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Fondness for sugars of enteric viruses confronts them with human glycans genetic diversity

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Abstract

Together, norovirus and rotavirus are responsible for the majority of gastroenteritis cases worldwide, leading to a large number of children deaths in low-income countries. Both attach to glycans of the histo-blood group antigen type (HBGAs) widely expressed in the digestive tract of vertebrates, albeit with interspecies differences. In humans, their synthesis is performed by glycosyltransferases encoded by the highly polymorphic *ABO*, *FUT2* and *FUT3* genes that are under long-term balanced selection. The combination of functional and null or weak alleles at these loci provides a diversity of glycan structures that define the ABO, secretor and Lewis phenotypes. At the initial stage of infection norovirus and rotavirus attach to these glycans although distinct strains of each virus present different specificities for individual glycans, hence exhibiting preferences for different human phenotypes. Absence or low expression of the recognized glycan motifs due to the genetic polymorphism is associated with resistance to the disease, showing that the HBGA polymorphisms provide a population-based innate protection. Epidemiologically dominant strains of either norovirus or rotavirus display specificity for glycan motifs present in large fractions of the population, which may differ between geographical areas in accordance with the frequency of the *ABO*, *FUT2*, *FUT3* gene polymorphisms. Evidence for virus adaptation to these geographical differences is amounting, indicative of a host-pathogen co-evolution and suggesting that enteric pathogens such as norovirus and rotavirus are likely driving forces behind the balanced HBGA polymorphisms.

Diarrheal disease affects millions of people of all ages worldwide. It is a leading cause of mortality in children younger than 5 years, second only to pneumonia (Liu et al. 2012a). Although a large array of pathogens is involved, enteric viruses are the principal agents of the disease, the two main viruses responsible for this burden being rotavirus (RV) and norovirus (NoV) (Banyai et al. 2018). Genetic adaptation to these viruses is to be expected given their massive extant impact on human populations, akin to other pathogens that imposed strong selection pressures during human evolution (Quintana-Murci 2019).

Norovirus is the leading cause of acute gastroenteritis when considered across all ages worldwide, with an estimate of 685 million cases amounting to 18% of all cases (Kirk et al. 2015). Although NoV gastroenteritis is generally rather mild, it is estimated to cause the death of 70,000 to 200,000 young children/year, the vast majority of them in low-income countries while there is no vaccine commercially available as yet (Banyai et al. 2018). NoVs are a group of genetically highly diverse viruses that belong to the *Caliciviridae* family. They are non-enveloped icosahedral viruses with a single stranded RNA genome, currently classified in ten genogroups, of which three infect humans: GI, GII and GIV, with GIV being comparatively rare. Owing to the virus diversity, genogroups are further subdivided into genotypes (Chhabra et al. 2019). Of these and for the past 20 years, the GII.4 genotype has been overwhelmingly dominant worldwide, claiming as many as 70-80% of NoV-related gastroenteritis cases. Every few years, increases in NoV outbreaks are recorded due to the emergence of antigenically distinct GII.4 variants (de Graaf et al. 2016). More recently, non-GII.4 norovirus genotypes such as the previously rare GII.17 genotype emerged and predominated in various parts of Asia (Ao et al. 2017; Kwok et al. 2017; Niendorf et al. 2017).

RV is the most common cause of diarrheal mortality in children under 5 years of age globally. Prior the availability of a vaccine, in 2008, RV caused an estimated 440.000 children deaths yearly, primarily occurring in low-income countries. Following introduction of vaccines in numerous countries, this number diminished substantially, with the most recent estimate counting 129.000 deaths/year (Tate et al. 2016; Troeger et al. 2018). Unfortunately, and for reasons that are still unclear, the vaccines prove less efficient in several low-income countries (Glass et al. 2014). RVs are double-stranded segmented and non-enveloped RNA viruses about 70 nm in size. They belong to the *Reoviridae* family. Based on the genetic variability of the VP6 proteins that constitute the viral capsid intermediate layer, at least 8 different species (A to H) of rotaviruses are defined (Matthijnssens et al. 2012). The vast majority of human

cases are caused by group A rotaviruses (RVAs). Within RVAs, the two outer capsid proteins VP7 and VP4 are used for further classification of strains, defining the G- and P- genotypes, respectively. The majority of cases is due to viruses carrying G1P[8], G2P[4], G3P[8], G4P[8], G12P[8] and G9P[8], although other G and P combinations are being found in increasing numbers (Desselberger 2014). Notably, recent reports describe increasing rotavirus genotype diversity and circulation of non-vaccine genotypes in post-vaccine era (Roczo-Farkas et al. 2018; Tanaka et al. 2017), though immune-escaped strains have yet to be identified.

A common feature of human NoVs and RVAs is that they bind to a set of glycan motifs called histo-blood group antigens (HBGAs), which include ABH and Lewis antigens, through the external domain of their protruding capsid protein: the P domain of the unique capsid protein for NoVs and the VP8* domain of the VP4 capsid protein for RVAs. This review does not attempt to provide a comprehensive view of the topic since most of the relevant work has recently been reviewed (Nordgren and Svensson 2019; Ramani et al. 2016; Ruvöen-Clouet et al. 2013; Schroten et al. 2016; Singh et al. 2015b; Tan and Jiang 2014). It rather aims at discussing the potential consequences of this shared virus property of binding to polymorphic glycans. We will argue that these enteric viruses likely constitute a major factor driving evolution of glycan polymorphism, although other factors such as pathogenic bacteria, parasitic diseases, the microbiota and nutritional factors could also be involved (Cooling 2015).

Common genetic polymorphisms of glycans in the human small intestine

The mucosal surface of the small intestine is lined with a thick layer of glycans, mainly O-glycans of the mucin type, that forms a barrier likely restricting virus access to the enterocyte cell plasma membrane. Upon entrance into the intestine, enteric viruses will first encounter these complex sugars that they will use for attachment in an initial phase of the infection process. Unlike proteins, glycans are not direct products of the genes encoding regions. Their synthesis requires a large set of proteins that includes glycosyltransferases. These enzymes are involved in glycan biosynthesis by adding monosaccharides from phosphorylated donor molecules to acceptors that can be lipids, proteins, or other saccharides. Based on sequence similarities, these enzymes have been classified into more than 100 families (Cantarel et al. 2009). Several human glycosyltransferases belonging to the GT6, GT10 and GT11 families

present common genetic polymorphisms that lead to a loss of function, or to a severely decreased catalytic activity. They contribute to synthesis of the so-called HBGAs. The frequency of these mutant alleles varies geographically. As a result, combinations of these genes polymorphisms generate glycan diversity both in terms of expressed glycan motifs and of their distribution across human populations. In addition, variations also exist between mammalian species. HBGAs substitute a wide variety of protein-bound glycans (*N*-glycans and *O*-glycans) as well as lipid-bound glycans (glycosphingolipids) found at the surface of epithelial cells of various tissues in all mammals and secreted free or in complex forms in biological fluids such as saliva and milk. In the human small intestinal mucosa, the target of enteric viruses, the glycosyltransferases genes involved in the synthesis of HBGAs are the *ABO* gene of the GT6 family, the *FUT2* or secretor gene of the GT11 family and the *FUT3* or Lewis gene of the GT10 family (Fig. 1a). As depicted, the ABO, secretor and Lewis phenotypes of each individual depend on the combined polymorphisms at the three loci *ABO*, *FUT2* and *FUT3*. The H antigen is synthesized by addition of a fucose residue in α1,2 linkage and forms the precursor of the A and B antigens, as well as of the Lewis b and Lewis y antigens. In populations of European ancestry, about 20% individuals are devoid of α1,2-linked fucose in the small intestinal surface epithelium due to homozygosity of a null *FUT2* allele. Addition of a fucose residue in α1,4 or α1,3 linkage generates the Lewis antigens. Null *FUT3* alleles are responsible for the Lewis negative phenotype, represented by below 10% of individuals in populations of European ancestry (Race and Sanger 1975). In addition to their genetic polymorphism, several members of these important glycosyltransferases gene families correspond to pseudogenes in humans while they remain functional in other species (Abrantes et al. 2009; Nystrom et al. 2015; Turcot-Dubois et al. 2007). A prime example is given by the *GGTA1* gene of the GT6 family. It encodes an α1,3galactosyltransferase that catalyzes the transfer of a galactose residue onto an N-acetyllactosamine (type 2 precursor) to generate the so-called alphaGal antigen (Fig. 1b). The gene is functional in all mammals with the exception of Apes. When functional, its tissue expression pattern varies in a species-dependent manner. Thus, the corresponding alphaGal antigen is strongly expressed in bovine small intestine epithelial cells, but not in the porcine corresponding cells whilst it is completely lacking in all human tissues (Macher and Galili 2008; Zakhour et al. 2009).

HBGA-binding specificity of NoVs and RVAs is a driver of their epidemiology

Initial studies on noroviruses showed that the capsid protein of the prototype Norwalk strain (GI.1) attached to HBGAs containing the α1,2-linked fucose dependent upon functional *FUT2* alleles, such as Lewis b, H and A antigens, but not B antigen and that volunteers of the nonsecretor phenotype were fully resistant to infection by that strain (Lindesmith et al. 2003; Marionneau et al. 2002). Consistent with the virus glycan specificity, B blood group individuals proved partially protected (Hutson et al. 2002). Later studies indicated that most other strains also attached to HBGAs, albeit with varying specificities (Huang et al. 2005; Huang et al. 2003; Ruvöen-Clouet et al. 2013; Tan and Jiang 2011). Based on their glycan specificities, human noroviruses have been classified into subgroups according to their dependency upon the ABO, the secretor or the Lewis phenotypes (Le Pendu et al. 2006; Tan and Jiang 2014). Structural analyses described the interactions between the virus capsid protein protruding domain (P-domain) and various HBGA oligosaccharides. Several distinct binding sites and modes of binding across the norovirus strains diversity have thus been uncovered, illustrating the adaptation of noroviruses to the human gut glycan diversity (Bu et al. 2008; Cao et al. 2007; Chen et al. 2011; Choi et al. 2008; Hansman et al. 2011; Koromyslova et al. 2015; Kubota et al. 2012; Qian et al. 2018; Shanker et al. 2014; Singh et al. 2015a).

A large number of epidemiological studies comprehensively reviewed recently (Nordgren and Svensson 2019) reported an overall strong protection effect of the *FUT2* mutant alleles in the homozygous state. However, the effect was not found in all studies. This is likely explained by the diversity of strains involved in outbreaks. Indeed, the glycan-binding site of some strains favors recognition of the α1,4-linked fucose added by the *FUT3* enzyme with little influence of the α1,2-linked fucose, allowing recognition of both the secretor and nonsecretor phenotypes (Huang et al. 2005). Most likely, these strains are dependent on the presence of functional *FUT3* alleles and spare Lewis negative individuals as demonstrated through a study conducted in Burkina Faso where the frequency of Lewis negative individuals is high (Nordgren et al. 2013). An impact of the ABO phenotypes has also been reported, again with disparities across studies, likely explained by variations in the strains patterns of glycan recognition (Ruvöen-Clouet et al. 2013).

An important aspect concerns the GII.4 strains that have emerged as globally dominant strains in the past 20 years and the more recently emerged GII.17 strains as dominant epidemiologically in some parts of Asia (Chan et al. 2015; de Graaf et al. 2016). Among noroviruses, GII.4 strains stand out not only because of their prevalence but also because of

their evolution with periodic replacement by new immune escape variants, akin to influenza virus (de Graaf et al. 2016; Mallory et al. 2019). The reasons behind their large epidemiological dominance remain unclear, but their HBGA-binding characteristics could represent one of the underlying driving forces. GII.4 strains appear to recognize all secretor individuals, regardless of their ABO and Lewis status. In addition, an increased relative affinity for HBGAs paralleled the appearance of epidemiological dominance of GII.4 variants (de Rougemont et al. 2011). These characteristics confer GII.4 strains a broad spectrum of susceptible hosts worldwide and might contribute to facilitate transmission (Ruvöen-Clouet et al. 2013; Tan and Jiang 2011). Quite similarly, the recently emerged GII.17 strains also show much increased and broad spectrum HBGA binding ability in comparison with their older variants, which could contribute to their strong epidemiological impact (Chan et al. 2015; Qian et al. 2018; Zhang et al. 2015). Unlike GII.4 strains, these emergent GII.17 strains failed to become dominant outside Asian countries where the major *FUT2* mutant alleles confer a weak, albeit not null, secretor phenotype that potentially expands the susceptible fraction of the population (Ferrer-Admetlla et al. 2009; Pang et al. 2001). The presence of true nonsecretors due to nonsense mutation in the *FUT2* mutant alleles of African and European populations might contribute to restrict their transmission outside these Asian countries. Alternatively, the more limited spread of emergent GII.17 strains in comparison with pandemic GII.4 strains might be related to their lower relative affinity for HBGAs.

Earlier work on animal rotaviruses indicated these viruses bind to sialic acid (Lopez and Arias 2004). However, more recently it was shown that similar to noroviruses, human rotaviruses attach to HBGAs in a strain-dependent manner with distinct P genotypes using different binding sites (Hu et al. 2018; Jiang et al. 2017; Ramani et al. 2016; Tan and Jiang 2014). Thus, the VP8* attachment protein domain from strains of the P[8] and P[4] genotypes specifically binds to the Lewis b antigen (Barbé et al. 2018; Huang et al. 2012; Liu et al. 2012b; Sun et al. 2016a). Epidemiological studies reported a strong association between RVA gastroenteritis and the secretor phenotype, consistent with the requirement of a functional *FUT2* allele for synthesis of the Lewis b antigen in the small intestine (Imbert-Marcille et al. 2013; Kambhapati et al. 2015; Nordgren et al. 2014; Sun et al. 2016b; Van Trang et al. 2014; Yang et al. 2017). Studies performed in Burkina Faso and China additionally reported a much lower risk among children presenting a Lewis negative phenotype, also consistent with the requirement of the FUT3 enzyme in the synthesis of the Lewis b structure (Nordgren et al. 2014; Yang et al. 2017) and in accordance with a recent structural study showing that both the

a1,2 and a1,4-linked fucose residues are involved in the P[8] VP8* binding site (Xu et al. 2019). Nonetheless, two studies conducted in Tunisia and Bangladesh, failed to detect any effect of the secretor phenotype for P[8] rotavirus infection (Ayouni et al. 2015; Lee et al. 2018). These seemingly contradictory observations may be explained by the co-circulation of classical P[8] strains (P[8]-1-3) with emerging P[8]-4 strains (Zeller et al. 2015) that present a distinct glycan recognition pattern in these countries where high frequencies of nonsecretor and Lewis negative individuals are present (authors manuscript in preparation). The study conducted in Burkina Faso reported an association between the Lewis negative phenotype and infection by P[6] strains, whereas no association with the secretor phenotype was detected for these strains. This could also be explained by their glycan-binding specificity since they recognize a motif of the HBGA type 1 precursor and that addition of the α1,4-linked fucose impairs binding (Barbé et al. 2018). As a result, Lewis positive individuals are less well recognized, irrespective of their secretor phenotype (Barbé et al. 2018; Liu et al. 2016). Interestingly, the frequency of the Lewis negative phenotype is much higher in Burkina Faso than in most regions of the world (≈ 30% vs <10%), likely explaining why these P[6] strains preferentially circulate in some geographical areas of Africa and Asia.

As depicted on Fig. 2, this could have a strong impact on the efficacy of vaccines in such countries since the two major presently available vaccines have a P[8] subtype, their VP8* attaching to the Lewis b epitope, akin to circulating P[8] strains. Accordingly, low vaccine take was observed among nonsecretor children (Bucardo et al. 2018; Kazi et al. 2017; Lee et al. 2018).

RV strains with P[9], P[14] and P[25] genotypes bind to the A blood group antigen and *in vitro* studies demonstrated that this antigen serves as a functional receptor for this group of strains that circulate in domestic animals while not frequently encountered in humans (Hu et al. 2012; Liu et al. 2012b; Matthijnssens et al. 2009). Likewise, a group C rotavirus strain mainly involved in animal infection and in limited human family-based outbreaks was recently shown to exclusively recognize the blood group A antigen (Sun et al. 2018). Considering that the frequency of A antigen expression at the intestinal level in the population does not exceed 30%, it is not surprising that such strains do not dominate the human epidemiology, but rather cause sporadic outbreaks. The shared presence of the A antigen in the human intestine with that of most other mammals, including pigs and cows, likely contributes to cross-species transmission of these strains.

Inversely, species-specific expression of HBGAs may represent a species barrier. Thus, both bovine specific GIII norovirus strains and the bovine specific P[5] rotavirus strains attach specifically to the alphaGal HBGA (Fig. 1b) that is not expressed in humans but present in the bovine small intestinal mucosa (Alfajaro et al. 2019; Zakhour et al. 2009). Its recognition by bovine-specific strains of both norovirus and rotavirus constitutes an interesting case of convergent host-species adaptation.

Conclusions

A common feature of human noroviruses and rotaviruses binding to HBGAs is that the combined *ABO*, *FUT2* and *FUT3* genes polymorphisms allow protection of a substantial fraction of individuals from the disease caused by any given strain. This corresponds to a population or herd innate protection that may have emerged from a host-pathogen co-evolution process as documented in the case of RHDV and European rabbits (Le Pendu et al. 2014; Ruvöen-Clouet et al. 2013).

Overall, epidemiologically dominant strains possess HBGA-binding characteristics that allow them to recognize a broad host-spectrum, facilitating their transmission. In contrast strains that bind to glycans expressed in a more limited fraction of the population show a globally lower epidemiological impact. Moreover, regional differences in the epidemiology of these viruses can be accounted for, at least in part, by the variable frequencies of HBGA polymorphisms across human populations. This may contribute, among other factors, to explain the variable vaccines efficacies observed across countries since available rotavirus vaccines are live attenuated viruses.

The *ABO* gene comprises a large number of alleles, making it one of the most polymorphic human genes. Consistent with a role in host-microbes interactions, several studies indicated that it underwent a long-lived balancing selection that contributed to maintain the two major functional alleles along with the silent alleles (Calafell et al. 2008; Segurel et al. 2012; Villanea et al. 2015). Likewise, a long history of balancing selection has been detected for *FUT2* alleles (Ferrer-Admetlla et al. 2009; Silva et al. 2010). Maintenance of their polymorphisms over long evolutionary times indicates strong selective pressure by pathogenic agents. Interestingly, signs of long-term adaptation in the human genome were recently shown to have primarily occurred in response to RNA virus selection pressure (Azevedo et al. 2015; Enard and Petrov 2018). Since ABH antigens are expressed in the gut of all mammalian

species, whilst their additional presence on the vascular endothelium and red blood cells is restricted to Old World Monkeys and Apes, respectively, the balancing selection at the *ABO* locus was suggested to have originated in response to co-evolution with gut pathogens (Segurel et al. 2013). Thus, considering the high burden they impose on human populations and their strong impact on young children, noroviruses and rotaviruses arguably constitute major drivers of the balanced polymorphisms at the *ABO*, *FUT2* and possibly *FUT3* loci.

Conflict of interest statement:

On behalf of both authors, the corresponding author states that there is no conflict of interest.

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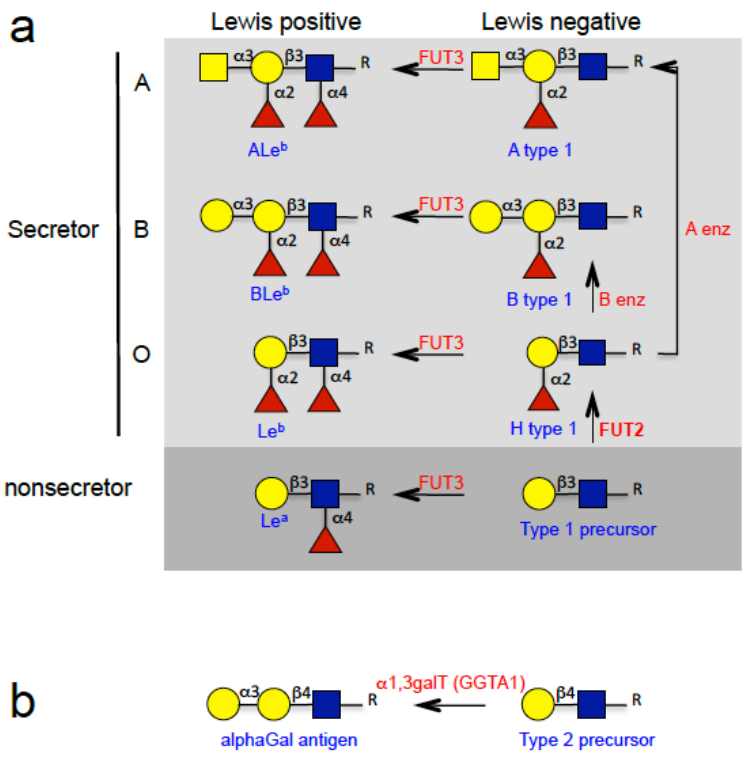


Figure 1: Biosynthesis of histo-blood group antigens in epithelial cells. **a/** synthesis of ABH and Lewis antigens starts from a precursor disaccharide (type 1 precursor) that represents the terminal portion of glycolipids, O- or N-glycans of glycoproteins. The enzymes FUT2 (in bold), FUT3, A and B (A enz, B enz) denoted in red, sequentially add monosaccharides to form the A, B, H and Lewis antigens denoted in blue. Polymorphisms of the *FUT2*, *FUT3* and *ABO* genes generate subgroups of people with distinct phenotypes with characteristic antigens expression (Secretor/nonsecretor, Lewis positive/Lewis negative, A, B and O). All allelic variants can be found in the BGMUT database (Patnaik et al. 2012). The *FUT2* G428A mutation introduces a stop codon and corresponds to a fully inactive allele found in many populations except in Asia. By Contrast, the A385T mutation found in Asia generates a protein with I>F amino acid change at position 129 which decreases its enzymatic activity. It is responsible for the so-called "secretor weak" phenotype. Of note, at each step of the biosynthesis, some untransformed structures remain (i.e. some type 1 precursor will still be available in Lewis positive individuals; or H type 1 in A or B secretors). **b**/ The alphaGal antigen is synthesized from type 2 precursor by addition of a galactose residue in α1,3 linkage. This is catalyzed by the α1,3 galactosyltransferase of the GT6 or ABO family

encoded by the *GGTA1* gene. The gene is functional in all mammal species but Apes. Owing to the lack of this epitope, humans possess circulating so-called natural anti-alphaGal antibodies, akin to natural anti-A and anti-B.

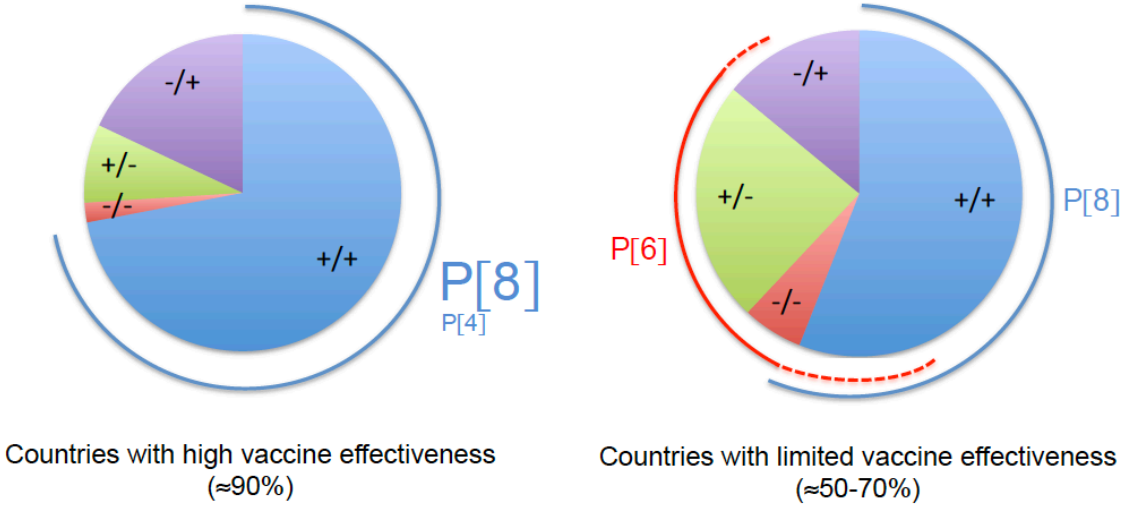


Figure 2: Impact of the frequencies of HBGA polymorphisms on rotavirus epidemiology and expected consequences on vaccine efficacy. Frequencies of HBGAs in two types of geographical areas are represented. In most developed countries (left) the combination of FUT2 and FUT3 positive individuals (Secretor/Lewis positive phenotype in blue) is high (Race and Sanger 1975), allowing circulation of strains with specificity for the difucosylated Lewis b antigen (P[8] and P[4]) that include the Rotarix and Rotateq attenuated live vaccine strains (Barbé et al. 2018; Desselberger 2014). Children with the remaining phenotypes, nonsecretor/Lewis positive (purple), Secretor/Lewis negative (green) and nonsecretor/Lewis negative (orange) are largely resistant to the disease caused by these strains (Imbert-Marcille et al. 2013; Kambhapati et al. 2015; Nordgren et al. 2014; Yang et al. 2017). These countries present a good match between genetic susceptibility to the disease, circulating strains and vaccine strains, explaining the high vaccine effectiveness. In countries where higher frequencies of either *FUT2* or *FUT3* null alleles are encountered such as Burkina Faso (Nordgren et al. 2014) (right), strains such as P[6] that favor infection of Lewis negative individuals (orange and green) and recognize glycans from Lewis positive individuals to some extent can maintain transmission (Barbé et al. 2018). In such countries there is a partial mismatch between susceptibility to the disease and that to vaccine strains, likely contributing to the observed lower vaccine effectiveness (Glass et al. 2014). Arc of circles indicate the susceptible fraction of the population to strains of the same color. Broken parts of the orange

arc indicate partial genetic susceptibility. +/+, +/-, -/+ and -/- indicate positivity or negativity for the Secretor and Lewis (FUT2/FUT3) characters, respectively.