some type 4 fimbriae have yet to be determined. For example, the function of the type 4 fimbria bundle-forming pili (BFP), an important virulence factor for pathogenic *E. coli* strains, is not yet known (Fig. 2). BFP may not be involved in initial adhesion; rather, it may participate in the formation of the bacterial colony by forming bundles that link one bacterium to another [20]. Although the function of and receptors for type 4 fimbriae remain unclear, bacterial virulence has been shown to decrease when type 4 fimbriae are deleted [16]. LPF medi-

ates the adhesion of *S. typhimurium* to murine Peyer's patches [21]. LPF was first described in *S. typhimurium*, and is found in numerous pathogenic *E. coli* strains [22]. Although its specific receptor remains unclear, extracellular matrix proteins (ECMs), which comprise an interlocking mesh of fibrous proteins and glycosaminoglycans, may act as a receptor for LPF of enterohemorrhagic *E. coli* O157:H7 (Fig. 3). ECMs are modified by various carbohydrate moieties, and the addition of mannose inhibits LPF-ECM interaction. Then mannose-containing carbohydrates may participate in bacterial adhesion by LPF [23].

In some cases, type 4 fimbriae are encoded on plasmids. Such plasmids frequently encode virulence factors for host bacteria, and are therefore called "virulence plasmids" [24]. PEF is required for bacterial attachment to intestinal epithelial cells. It specifically binds to trisaccharide Galβ1-4(Fucα1-3)GlcNAc, also known as the Lewis X (Le^X) blood group antigen (Fig. 3) [13]. The Le^X antigen is defined by the presence of a terminal Galβ1-4(Fucα-3)GlcNAc moiety on saccharide chains of glycoproteins or glycosphingolipids; in the human intestine, it is expressed mainly in crypt epithelial cells [25]. *S. typhimurium* possesses PEF as an adhesin that binds to a crypt-specific histo-blood group antigen that may be relevant to the pathogenesis of human infections. Abundant crypt abscesses are commonly found in *S. typhimurium* patients, raising the possibility that the pathogen may bind to human crypt epithelium at a later stage of infection. In a situation where Peyer's patches are unavailable because of an inflammatory reaction, *Salmonella* can colonize at the crypt epithelium remaining intact and persist on the surface of the host intestinal tract [13, 25].

On the other hand, some type 4 fimbriae participate in "fimbria-mediated (pilus-mediated) conjugal transfer" of so-called "conjugative plasmids". Conjugative plasmids can also be virulence plasmids if they encode not only the structural genes of the fimbriae but also other virulence factors, such as a drug resistance gene. These conjugative plasmids spread to other bacteria by horizontal transfer, and type 4 fimbriae encoded on the plasmids play an important role in this event. For example, the R64 plasmid, which encodes the *pilV* gene and engages in the adhesion of type 4 fimbriae, recognizes the di-saccharide moiety of bacterial surface polysaccharides (the core oligosaccharide or O-antigen unit of lipopolysaccharides, a unique structure of the bacterial cell surface) and determines the recipient bacteria of the conjugal transfer [26, 27].

Categorized as π-fimbriae, the std fimbriae are well conserved among *S. enterica* serotypes but absent from related bacterial species (Fig. 2). Std fimbriae recognize and bind the H type 2 histo-blood group oligosaccharide, the terminal Fucα1-2Galβ1-4GlcNAc moiety. This structure represents the H type 2 oligosaccharide of the O blood group antigen [14]. The H type 2 oligosaccharide of the O blood group antigen moiety is expressed as part of the mucin-type sugar chains of glycoproteins in the host cell. The terminal Fucα1-2 moiety of H type 2 oligosaccharide of the O blood group antigen is essential for the recognition of Std fimbriae (Fig. 3).

Carbohydrate molecules act not only as "anchors" for pathogens but also as the determinants of host and tissue specificity. The variety of adhesion factors carried by a bacterium reflects its pathogenic profile, magnitude of virulence, host specificity, and tissue specificity. In the case of *Salmonella* and assortative bacteria, the FimH adhesins show amino acid sequence diversity. This diversity in FimH structure results in the variation in affinity profiles. *E. coli* FimH shows a high affinity for aromatic α-mannosides as well as Manα1-3 structures. On the other hand, the FimH of *Salmonella* species shows a high affinity for α-mannosides and a low affinity for aromatic α-mannosides [19]. In the case of *Salmonella*, allelic variation of FimH adhesion directs not only host cell-specific recognition but also distinctive binding to mammalian and avian receptors. This allele-specific binding profile parallels the host specificity of the respective FimH-expressing pathogen [28]. Similarly, the Lewis b (Le^b) blood group phenotype in combination with secretor status may hinder colonization of *Helicobacter pylori* in certain populations [29]. *H. pylori* express blood group antigen b-binding adhesion (BabA), and BabA binds to Le^b antigens. *Salmonella* and assortative bacteria contain various adhesion factors, including several kinds of fimbriae, which contribute to bacterial virulence; however, analyses of their specific receptor moieties and functions are not yet complete [13, 15].

Carbohydrate moieties on the surface of pathogens are also recognized by hosts and trigger host defense mechanisms. The bacterial surface is covered with various kinds of carbohydrates. For gram-negative bacteria, including *Salmonella*, the major carbohydrate component of the bacterial surface is lipopolysaccharide (LPS). LPS is categorized as a glycolipid, and is a major component of the bacterial outer membrane. Because the saccharide moieties of LPS differ structurally from mammalian carbohydrates, they function as targets of the host immune response. To avoid this host immune response, the LPS of some bacteria, for example *C. jejuni*, is structurally similar to the glycosphingolipids of gangliosides [30, 31]. Similarly, the LPS of most *H. pylori* strains expresses the Le^a and Le^b antigens [29].

Interestingly, the carbohydrate on the surface of the

host cell itself can be involved in the host defense mechanism. The *Salmonella* flagella component FliC contributes to bacterial attachment to the host cell by interacting with ganglioside molecules on the surface of the host cell, but gangliosides also act as co-receptors for *Salmonella* enterica FliC and promote FliC induction of the human innate immune response [32]. Gangliosides, i.e. sialic acid-containing glycosphingolipids, are ubiquitous components of eukaryotic cell membranes that have been identified as receptors for bacterial toxins and viruses. An *in vitro* assay showed that a nonflagellated mutant of *S. enteritidis*, constructed by disrupting the *fliC* gene, was about 50-fold less invasive than the wild-type strain, but bacterial adherence was unaffected [33]. At the attachment of *Salmonella enteritidis* FliC to the host cell surface, gangliosides thus function as receptors.

On the other hand, the flagella component protein FliC induces the host innate immune response by binding to Toll-like receptor 5 of the host cell, and gangliosides react as co-receptors with TLR5 on the FliC-induced response. An *in vitro* assay showed that the incorporation of exogenous ganglioside GD1a into the Caco-2 cell membrane increased the effect of FliC. Incubation of Caco-2 cells with a glucosylceramide synthase inhibitor reduced the innate immune response stimulated by FliC [32].

Interaction between Enteric Protozoa and Carbohydrates

Human enteropathogenic protozoas include the apicomplexans *Toxoplasma gondii* and *Cryptosporidium* as well as *Giardia* and *Entamoeba histolytica*. They are all zoonotic pathogens that invade and colonize their target tissues in the alimentary tract of the human host. They form hard cysts that resist degradation in the stomach. Host-derived proteases and low pH trigger their excystation [34].

In this section, we describe the role of carbohydrates in *Toxoplasma gondii* invasion of intestinal epithelial cells. The ability of *T. gondii* to infect Chinese hamster ovary (CHO) cells deficient in sialic acids was reduced by 26.9% compared to wild-type cells, indicating that sialic acid is critical for attachment and invasion of *T. gondii* (Fig. 4) [35]. *T. gondii* microneme protein 1 (TgMIC1) forms a macromolecular complex with TgMIC4 and TgMIC6. Single deletion of the *TgMIC1* gene significantly decreases the invasion of host cells, suggesting an essential role for TgMIC1 in host cell attachment and invasion of *T. gondii* [36]. Structural analysis of TgMIC1 revealed a novel cell-binding motif called microneme adhesive repeat region (MARR), which provides a specialized structure for glycan

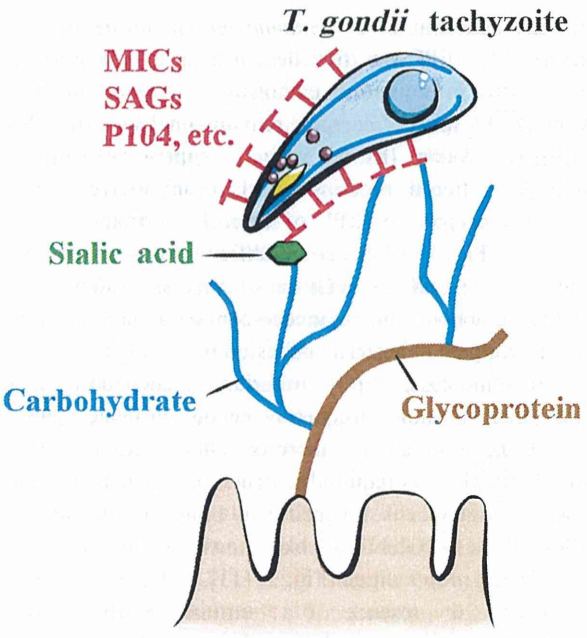

Fig. 4. Schematic image of enteric pathogen (in this case *T. gondii*) invasion showing secreted proteins attached to carbohydrates on host cells.
Some of the proteins from *T. gondii* tachyzoite (e.g., MICs, SAGs, P104) can be secreted or membrane-bound and attached to sialic acids, carbohydrates and glycoproteins during invasion.

discrimination [37]. Carbohydrate microarray analyses showed that TgMIC13, TgMIC1 and its homologue *Neospora caninum* MIC1 share a preference for α2-3- over α2-6-linked sialyl-N-acetyllactosamine sequences [38]. P104, a PAN/apple domain-containing protein expressed at the apical end of the extracellular parasite, functions as a ligand in the attachment of *T. gondii* to chondroitin sulfate and other receptors on the host cell, facilitating invasion by the parasite (Fig. 4) [39].

T. gondii display GPI-anchored surface proteins identified as surface antigen glycoprotein (SAG) 1 related sequences (SRS) [40]. SAG1, SAG2A and SAG3 have some capacity for host cell attachment through glycan recognition (Fig. 4) [41, 42]. SAG3 binds to sulfated proteoglycans such as heparin, fucoidan, and dextran sulfate with high affinity [43]. Targeted disruption of SAG3 significantly reduces host cell binding of *T. gondii* [41].

E. histolytica fibronectin receptor (EhFNR) shows 99% homology to the intermediate subunit-2 of the Gal/GalNAc-specific lectin [44]. Electron microscopy revealed the close association of a purified EhFNR complex to adhesion plates and phagocytic invaginations. Lipid rafts participate in interactions between *E. histolytica* and the host

extracellular matrix, and it appears that raft-associated Gal/GalNAc lectin serves as a collagen receptor [45].

Cryptosporidium parvum surface receptors, GP900 and proteolytic fragments of the 60-kDa precursor protein, GP40 and GP15, are characterized as mucin-like and heavily O-glycosylated proteins [46–48]. The GP900 and GP40 of sporozoites and merozoites have carbohydrate residues that are bound by αGalNAc-specific lectins, suggesting that αGalNAc residues are involved in the attachment of parasites to host cells via adherence to internal mucus.

Apicomplexan protozoan parasites also induce host innate immune responses via the carbohydrate molecules present on their cell surface [49]. Glycosylphosphatidylinositol (GPI) protein anchors are abundant in the membranes of tachyzoites and other apicomplexan protozoan parasites including *Trypanosoma*, *Leishmania* and *Plasmodium* spp., where they can serve as ligands for innate recognition [50]. The GPI moieties of *T. cruzi* and *P. falciparum* were found to be TLR2 ligands [51, 52], and *T. gondii* both stimulate cytokine production in macrophages and serve as TLR2 as well as TLR4 agonists. In the case of *T. gondii*, GPI induces TNF-α production in macrophages through the activation of the transcription factor NF-κB [53].

Comparison of the Interactions between Enteric Microbes and Carbohydrates

Carbohydrates serve as receptors for infections by viruses, bacteria and protozoa, but the usage of carbohydrates by these microbes varies depending on the microbe. At the initial infection step, these organisms do not simply utilize the electrical forces created by the positive and negative charges of the carbohydrates; rather, they make use of other systems in certain instances. One similarity shared by all three microbes regarding their interactions with carbohydrates, however, is that heparan sulfate plays an important role at entry or invasion of the host cell.

Blood group antigen oligosaccharides are highly expressed in the gastrointestinal epithelium [54]. However, there are individual differences in terms of the presence of these antigens. In addition, there are individual differences in sensitivity to pathogens that recognize and bind to blood group antigens, such as norovirus and *H. pylori*. These individual differences in antigen expression profiles benefit the survival of the host species because the risk of an attack by a fatal virulent pathogen may be decreased to avoid extinction.

The Structure of Carbohydrates on the Surface of the Gastric and Intestinal Epithelium

A large array of glycoproteins, glycolipids and proteoglycans decorate the surface of animal cells. These glycoconjugates mediate many fundamental cellular processes, including cell-cell and cell-matrix adhesion, motility, growth and signaling [55–57]. Mucosal tissues represent the site of infection or route of access for most parasites, including viruses, bacteria and protozoa [58]. On the surface of the mucosal tissues of the gastrointestinal tracts, various carbohydrate moieties are present and play a crucial role in infection.

Mucosal surfaces are coated with a layer of viscous mucus that ranges in thickness from 300 μm in the stomach to 700 μm in the intestine [59–61]. Mucin glycoproteins from mucus-producing cells in the epithelium or submucosal glands are the major macromolecular constituent of mucus and are responsible for the viscous properties of the mucus gel. In addition to forming a relatively impervious gel, which acts as a lubricant, a physical barrier and a trap for microbes, mucus provides a matrix for a rich array of antimicrobial molecules. Underneath the mucus layer, the cells present a dense forest of highly diverse glycoproteins and glycolipids, which form the glycocalyx. Membrane-anchored cell-surface mucin glycoproteins are a major constituent of the glycocalyx in all mucosal tissues. The oligosaccharide moieties of the molecules that form the glycocalyx and the mucus layer are highly diverse, and the average turnover time of the human jejunal glycocalyx is 6–12 h [62]. Consequently, both the secreted and adherent mucosal barriers are constantly renewed and can rapidly adjust to changes in the environment, for example, in response to microbial infection.

Epithelial mucins are a heterogenous family of large complex glycoproteins containing a dense array of O-linked carbohydrates typically comprising over 70% of their mass. The carbohydrate structures present on mucosal surfaces vary according to cell lineage, tissue location and developmental stage [58]. Mucin glycosylation can alter in response to mucosal infection and inflammation, and this may be an important mechanism for unfavorable changes in the niche occupied by mucosal pathogens. The O-linked glycans of muchin proteins contain 1–20 residues, which occur both as linear and branched structures [58].

In addition to the O-linked glycans, mucins contain a smaller number of N-linked oligosaccharides, which have been implicated in folding, oligomerization (MUC2) and surface localization (MUC17) [63–65]. The terminal structures of mucin oligosaccharides are highly heterogeneous

and vary between and within species as well as between and even within tissues. The array of oligosaccharide structures on individual mucin molecules is also somewhat determined by stochastic events as the mucin protein moves through the Golgi apparatus [66]. The secreted mucins themselves likely function as decoys for adhesins that have been evolved by pathogens to engage the cell surface, as the mucins express many of the oligosaccharide structures found on the cell surface and are constitutively produced in large amounts, constantly washing the mucosal surfaces [58].

Proteoglycans are present on the cell surface [67] and are also components of glycocalyx. Glycosaminoglycan chains are composed of highly sulfated saccharides that give the cell surface a potent negative charge. One of the prototypical membrane proteoglycans is syndecan-1, which carries conserved attachment sites for glycosaminoglycan chains [67]. The syndecans exemplify hybrid proteoglycans because they contain mixtures of the two major types of glycosaminoglycan chains, heparan sulfate and chondroitin sulfate. The other major family of membrane proteoglycans is the glypicans, which contain GPI anchors in a tissue-specific and temporally regulated manner. Their presence in the basolateral membranes of polarized cells varies [68].

Glycolipids are also a component of the cell membrane. A large variety of glycolipids is present on the surface of animal cells. The carbohydrate moieties vary, and each glycolipid may exhibit a special function, as an annular lipid, surface receptor marker or matrix lipid. For brain and neuronal cells, gangliosides (sialic acid-bearing glycolipids) are the major cell surface determinants [69]. Glycolipids function as the receptor for various biologic factors and also as the receptor for various pathogens. They are present at the undermost part of the glycocalyx. Pathogens can recognize the glycolipids, directly bind to the cell membrane, and invade the host cell. Glycolipids also function as receptors for certain effector molecules, such as bacterial toxins, produced by pathogens and directly react with the host cell. For example, cholera toxin binds to ganglioside GM1 [70].

Thus, for pathogens living in the outer mucus layer, it is difficult to make contact with the surface of normal epithelial cells because of the huge amount of mucin that functions as a "decoy" or "physical barrier". Mucosal pathogens have, therefore, developed mechanisms to subvert these defense mechanisms of the mucosal layer. On the other hand, intestinal M cells, specifically designed to capture and present microbes to the underlying lymphoid tissue, can be regarded as a "hole" in the mucin barrier. The dome epithelium lacks goblet cells and therefore does not produce gel-forming mucins. Their apical cell surface has only sparse microvilli and an apparently thin glycocalyx [71, 72].

M cells are specialized epithelial antigen-transporting cells that constitute a minor proportion (5%~10% in humans and mice) of the follicle-associated epithelium that covers the lymphoid follicles of organized gut-associated lymphoid tissue such as Peyer's patches [73–76]. Glycoprotein 2 (GP2) was identified as an M cell-specific molecule [77]. The GP2 expressed on M cells functions as a bacterial uptake receptor [77]. GP2 recognizes FimH, a major component of the type 1 fimbriae, which binds to certain glycoproteins on mammalian cells in a mannose-dependent manner [78].

Consequently, even though M cells constitute only a very small percentage of mucosal epithelial cells, they are the major point of attachment and/or entry used by numerous mucosal pathogens including bacteria (e.g., *S. typhimurium*, *Shigella flexneri*, *Yersinia enterocolitica* and *Vibrio cholerae*), viruses (e.g., reovirus, HIV-1 and polio virus) and parasites (e.g., *Cryptosporidia*) [72, 79, 80].

The Association between Carbohydrates and Microbial Infection

During cell–pathogen interactions (i.e., infection and/or invasion), carbohydrates function as receptors for various pathogens. On the other hand, carbohydrates (glycoconjugates) can also function as a barrier to infection. On the surface of mucosal tissue, the glycocalyx physically prevents microbes from accessing the cell membrane. Some glycoconjugates, a component of the glycocalyx, contain carbohydrate structures that are recognized by pathogens. Mucins often contain oligosaccharide moieties that correspond to the receptor for various pathogens. On the surface of the mucosal layer, microbes binds to these receptor moieties and are captured at the mucus layer, which consequently blocks the infection. Moreover, when secretory mucins containing receptor carbohydrate structures "trap" pathogens, the pathogens are also carried away. M cells are specialized epithelial antigen-transporting cells scattered in the follicle-associated epithelium that covers the gut lymphoid follicles such as Peyer's patches. M cells can efficiently engulf particles as large as bacteria; however, the mucus layer of M cells and the surrounding area is relatively thin. Glycoconjugates such as GP2 are expressed on the surface of M cells and function as receptors for bacterial attachment [74]. In the case of the host-parasite interaction, the various kinds of glycoconjugates sometimes function as receptors for the invading pathogens, but they can also function as barriers

and traps for the host defense system.

Future Perspectives

In recent years, the damage caused by enteric pathogens, especially norovirus and *Salmonella*, has expanded through the food chain [4, 5, 81]. These pathogens cause food poisoning in humans and gastrointestinal diseases in animals all over the world. Even today, they are often responsible for large-scale outbreaks of food poisoning. Therefore, the prevention and treatment of infections caused by these pathogens is essential.

In this review, we discussed the interaction between host cells and microbes such as viruses, bacteria and protozoa that involve carbohydrates such as sialic acids, heparan sulfate, and the carbohydrate moieties of ABH and Lewis antigens, mannose components, ECMs and Le^X. The development and use of drugs that target these carbohydrates is anticipated, even though the microbes vary widely and have different modes of infection. Accordingly, when an anti-microbial drug is developed on the basis of the interaction between a microbe and a carbohydrate, host cell modification of the drug's structure and/or inhibition of the mode of infection will need to be individualized while still taking advantage of the similarities between interactions.

Moreover, the host gastrointestinal tract cell surface, which is the object of microbial infection, is composed of glycoproteins, glycolipids, and proteoglycans. These molecules are potential targets for carbohydrate drugs used in the treatment of infectious diseases.

Oseltamivir and zanamivir are neuraminidase inhibitors that competitively inhibit the activity of the viral neuraminidase on the sialic acid that is found on glycoproteins on the surface of host cells [82]. By blocking the activity of this enzyme, they prevent new viral particles being released from infected cells.

There are various kinds of polysaccharides on the surface of bacteria. Lipoteichoic acid (LTA), a type of glycolipid, is a component of the bacterial cell wall of gram-positive bacteria. Studies have shown that LTA stimulates the immune system [83, 84]. Recently, LTA has been studied for use as a novel kind of biologically active substance.

Recently, sulfated polysaccharides have been analyzed as drug candidates for protozoan infectious diseases [3, 85, 86]. According to our data, the sulfated positions in the carbohydrates can be critical for the inhibitory quality [3]. Collectively, these studies highlight the possibility that carbohydrate drugs may be developed for the prophylaxis and treatment of parasitic infectious diseases. The results of our studies highlight the possibilities for countermeasures against malaria and toxoplasmosis [3, 85].

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