The binding mechanism of *Streptococcus suis* accessory virulence factor and adhesin SadP to globotetraosylceramide

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Abstract

Streptococcus suis is part of the pig commensal microbiome and a major pathogen causing pneumonia and meningitis in pigs and occasionally also zoonotic meningitis. According to genomic analysis, *S. suis* is divided into asymptomatic carriage, respiratory and systemic strains with distinct genomic signatures. The virulence factor *S. suis* adhesin P (SadP) recognizes the galabiose Galα1–4Gal-oligosaccharide. Based on its oligosaccharide fine specificity, SadP can be divided into subtypes P_N and P_O. We show here that subtype P_N is distributed in the systemic strains that cause meningitis, whereas type P_O is found in asymptomatic carriage and respiratory strains. Both types of SadP are shown to predominantly bind to pig lung globotriaosylceramide (Gb3). However, SadP adhesin from systemic subtype P_N strain also binds to globotetraosylceramide (Gb4). Mutagenesis studies of the galabiose-binding domain of type P_N SadP adhesin showed that the amino acid asparagine-285, which is replaced by an aspartate residue in type Po SadP, was required for binding to Gb4 and, strikingly, it was also required for interaction with the glycomimetic inhibitor phenylurea-galabiose. Molecular dynamics simulations provided further insight into the role of Asn-285 for Gb4 and phenylurea-galabiose binding, suggesting additional hydrogen bonding to terminal GalNAc of Gb4 and urea-group. Thus, the Asn-285-mediated molecular mechanism of type P_N SadP binding to Gb4 could be used as a candidate to selectively target *S. suis* in invasive systemic disease without interfering with commensal strains, which may open up new venues for developing intervention strategies against this pathogen.

Introduction

Bacterial adhesion to host cell surfaces is a prerequisite for infectious disease. Host cell surfaces are heavily covered by surface carbohydrates that form the glycocalyx layer (1, 2). Pathogenic bacteria and their toxins can treacherously exploit carbohydrates to attach and invade cells. One example is a group of endogenous glycosphingolipids, known as globo series membrane glycosphingolipids, which are grouped based on the Galα1–4Gal (galabiose) structure. Globo series glycolipids are cellular receptors for toxic action

67 of Verotoxins and for the attachment of bacteria, such as uropathogenic *Escherichia coli*, *Streptococcus suis*
68 and *Pseudomonas aeruginosa* (3–6).

69 Since antibiotics are increasingly losing their power, alternative antimicrobial compounds need to be
70 invented and developed (7, 8). Transformation of bacteria to antibiotic-resistant forms can be overcome by
71 developing compounds that block *in vivo* colonization and virulence factors without killing the pathogens. Cell
72 surface carbohydrate glycomimetics are the most tempting pipeline for the development of new generation of
73 antimicrobials (9, 10).

74 *Streptococcus suis* is found as a commensal bacterium in all pigs and it is an important pig pathogen
75 causing septicemia, pneumonia and meningitis. It also causes severe zoonotic meningitis. Based on clinical
76 outcome, the *S. suis* strains can be classified as asymptomatic carriage, respiratory and systemic strains. Recent
77 data show that *S. suis* produces an alarmingly vast array of factors causing high antibiotic resistance (11).
78 Genomic analysis shows that the asymptomatic carriage and systemic strains have clear differences in their
79 core and accessory genomes, whereas respiratory strains have more overlapping features (12). This could
80 suggest that environmental factors such as overcrowding and synergistic activities with other keystone
81 pathogens (13), can alter pigs to develop severe symptoms and pneumonia. Instead, the virulence genes are
82 enriched in systemic strains and their accessory genomes contribute to the invasive *S. suis* infections and
83 meningitis (12). There is multiple and redundant colonization and virulence factors required for *S. suis* disease.
84 The distribution of virulence factors is also different depending on the geographical regions impacting the
85 accessory genomes, which hampers the development of effective vaccines (14). In order to develop new
86 therapeutics and vaccines the molecular mechanisms of accessory virulence factors need to be resolved in
87 atomic level.

88 *S. suis* strains expressing SadP adhesin bind specifically to Galα1–4Gal-containing oligosaccharides
89 (15). Interestingly, galabiose-binding strains can be divided to subtypes P_N and P_O based on how they recognize
90 galabiose-containing carbohydrates in hemagglutination assays (16). Type P_N strains recognize galactose, *N*-
91 Acetylgalactosamine, and the ceramide-linked oligosaccharides Gb3 (Galα1–4Galβ1–4Glc) and Gb4
92 (GalNAcβ1–3Galα1–4Galβ1–4Glc). Subtype P_O recognizes only galactose and preferentially binds to Gb3.
93 Recently, *S. suis* galabiose-binding adhesin SadP was identified as an LPNTG-anchored cell-wall protein (6).

94 The carbohydrate interaction of SadP has been shown to mediate *S. suis* binding to pharyngeal epithelium and
95 intestinal epithelial cells (16, 17). In an *S. suis* murine infection model, the mice deficient in globotriaosyl
96 ceramide (Gb3) expression (knockout in alpha-1,4-galactosyltransferase A4GALT) developed less severe
97 brain inflammation and injury (18). Recently, low picomolar concentrations of glycomimetic 3-phenylurea-
98 galabiose-containing dendrimers were shown to block *S. suis* SadP (type P_N) adhesin binding activity (19).
99 However, the molecular basis of differences in galabiose-binding mechanisms of SadP adhesins have remained
100 elusive. In the present study, we have characterized the distribution of SadP subtypes in *S. suis* strains and the
101 molecular binding mechanism of type P_N and P_O SadP to globosyl oligosaccharides. The results show that *S.*
102 *suis* SadP type P_N is distributed in the systemic strains and its specific N285-mediated binding mechanisms to
103 globotetraosyl ceramide distinguishes it from type P_O sadP.

104 # Results

105 ## Sequence analysis of SadP subtypes P_N and P_O, structural modelling and distribution in *S.*
106 ## *suis* systemic, respiratory and non-clinical strains

107 SadP adhesins are 80 kDa LPNTG-anchored cell-wall proteins, which contain the signal sequence for
108 secretion, the N-terminal galabiose binding domain, tandem repeat domains and C-terminal LPNTG cell-wall
109 anchor domain (6). The galabiose-binding domains have no significant sequence homologs to other bacterial
110 proteins or to other carbohydrate binding domains. The SadP N-terminal galabiose-binding domains (aa125-
111 328) of hemagglutinating type P_N and type P_O strains were cloned, sequenced and compared with multiple
112 alignment (Fig 1A). The structure consists of three α-helixes and ten β-strands (β1-β10) that form a β-
113 sandwich core domain. The sequences of the N-terminal galabiose-binding domain of type P_N SadP adhesins
114 are 100 % identical and are found in virulent serotype 2 strains. There is more sequence variation in the
115 galabiose-binding site of type P_O SadP. The carbohydrate binding sites of types P_N and P_O are highly conserved
116 (Fig 1B). Interestingly there is a conservative change at position 285 from asparagine to aspartate, which could
117 have an effect for the interaction of type P_N SadP with GalNAcβ1–3Galα1–4Gal-oligosaccharide.

118 The distribution of *sadP* genes in clinical and non-clinical strains analyzed with core genome phylogeny
119 analysis is shown in Figure 1C. The gene of *sadP* type P_N was found in 91.9 % of systemic *S. suis* isolates

120 (88.1 % of strains isolated from brain), whereas only less than 1 % of strains had the gene encoding *sadP* type
121 P_O. Based on the maximum-likelihood core genome phylogeny analysis the type P_N SadP gene is found in
122 clonal virulent *S. suis* strains, which mostly belong to serotype 2. Interestingly, also serotype 14 strains isolated
123 from human meningitis cases have type P_N gene. Type P_O *sadP* was found more frequently in respiratory and
124 non-clinical strains.
125

126 **Purification and analysis of glycosphingolipid composition of porcine lung**

127 The interaction of recombinant SadP with globo series glycolipids has not been thoroughly
128 characterized. Moreover, whether SadP binds to Gb3 or Gb4 isolated from the pig tissues has not yet been
129 directly shown. The glycolipids were isolated from porcine lung and erythrocytes, in order to control that the
130 glycolipids isolated from the lungs were not contaminants derived from the erythrocytes remaining in the
131 lungs. The total non-acid glycosphingolipid fractions were hydrolyzed with endoglycoceramidase II of
132 *Rhodococcus* sp., and the oligosaccharides thereby obtained were analyzed by LC-ESI/MS using graphitized
133 carbon columns. This method gives resolution of isomeric oligosaccharides, and the MS^2 analyses gives
134 complete sequence information and allows differentiation of linkage positions by diagnostic cross-ring ^{0,2}A-
135 type fragment ions (20).

136 The base peak chromatograms from LC-ESI/MS of the oligosaccharides obtained by hydrolysis of the
137 total non-acid glycosphingolipid fractions of porcine erythrocytes and lung are shown in Figure 2A. By
138 comparison of the retention times and MS^2 spectra of oligosaccharides obtained from reference
139 glycosphingolipids, the major oligosaccharides obtained from porcine lung were tentatively identified as
140 globotriaosylceramide (Gb3, detected as a $[M-H^+]^-$ ion at *m/z* 503) and the blood group H type 2
141 pentasaccharide (H5-2, detected as a $[M-H^+]^-$ ion at *m/z* 852) (Figure 2A). The major oligosaccharides from
142 porcine erythrocytes were globotriaosylceramide (Gb3, detected as a $[M-H^+]^-$ ion at *m/z* 503),
143 globotetraosylceramide (Gb4, detected as a $[M-H^+]^-$ ion at *m/z* 706), and the blood group A type 2
144 hexasaccharide (A6-2, detected as a $[M-H^+]^-$ ion at *m/z* 1055) (Fig 2B). Thus, globotriaosylceramide was found
145 in both samples, but otherwise the two samples were significantly different. The total non-acid
146 glycosphingolipid fraction from porcine lung was thereafter separated by Iatrobeads chromatography. Aliquots

147 of the fractions obtained were analyzed by thin-layer chromatography, and fractions that were coloured green
148 by anisaldehyde were tested for binding of SadP using the chromatogram binding assay. The fractions were
149 thereafter pooled according to the mobility on thin-layer chromatograms and their SadP binding activity.
150

151 **The binding of SadP to neutral glycolipids isolated from porcine lung using TLC overlay**
152 **assay**

153 The separations gave two SadP binding fractions migrating in the triglycosylceramide region. One
154 fraction (0.2 mg) migrating as a single band was denoted fraction PL-1 (Fig 2B, lane 1), and one fraction (0.3
155 mg) migrating as a double band was denoted fraction PL-2 (Fig 2B, lane 2). In addition, one SadP binding
156 fraction (0.4 mg) with compounds migrating as tetraglycosylceramides was obtained (denoted fraction PL-4;
157 Fig 2B, lane 4).
158

159 **LC-ESI /MS of native SadP binding glycosphingolipids from porcine lung**

160 ESI/MS of the native fraction PL-1 gave a major $[M-H^+]^-$ ion at *m/z* 1132 (S1A Fig), indicating a
161 glycosphingolipid with three Hex, and sphingosine with non-hydroxy 24:1 fatty acid. MS^2 of the $[M-H^+]^-$ ion
162 at *m/z* 1132 gave a series of Y ions (Y_0 at *m/z* 646, Y_1 at *m/z* 808, and Y_2 at *m/z* 970) demonstrating a Hex-
163 Hex-Hex sequence combined with sphingosine with non-hydroxy 24:1 fatty acid (S1B Fig).
164 A $[M-H^+]^-$ ion at *m/z* 1132 was also obtained by ESI/MS of the native fraction PL-2 (S2 Fig). Here, the
165 major $[M-H^+]^-$ ion was seen at *m/z* 1022 (S2AB Fig), demonstrating a glycosphingolipid with three Hex, and
166 sphingosine with non-hydroxy 16:0 fatty acid. Also, here a Hex-Hex-Hex sequence was demonstrated by the
167 series of Y ions (Y_0 at *m/z* 536, Y_1 at *m/z* 698, and Y_2 at *m/z* 860) from MS^2 (S2D Fig).
168

169 **Endoglycoceramidase digestion and LC-ESI /MS of SadP binding glycosphingolipids from**
170 **porcine lung**

171 The base peak chromatograms from LC-ESI/MS of the oligosaccharides obtained by
172 endoglycoceramidase digestion of fractions PL-1 and PL-2 were very similar (S3AB Fig). Both had a $[M-H^+]^-$

173 ion at *m/z* 503 which eluted at the same retention time (17.4-18.4 min) as the saccharide obtained from
174 reference globotriaosylceramide (S3C Fig), while the saccharide from reference isoglobotriaosylceramide
175 eluted at 20.0-20.4 min (Figure S3D).

176 MS^2 of the ion at *m/z* 503 of fractions PL-1 and PL-2 gave in both cases two C-type fragment ions (C_1
177 at *m/z* 179 and C_2 at *m/z* 341) identifying a Hex-Hex-Hex sequence (Figure S3EF). A 4-substitution of the
178 internal Hex was demonstrated by the $^{0,2}A_2$ fragment ion at *m/z* 281 (20–22) . Taken together with the similarity
179 to the MS^2 spectrum of reference globotriaosyl saccharide (S3G Fig), this allowed identification of the
180 saccharides of fractions PL-1 and PL-2 as globotriaosyl saccharides (Galα1–4Galβ4Glc).

181 LC-ESI/MS of the oligosaccharides obtained by hydrolysis of fraction PL-4 with *Rhodococcus*
182 endoglycoceramidase II allowed a tentative identification of a globotetraosyl saccharide (GalNAcβ1–3Galα1–
183 4Galβ1–4Glc). This conclusion was based on the following spectral features: First, the base peak
184 chromatogram of fraction PL-4 had a $[M-H^+]^-$ ion at *m/z* 706 (Figure S4A), and MS^2 of this ion (S4B Fig) gave
185 a C-type fragment ion series (C_1 at *m/z* 220, C_2 at *m/z* 382, and C_3 at *m/z* 544), demonstrating a HexNAc-Hex-
186 Hex-Hex sequence. The $^{0,2}A_3$ fragment ion at *m/z* 484 demonstrated a 4-substituted Hex, while the $^{0,2}A_4$ ion at
187 *m/z* 646, and the $^{0,2}A_4$-H_2O ion at *m/z* 628, were derived from cross-ring cleavage of the 4-substituted Glc of
188 the lactose unit at the reducing end. The features of this MS^2 spectrum were very similar to the MS^2 spectrum
189 of the reference globotetraosyl saccharide (S4C Fig)

190 The base peak chromatogram of fraction PL-4 (S4A Fig) also had two $[M-H^+]^-$ ions at *m/z* 998, eluting
191 at 19.4 min and 21.4 min. In both cases MS^2 demonstrated a Fuc.Hex-(Fuc-)HexNAc-Hex-Hex sequence, and
192 the diagnostic ion at *m/z* 348 (S4D Fig) identified a Le^b hexasaccharide, whereas the diagnostic ion at *m/z* 510
193 (S4E Fig) identified a Le^y hexasaccharide (21).

194

195 **SadP subtype P_N and P_O binding to purified glycolipids**

196 TLC overlay assay is a powerful method to analyze glycolipid receptor function. The carbohydrate-
197 binding specificity of SadP to globo series isoreceptors was determined using purified glycolipids (all TLC
198 binding results are summarized in Table 1). Type P_N bound preferentially to Gb3 and P1 glycolipid, and also
199 weakly to Gb4 and the Forssman glycolipid (Fig 2C). SadP type P_O also bound strongly to Gb3 and P1, i.e. to

200 glycolipids with terminal Galα1–4Gal, whereas there was no binding to Gb4 and the Forssman glycolipid (Fig
201 2D). There was no binding to the non-acid glycolipid fraction from the pig intestine, containing the Globo H.
202 The type P_N SadP binding to dilutions of globo series glycolipids was analyzed with TLC overlay assay
203 to the detection limit for the various glycolipids (S5A Fig). The full length adhesin bound mainly to P1
204 glycolipid, with a detection limit at 0.4 μg, whereas the detection limit for the Gb3 glycolipid was 0.8 μg. The
205 detection limit of SadP(31-328) *N*-terminal domain was 0.2 μg for both Gb3 and P1.
206 Next, the SadP binding to 250 ng of glycolipids immobilized in plastic microtiter wells was
207 quantitatively evaluated by solid phase binding assay (S5B Fig). No binding to the Gb2 glycolipid,
208 galabiosylceramide was detected, whereas there was weak binding to Galα1–4Galβ1–O-*bis*-$(SO_2\text{-}C_{16}H_{33})_2$.
209 SadP was found to bind stronger to Gb3 with non-hydroxy ceramide than to Gb3 with hydroxy ceramide.
210 There was also binding to Gb4 and iGb3 isoglobotriaosylceramide. Binding to P1 pentaosylceramide was at
211 the same level as binding to Gb3 with non-hydroxy ceramide. The difference in the binding to iGb3 (Galα1–
212 3Gal- containing glycolipid) in the microtiter well assay compared to TLC overlay assay could be due to the
213 difference in the presentation of the binding epitope and the clustering of the glycolipid moieties.
214

215 **Galα1–4Gal-dependent endothelial cell binding activity of *S. suis* SadP**

216 *S. suis* type P_N WT strain D282 and the corresponding mutant strain D282Δ*sadP,* containing an insertion
217 mutation into SadP gene, were compared for their binding activity to cultured cell line EA.hy926, which is a
218 primary human umbilical vein cell line fused with a thioguanine-resistant clone of A549 (human lung
219 adenocarcinoma cell line). In addition, binding of purified fluorescently labelled SadP was analysed for the
220 binding to EA.hy926 cells. The cells were grown into glass coverslips for 48 h and the bacteria grown into
221 early log phase were added to cells and were let to adhere for 1 h. After washing and staining with DiffQuick
222 the bacteria were enumerated. The average adherence of wild-type bacteria was calculated to be 8.7 ± 0.5
223 bacteria/field, whereas the mean adhesion of 1.3 ± 0.5 of the insertion mutant Δ*sadP* was significantly less
224 (unpaired t test > 0.0001) (Fig 3A). In addition, the binding of the WT strain was inhibited with 10 μg/ml

225 pigeon ovomucoid, which contains *N*-linked glycans with terminal Galα1–4Gal (23). The inhibitor reduced
226 the adherence of *S. suis* bacteria to the cells to 0.7 ± 0.1 bacteria/field.
227 For flow cytometry assay, the cells were grown in wells, washed and tested for the binding of FITC
228 labelled SadP. After washing, the cells were harvested with scraping and analyzed with flow cytometer. The
229 flow cytometry results (dot blot and the histogram) are presented in Figure 3BCD. The median SadP binding
230 with and without inhibitor (pigeon ovomucoid, 10 μg/ml) were 56.2 and 14.9 per 10 000 total events (median
231 of untreated cells was 12.8).
232

233 **Fine specificities toward Gb3 and Gb4 oligosaccharide structures**

234 Next, the ability of the type P_N SadP-D282(31-328) and P_O SadP-6407(31-328) recombinant adhesin
235 constructs to recognize galabiose glycoconjugates was analyzed using isothermal titration calorimetry (Fig
236 4AB). Both type P_N and P_O adhesins were titrated with oligosaccharides representing the terminal epitopes of
237 Gb3 and Gb4, the TMSEt (2-trimethylsilylethyl) glycosides of Galα1–4Gal and GalNAcβ1–3Galα1–4Gal
238 (24). The dissociation constant values (K_D) of type P_N SadP-D282(31-328) and type P_O SadP-6407(31-328)
239 interaction with Galα1–4Gal were 13.0 ± 1.5 μM (n=0.85, ΔH=-69.0±2.0 and -TΔS=41.1) and 3.5 ± 1.6 μM
240 (n=0.85, ΔH=-40.0±2.7 and -TΔS=8.8) respectively. The K_D for interaction of P_N and P_O adhesins with
241 GalNAcβ1–3Galα1–4Gal compared to Galα1–4Gal were 2.6-fold higher with type P_N (K_D= 33.7±3.5 μM,
242 n=1.14, ΔH=-40.1±2.0 and -TΔS=14.0) and 269-higher with type P_O (K_D= 940±680 μM, n=0.13, ΔH=-
243 197±5500 and -TΔS=179).
244 Then, both adhesins were analyzed with AlphaScreen competitive inhibition assay (Fig 4C) for their
245 interaction with Galα1–4Gal in comparison to a glycomimetic inhibitor 3'-phenylurea-derivative (3'-
246 phenylurea-Galα1–4Gal β1–methoxyphenyl), which is a low nanomolar inhibitor of type P_N SadP (19, 25).
247 The binding of His-tagged recombinant adhesins to biotinylated pigeon ovomucoid was inhibited with the
248 above oligosaccharides. The IC_{50} values of type P_N adhesin for Galα1–4Galβ1–methoxyphenyl and 3'-
249 phenylurea-Galα1–4Gal β1–methoxyphenyl were 1 μM and 0.030 μM, whereas with type P_O adhesin the
250 corresponding values were 0.3 μM and 70 μM respectively. Also 4 other recombinant type P_O SadP N-

251 terminal-domains were tested using 10 μM inhibitor concentrations (Fig 4D). For all type P_O adhesins the
252 inhibition obtained with the C3'-phenylurea-derivative was weaker than the inhibition obtained with Galα1–
253 4Gal.
254

255 **Site-specific mutation changes the specificity of type P_N recombinant adhesin to type P_O**

256 The binding mechanism of type P_N and P_O SadP was further studied by site-directed mutagenesis. Type
257 P_N adhesin SadP-D282(125-329) was mutated and the mutants were analyzed for the binding to galabiose
258 oligosaccharides with AlphaScreen competitive inhibition assay and ITC. Multiple alignment of SadP
259 homologues allowed us to predict amino acids from the galabiose-binding region that differed between type
260 P_N and P_O (Fig 1A). Based on that, the site-specific amino acid change N285D and E292Q, deletion Δ244-246
261 and N285D&Δ244-246 mutants were constructed into the type P_N SadP(125-328) cloned into the plasmid
262 pET28a. In addition, the 28 amino acid long region H216-D246 of the type P_N was replaced by the
263 corresponding region of type P_O.
264 The WT SadP and mutants were expressed and purified as described in the methods and analysed with
265 SDS-PAGE (S6 Fig). The galabiose-binding strengths of the above mutant constructs, full length SadP, SadP
266 *N*-terminal constructs SadP(31-328), SadP(125-328) and as a negative control site-specific mutant SadP(31-
267 328)W258A, were compared by AlphaScreen asssay (S7 Fig). The binding of full-length SadP to biotinylated
268 pigeon ovomucoid was weaker compared to the *N*-terminal domain constructs, which could be due to a larger
269 size of the full length SadP. The size of the protein could increase the distance of the acceptor and donor beads,
270 and hence reduce the transmission of the singlet oxygen during the assay (19). As a negative control for the
271 assay, there was no binding of site-specific mutant W258A to pigeon ovomucoid. Of the mutants in the type
272 P_N SadP(125-328) background, mutants N285D and E292Q bound well whereas the binding of mutants Δ244-
273 246 and H216-D246delinsDELFNRFPNKVDSTNNGDGAPFRFFNKE was reduced. The binding of
274 N285D&Δ244-246 mutant was abolished.
275 Next the specificities of mutants were analyzed with AlphaScreen assay using phenylurea-derivative
276 and Galα1–4Gal (S7B - F Figs). All mutants were equally inhibited by the Galα1–4Gal oligosaccharide, but

277 only with the site-specific mutant N285D the inhibitory power of Phenylurea-Galα1–4Gal was weaker
278 compared to Galα1–4Gal, suggesting a specific switch from type P_N to P_O specificity.

279 Next, the Alphascreen inhibition assay was used to compare the effect of site-specific mutation in
280 N285D to the specificity between Galα1–4Gal (terminal Gb3 structure) and GalNAcβ1–3Galα1–4Gal
281 (terminal Gb4 structure) TMSEt glycosides. SadP(125-329) type P_N and site-specific mutant N285D were
282 similarly inhibited with Galα1–4Gal, whereas N285D was not inhibited with even higher concentrations of
283 GalNAcβ1–3Galα1–4Gal (Fig 5AB).

284 The K_D values of type P_N SadP(125-328) and site-specific mutant N285D for oligosaccharides was
285 analyzed with isothermal titration calorimetry (Fig 5C). The wild type SadP(125-329) K_D values for Galα1–
286 4Gal and GalNAcβ1–3Galα1–4Gal were 3.4±0.09 (n=0.76, ΔH=92.0±0.3 and -TΔS=60.8) and 36.0±4.8 μM
287 (n=0.56, ΔH=70.2±5.0 and -TΔS=44.7) respectively. The K_D of site specific mutant N285D with Galα1–4Gal
288 was 22.7±7.2 μM (n=0.52, ΔH=26.8±5.4 and -TΔS=20.5) (6-fold increase compared to wild-type SadP),
289 whereas there was no interaction between N285D and GalNAcβ1–3Galα1–4Gal. Thus, the above results
290 suggest that N285 has a specific role in SadP type P_N binding to GalNAcβ1–3Galα1–4Gal.

291 The effect of N285D mutation to SadP binding to glycolipids incorporated into POPC and POPC-
292 cholesterol liposomes was analyzed by dotting liposomes to PVDF membrane and binding of his-tagged
293 adhesins to immobilized liposomes (Fig 6). WT SadP type P_N bound to Gb4 of both non-cholesterol and
294 cholesterol-containing liposomes, whereas there was no binding by N285D mutant. The acyl chain length or
295 hydroxylation of ceramide had no major effects for Gb3 binding.

296

297 **Structural comparison of recombinant SadP type P_N and its N285D mutant**

298 The site-specific mutant SadP(125-329)N285D was crystallized with five molecules in the
299 crystallographic asymmetric unit (Fig 7A, Table S1). All molecules are similar with subtle differences as
300 suggested by the low root mean square deviation (r.m.s.d) between them (0.25-0.31 Å). The structure of the
301 N285D mutant is similar to that of the native SadP (PDB id 5BOB) with r.m.s.d. of 0.26 Å for 199 aligned
302 residues. The structure consists of three α-helixes and ten β-strands (β1-β10) that form a β-sandwich core

303 domain (Fig 7B). The first β-sheet of the β-sandwich is formed by antiparallel β1-β10-β9-β4-β7-β6 strands
304 and the second β-sheet by β2-β3-β8-β5 in antiparallel fashion.
305 Structural superposition with the Galα1–4Gal – Fhc structure revealed small differences (Fig 7C). The
306 side chain of D285 was found slightly rotated compared to the N285 side chain in the wild type.
307

308 **Resolution of the interaction mechanisms of SadP to globo series glycolipids and C3'-**
309 **Phenylurea–Galα1–4Gal**

310 The key amino acids of both types P_N and P_O are conserved. Y198, Q255, R238 and G233 forms
311 hydrogen bonds with the HO–3', HO-4' and HO-6' of the α'-Gal and the K316 with HO-2 and HO-3 of the β-
312 Gal pyranose ring. W258 most likely forms CH-π interactions with the hydrophobic face of the disaccharide
313 (Fig 7C). Type P_N SadP N285 is on the edge of the binding pocket, and it potentially interacts with the terminal
314 GalNAcβ1–3 of Gb4 or 3-phenylurea-group. To study the SadP interaction with the receptor saccharide
315 Galα1–4Galβ1–4Glc in solution, STD-NMR was applied using type P_N SadP(125-329) and the corresponding
316 mutant N285D (Fig 7D). STD-NMR results suggest that both the type P_N SadP and the mutant N285D interact
317 mainly with the two terminal galactose units of Gb3. With the mutant N285D the interactions of H-4′ and H-
318 4″ are, however, somewhat weaker compared to the interaction of H-6″. Additionally, the mutant N285D does
319 not seem to have a clear interaction with the β-glucoside unit at the reducing end of Gb3, whereas the type P_N
320 SadP appears to have interactions with H-2, H-3 and H-4.
321 In order to find a plausible hypothesis explaining the binding preferences of the galabiose, GalNAcβ1–
322 3Galα1–4Gal and phenylurea-galabioside for WT and the N285D mutant, molecular dynamic simulations of
323 their respective complexes were performed. Briefly, the ligand structures were built without the TMSEt
324 aglycon to simplify the simulations and were then placed in the binding site of SadP (pdb id 5BOA) with the
325 Galα1–4Gal disaccharide oriented as in the crystal structure. The terminal GalNAcβ1 residue was oriented
326 with the dihedral glycosidic bond angles minimized with the H1 parallel to H4' of Galα1–4Gal. The three
327 complexes with WT were mutated by exchanging N285 for D285. The complexes were unrestrainedly
328 subjected to 100 ns molecular dynamics simulations and all starting conformations converged towards similar

329 stable complex geometries (Fig 8A-E), except for the phenylurea derivative in complex with the N285D mutant
330 for which light constraints on the backbone atoms of protein secondary structures were applied (Fig 8F). The
331 α-face of the β-galactoside residue of all three ligands stacked to W258 forming CH-π interactions and the
332 galabiose disaccharide moiety in all simulations retained the interactions and hydrogen bonds observed in the
333 X-ray structure with the Gb3 trisaccharide (PDB id 5boa). The HO-4' of galabiose did not interact directly
334 with N285, but instead via N285 sidechain NH hydrogen bond donation to a network of hydrogen bonds
335 involving 3-5 water molecules and the G233 carbonyl oxygen (Fig 8A and S9 movie). Mutation of N285 to
336 D285 influenced the directionalities of the hydrogen bonding partners in this network (Fig 8D and S10 movie),
337 which may explain the different STD-NMR data with WT and the D285 mutant. The simulations with the
338 GalNAcβ1–3Galα1–4Gal and the phenylurea-galabioside in complex with the WT protein converged to
339 geometries that revealed a highly populated interaction between the ligands and N285. The ring oxygen of the
340 GalNAc residue of the trisaccharide and the urea carbonyl oxygen of the phenylurea derivative accepted
341 hydrogen bonds from the N285 side chain NH_2 (Fig 8B-C and S11 - S12 movies). The GalNAc HO-4 of the
342 trisaccharide formed transient hydrogen bonds to side chain amide groups of E286 and E234, while the phenyl
343 ring of the phenylurea ligand did not form any persistent interactions with any protein residue. The highly
344 populated hydrogen bonds of the trisaccharide GalNAc ring oxygen and the phenylurea carbonyl oxygen to
345 N285 could not form in the N285D mutant (Fig E-F and S13-14 movies). Instead, it was disrupted by the
346 formation of a water network between the D285 side chain carboxylate and the GalNAc ring oxygen of the
347 trisaccharide (Fig 8E), while the phenylurea moiety of the phenylurea galabioside rotated away from the D285
348 side chain carboxylate (Fig 8F). This lack of direct hydrogen bond interactions of the GalNAc ring oxygen
349 and urea carbonyl oxygen may at least partly explain the less efficient binding of the trisaccharide and phenyl
350 urea derivative to the N285D mutant.
351

352 **Discussion**

353 SadP carbohydrate specificity to neutral glycolipids from lungs was studied by TLC overlay assay. The
354 carbohydrate receptors for *S. suis* adhesion in respiratory tract and lungs have remained elusive. We studied
355 here how SadP type P_N and P_O recognize glycolipids isolated from pig lung. The major pig lung neutral

356 glycolipids were identified as Gb3, Gb4, the H type 2 pentaosylceramide, the Galili pentaosylceramide and
357 Le^b and Le^y hexaosylceramides (Fig 2). In TLC overlay assay, type P_N SadP bound to Gb3 and Gb4, whereas
358 type P_O SadP bound only to Gb3. Both SadP types showed no binding to Galα1–3Gal-containing Galili
359 pentaosylceramide. (Fig 2AB, Table 1). Therefore, our findings suggest that globo series glycolipids are the
360 major carbohydrate receptors for *S. suis* in pig lung. Although fucose-binding lectins have been described both
361 in bacterial and fungal lung pathogens, no fucose-specific binding activity was found in SadP. The globo series
362 glycolipids have been shown to be widely expressed in many tissues of pigs (26); hence, they can potentially
363 serve as SadP receptors for other host organs and brain capillary veins critical for *S. suis* invasive infection.
364 We show that the binding of type P_N *S. suis* serotype 2 *sadP*-mutant to endothelial cell line was significantly
365 reduced and binding of both the WT *S. suis* bacteria and recombinant SadP adhesin were inhibited with the
366 galabiose-containing pigeon ovomucoid.

367 The oligosaccharide inhibition assays performed with both whole bacteria and recombinant adhesin
368 suggest that the reducing end β-Glc of Gb3 is required for optimal binding (16, 19). The TLC overlay assay
369 using purified glycolipids showed that SadP bound strongest to the P1 glycolipid (Fig 2BC and S5A Fig). The
370 preferential binding to the P1 glycolipid might also be due to a more optimal presentation of the epitope on
371 the longer core chain, whereas hindered presentation of binding epitope in galabiosyl ceramide might explain,
372 why SadP did not bind to Gb2 in TLC overlay assay. The presence of P1 structure is not well known in pig,
373 however it was found in α1,3GalT knockout pig kidney, since this glycosyltransferase is a direct competitor
374 of α1,4GalT (27). This might be important for surveillance of pathogens in xenotransplantation.

375 The fine specificity of SadP subtypes was further analyzed with ITC and competitive inhibition assay.
376 The ratio of K_D values (Galα1–4Gal / GalNAcβ1–3Galα1–4Gal) for type P_N SadP was 0.4 whereas for type
377 P_O it was 0.004, which is in accordance to the corresponding hemagglutination inhibition MIC values observed
378 with bacterial hemagglutination assays (16). Moreover, the IC_{50} values for Galα1–4Gal and 3'-phenylurea-
379 Galα1–4Gal are in accordance to previous hemagglutination inhibition MIC concentrations for type P_N and P_O
380 *S. suis* (25).

381 The mechanism of how the two SadP subtypes differ in their recognition of Gb3, Gb4 and glycomimetic
382 3-phenylurea-galabiose has not been studied before. The multiple-sequence alignment of SadP showed that

383 specific amino acids G233, E249 and N285 of type P_N in galabiose-binding domain are different compared to
384 type P_O SadP (Fig 1A). Of these, only substitution from asparagine to aspartate at position 285 is found in all
385 hemagglutinating type P_O adhesins. To analyze the mechanisms how SadP type P_N can bind to Gb4 terminal
386 trisaccharide (GalNAcβ1–3Galα1–4Gal) and 3'-phenylurea-galabiose, we designed mutations to type P_N SadP
387 and analyzed their binding to galabiose. The SadP type P_N region from H216 to D246 was swapped to the
388 corresponding region of type P_O (to contain substitution from amino acid G to N at position 233). The binding
389 of this mutant to galabiose was reduced compared to the wild type adhesin (S6A Fig), but was still sufficient
390 to further analyze the oligosaccharide specificity. Deletion Δ244-246 and site-specific mutations N285D and
391 E292Q bound also to galabiose at sufficient level (S6A Fig) allowing testing with 3'-phenylurea-derivative to
392 compare for type-specificity. Of these mutants, only N285D lost the ability to be efficiently inhibited by 3'-
393 phenylurea-derivative (S6B-F Fig), suggesting that N285 has an important role in interacting with the
394 phenylurea-group. The amino acid region 216-246 including G233N substitution have possibly no significant
395 role alone in the interaction with HO-3' substituted phenylurea-galabiose. However, G233 could still
396 synergistically interact with phenylurea. Therefore, the N285D mutant was chosen for further studies for the
397 type P_N binding mechanism. The WT and N285D mutant were compared for their binding to the soluble Gb4
398 terminal trisaccharide GalNAcβ1–3Galα1–4Gal and to globo series glycolipids Gb3 and Gb4 (Figs 5 and 6).
399 The results show consistently that N285 plays a specific role in Gb4 binding as demonstrated by competitive
400 inhibition assay, ITC and liposome binding assay.

401 Molecular dynamics calculations were performed with the structures representing type P_N SadP(125-
402 329) and its N285D site-specific mutant. Both proteins were analyzed with Galα1–4Gal, GalNAcβ1–3Galα1–
403 4Gal and 3'-phenylurea-Galα1–4Gal. In accordance to the co-crystal structure (PDB id. 5boa), the galabiose
404 HO-4', HO-6', HO-2 and HO-3 were hydrogen bonded to Y198, G233, R238, Q255 and K316. Hydrophobic
405 interaction with the α-face of the β-galactoside stacked to W258 forming CH-π interactions. The above
406 interactions were conserved in WT and N285 mutant. WT SadP N285 formed hydrogen bonds to GalNAc O-
407 5 ring oxygen of GalNAcβ1–3Galα1–4Gal and to urea's carbonyl group (Fig 8B). The amino acid D285 of
408 site-pecific mutant formed hydrogen bonds with solvent water molecules when simulated with GalNAcβ1–
409 3Galα1–4Gal and 3'-phenylurea-Galα1–4Gal. These results together with the AlphaScreen and ITC data give

410 us a plausible explanation for the molecular mechanism of how type P_N SadP interact with Gb4 terminal
411 GalNAc and with phenylurea-galabiose derivative. In addition, WT SadP amino acid G233 interacts with the
412 terminal GalNAc of Gb4 via hydrogen bond to N-Acetyl-group or to urea's -NH group (Fig 8C).

413 SadP does not have any sequence homologs in other galabiose-recognizing proteins, however
414 structurally *E. coli* PapG and SadP galabiose-binding sites share some similarities. They both contain a β-sheet
415 composed of antiparallel β-strands, which are adjacent to the galabiose-binding domain (PDB; *E. coli* 1j8r, *S.*
416 *suis* 5boa). In SadP, the binding site is formed by the alpha-helix and a non-helix loop, whereas in PapG the
417 galabiose binding site is located in the middle of two non-helix loops. Other galabiose binding proteins such
418 as *P. aeruginosa* LecA (4yw6), *E. coli* verotoxin (1bos) and *Lyophyllum decastes* fungal lectin (4ndv) show
419 different combining site architectures. As previously suggested, the galabiose-binding adhesin SadP from
420 gram-positive and *E. coli* P fimbrial adhesins from gram-negative bacteria are an example of convergent
421 evolution towards binding to the galabiose oligosaccharide. The structural similarities thus confirm this
422 hypothesis.

423 Hemagglutination positive strains expressing type P_N SadP from pig and zoonotic meningitis strains
424 belong to serotype 2 and clonal group CC1 (6, 17). *S. suis* hemagglutination type P_O strains were mostly found
425 from serotype 4 and were isolated from lungs of strains causing pneumonia (28). The majority of strains that
426 have the gene encoding type P_N SadP belongs to a distinct population consisting of systemic isolates, which
427 were identified in a large BRaTP1T consortium functional genomic study (12). *S. suis* strains that cause human
428 meningitis comprise a separate clade and are thought to have evolved when the pig farming was intensified in
429 1920s (12). Zoonotic *S. suis* strains as a specific population have been thought to exponentially spread to
430 different geographical areas due to the selection of pigs that are optimal in terms of productivity. The BRaTP1T
431 consortium study of *S. suis* genomic signatures for pig and human infections has suggested that the systemic
432 infections are genetically determined and the genome size of highly virulent strains is reduced and enriched
433 with virulence genes. Since the type P_N SadP adhesin gene has not been lost in strains causing systemic
434 infections, it is tempting to speculate that the recognition of Gb4 may play a specific role in invasive infections.
435 In a previous study by Ferrando et al. (2017), type P_N SadP (designated SadP1) present in CC1 clonal group
436 of *S. suis* strains (17) was found to specifically adhere better to human intestinal cells (Caco-2) than to pig

437 intestinal cells. This could indicate that type P_N SadP has specific binding preferences to human intestine, thus
438 promoting zoonosis.

439 The results of the present study could have implications toward the therapeutic applications targeting
440 SadP and *S. suis* systemic infections (summarized in Fig 9). The gene encoding SadP type P_N has a downstream
441 homolog, which is a pseudogene (has a stop codon). It could be speculated, that the gene encoding SadP type
442 P_N is a putatively duplicated gene, which has evolved to bind Gb4 (Figure 9A). This study shows the molecular
443 mechanism how N285 contributes to the binding of terminal GalNAcβ1- saccharide of Gb4 by a specific
444 interaction with GalNAc hexose ring oxygen (Figure 9BC). The analogous N285-mediated binding
445 mechanisms to Gb4 and glycomimetic phenylurea-galabiose could be utilized in the design of therapeutics
446 against the invasive systemic infections without disturbing the commensal *S. suis* bacteria colonizing pig upper
447 respiratory tract.

448

449 # Materials and Methods

450 ## Bacterial strains

451 The chromosomal DNA was isolated from type P_N and P_O *S. suis* strains as described before (6) using
452 GelElute bacterial genomic DNA kit according to the manufacturer's instructions. *Streptococci* were grown in
453 Todd Hewitt broth supplemented with 0.5 % yeast extract or in Columbia agar plates supplemented with 5 %
454 sheep blood in 5 % CO_2 at 37°C and *E. coli* strain were grown in LB medium. Antibiotics used were 30 µg/ml
455 (pET28) and 100 µg/ml ampicillin pET46EkLIC) in *E. coli* and 500 µg/ml kanamycin for *S. suis* D282Δ*SadP*
456 mutant (6).

457 *Escherichia coli* NovaBlue (Novagen) was used for the cloning of SadP constructs and strain
458 BL21(DE3) for expression of the adhesin.

459

460 **Cloning and construction of recombinant adhesins**

461 The galabiose binding *N*-terminal domains of SadP from hemagglutination subtypes P_N and P_O were
462 cloned into pET46EkLIC vector as follows: The primer pairs SadPDER48
463 (gacgacgacaagatagaatcgctagaaccagatgtt) and SadPDER49 (gaggagaagcccggtttattcttctcaagggtaatctc) were
464 designed to clone the 882 bp fragment of the adhesin *N*-terminal galabiose binding domain. The fragments
465 were amplified with Phusion HotStart II DNA polymerase and were cloned into LIC-vector (LIC, ligation
466 independent cloning) pET46EkLIC (Novagen). The ligation products were transformed into NovaBlue
467 competent cells. This construct yielded a 33.4 kDa 6xHis-tagged fusion protein (SadP(31-328)). The sequence
468 of *N*-terminal domains of SadP homologs were verified by sequencing with T7 promoter and T7 terminator
469 primers. The vectors were transformed into expression strain BL21(DE3).

470 Site-specific mutant SadP(31-328) W258A was constructed by PCR with 5'-phosphorylated forward
471 primer tgg aac gca tct gct ggt caa gct and reverse primer ttg aga att aaa acc att ttc. The PCR product was
472 amplified with Phusion HotStart II DNA polymerase and the PCR fragment was ligated with T4 ligase
473 (Promega) and transformed into Novablue competent cells. The resulting plasmid SadP(31-328)W258A-
474 pET28a was sequenced to verify the mutation.

475 Synthetic gene construct and the corresponding site-specific mutants for WT SadP(125-328) type P_N
476 were obtained from Genscript. Site-specific mutants constructed were Δ244-246 (PSAD-1), N285D (PSAD-
477 2), E292Q (PSAD-3), N285D&Δ244-246 (PSAD-4) and H216-
478 D246delinsDELFNRFPNKVDSTNNGDGAPFRFFNKE (PSAD-5) (replacement of aa 216-242 into
479 corresponding sequence of type P_O of strain 6107).

480

481 **Bioinformatics**

482 To compare the distribution of SadP alleles in *S. suis* from different infections e.g. invasive, respiratory
483 and non-clinical samples, the presence of either P_N or P_O allele was detected from 374 previously published *S.*
484 *suis* isolates (12) using SRST2 software version 0.2.0 with default settings (29). The SadP genes from *S. suis*
485 P1/7 (AM946016.1) and 6407 (NZ_CP008921.1) were used as reference sequences for P_N and P_O, respectively.

486 The distribution of P_N and P_O alleles in the *S. suis* phylogeny was investigated by creating a core-genome
487 maximum-likelihood tree using Roary version 3.12.0 (30) and RAxML version 8.2.8 (31) from the 374
488 isolates.
489

490 **Expression and purification of SadP proteins**

491 The bacteria were grown at 30°C, 250 rpm, to an OD600 of 0.5, and the protein expression was induced
492 with 0.2 mM IPTG for 3.5 hours. Bacteria were harvested by centrifugation with 3000 x g, at +4°C and stored
493 at -84°C. The recombinant protein was purified with Ni-NTA affinity chromatography. Briefly, bacteria were
494 lysed with 0.4 mg/ml hen egg lysozyme (Sigma) in 50 mM sodium phosphate buffer pH 8.0, containing 0.5 M
495 NaCl, EDTA-free protease inhibitor cocktail (Pierce), 20 mM imidazole, 20 µg/ml deoxyribonuclease and 1
496 mM $MgCl_2$ on ice for 30 mins. The lysate was sonicated to further homogenize the cell debris and was
497 centrifuged at 20000 x g, +4°C for 30 min. The filtered lysate was purified with Ni-NTA affinity
498 chromatography using HiPrep FF column connected to Äktaprime plus, GE Healthcare at +25°C. Further
499 purification was done with a gel filtration HiLoad 16/60 Superdex 200 column using Tris-HCl, pH 7.5, 0.15
500 M NaCl as running buffer. The purity of the recombinant proteins was analyzed with SDS-PAGE
501 chromatography. For native gel electrophoresis, the recombinant proteins were diluted to sample buffer
502 without SDS and were separated with 8 % polyacrylamide gel.
503

504 **Crystallization**

505 SadP N285D mutant (15 mg/ml) was crystallized with the hanging-drop vapor-diffusion method. The
506 well condition contained 1.3-1.5 M sodium citrate tribasic, 0.1 M sodium cacodylate, pH 6.5. Equal volumes
507 of well solution and protein (2 µL+2µL) were mixed and the crystals grew at 16 °C, initially as haystacks of
508 very thin needles. Single crystals suitable for data collection were subsequently grown by using the seeding
509 technique. A small part of the haystack was crushed with a metallic needle in the crystallization drop and 0.2
510 µL were diluted in 20 µL of mother liquor to create a seeding stock. Pre-equilibrated (1-d old) crystallization
511 drops were seeded with 0.1 µL of the seeding stock. Single crystals started to grow after ~3 days.

512

513 **Data collection and crystal structure determination**

514 Diffraction data were collected on the BioMAX beamline at MAX IV (Lund, Sweden) from a single
515 crystal under cryogenic temperatures (100K). The crystal diffracted to 1.85 Å but the resolution was later
516 truncated during processing to 2.05 Å owing to completeness. The crystal was found to belong to the *C*2 space
517 group. Data processing was carried out with automated procedures in EDNA (32) and scaling was done with
518 AIMLESS (33).

519 Molecular replacement with PHASER (34) was carried out to obtain initial phases using the native
520 structure as a template. Five molecules in the crystallographic asymmetric unit were located (Matthews
521 coefficient 2.67 $Å^3$/Da corresponding to ~53.9% solvent content). Initial building of the structure was carried
522 out using the automated building procedure in BUCCANEER (35) using the ccp4i2 interface (36). After the
523 initial building that produced an almost complete structure, the refinement continued in PHENIX v.1.17.1-
524 3660 (37) using simulated annealing at 1000K with maximum likelihood as target function. The first round of
525 simulated annealing resulted in R_{work}/R_{free} of 0.227/0.269. Inclusion of waters and rounds of manual rebuilding
526 using COOT (38) alternated with PHENIX refinement resulted in the final structure with R_{work}/R_{free} of
527 0.174/0.221 (Table S1). A glycerol molecule was found bound in each of the A, C, and D subunits. Two
528 glycerol molecules were located in the binding site of subunit B. The structure has been deposited to the Protein
529 Data Bank under the accession code 6YRO

530

531 **Isolation of SadP binding glycosphingolipids from porcine lung**

532 Non-acid glycosphingolipids were isolated from porcine lung as described (39). Briefly, the lung tissue
533 was lyophilized, and then extracted in two steps in a Soxhlet apparatus with chloroform and methanol (2:1 and
534 1:9, by volume, respectively). The material obtained was subjected to mild alkaline hydrolysis and dialysis,
535 followed by separation on a silicic acid column. Acid and non-acid glycosphingolipid fractions were obtained
536 by chromatography on a DEAE-cellulose column. In order to separate the non-acid glycolipids from alkali-
537 stable phospholipids, this fraction was acetylated and separated on a second silicic acid column, followed by

538 deacetylation and dialysis. Final purifications were done by chromatographies on DEAE-cellulose and silicic
539 acid columns.

540 The total non-acid glycosphingolipid fraction (9 mg) from porcine lung was first separated on an
541 Iatrobeads (latrobeads 6RS-8060; Iatron Laboratories, Tokyo) column (1.0 g) and eluted with increasing
542 volumes of methanol in chloroform. Aliquots of the fractions obtained were analyzed by thin-layer
543 chromatography. Fractions that were coloured green by anisaldehyde were tested for binding of SadP using
544 the chromatogram binding assay. SadP bound to a fraction containing glycosphingolipids migrating in the tri-
545 and tetraglycosylceramide regions on thin-layer chromatograms. This fraction (1.0 mg) was further separated
546 on an Iatrobeads column (1.0 g), eluted with chloroform/methanol/water 65:25:4 (by volume), 30 x 0.5 ml,
547 followed by chloroform/methanol/water 65:25:4, 10 mi. The SadP binding triglycosylceramide was eluted in
548 fractions 12-17, and these fractions were pooled into one fraction migrating as a single band (0.2 mg, denoted
549 fraction PL-1), and fraction migrating as a double band (0.3 mg, denoted fraction PL-2) on thin-layer
550 chromatograms. In addition, a SadP tetraglycosylceramide was present in fractions 19-31, and pooling of
551 these fractions gave 0.4 mg (denoted fraction PL-4).

552

553 **Reference glycosphingolipids**

554 Total acid and non-acid glycosphingolipid fractions were isolated as described (39), and the individual
555 glycosphingolipids were obtained by repeated chromatography on silicic acid columns, and by HPLC, and
556 identified by mass spectrometry (20, 40) and 1H NMR spectroscopy (41).

557

558 **Thin-layer chromatography**

559 Aluminum- or glass-backed silica gel 60 high performance thin-layer chromatography plates
560 (Merck, Darmstadt, Germany) were used for thin-layer chromatography, and chromatographed with
561 chloroform/methanol/water (60:35:8 by volume) as solvent system. The different glycosphingolipids
562 were applied to the plates in quantities of 4 μg of pure glycosphingolipids, and 20-40 μg of
563 glycosphingolipid mixtures. Chemical detection was done with anisaldehyde (42).

564

565 **Radiolabeling**

566 Aliquots of 100 µg of the different SadP protein preparations were labeled with ^{125}I by the Iodogen
567 method according to the manufacturer's instructions (Pierce/Thermo Scientific), giving approximately 2000
568 cpm/µg protein.

569

570 **Chromatogram binding assays**

571 Binding of radiolabeled proteins to glycosphingolipids on thin-layer chromatograms was done as
572 described (43). Chromatograms with separated glycosphingolipids were dipped for 1 min in diethylether/n-
573 hexane (1:5, by volume) containing 0.5% (w/v) polyisobutylmethacrylate (Aldrich Chern. Comp. Inc.,
574 Milwaukee, WI). After drying, the chromatograms were soaked in PBS containing 2% (w/v) bovine serum
575 albumin, 0.1% (w/v) NaN_3 and 0.1% (w/v) Tween 20 (Solution A), for 2 h at room temperature. Thereafter
576 the plates were incubated with ^{125}I- labeled SadP protein (l -5 x 10^6 cpm/ml) for 2 h at room temperature. After
577 washing six times with PBS, and drying, the thin-layer plates were autoradiographed for 12 h using XAR-5
578 x-ray films (Eastman Kodak, Rochester, NY).

579

580 **Microtiter well assay**

581 Binding of radiolabeled SadP to glycosphingolipids in microtiter wells was performed as described (43).
582 In short, 250 µg of pure glycosphingolipids in methanol were applied to microtiter wells (Falcon 3911, Becton
583 Dickinson Labware, Oxnard, CA). When the solvent had evaporated, the wells were blocked for 2 h at room
584 temperature with 200 µl of BSA/PBS. Thereafter, the wells were incubated for 4 h at room temperature with
585 50 µl of ^{125}I-labeled SadP (2 x 10^3 cpm/µl) diluted in BSA/PBS. After washing 6 times with PBS, the wells
586 were cut out and the radioactivity was counted in a gamma counter.

587

588 **LC-ESI/MS of native glycosphingolipids**

589 Native glycosphingolipids were analyzed by LC-ESI/MS as described (44). Glycosphingolipids were
590 dissolved in methanol:acetonitrile in proportion 75:25 (by volume) and separated on a 200x0.150 mm column,
591 packed in-house with 5 µM polyamine II particles (YMC Europe GmbH, Dinslaken, Germany). An
592 autosampler, HTC-PAL (CTC Analytics AG, Zwingen, Switzerland) equipped with a cheminert valve (0.25
593 mm bore) and a 2 µl loop, was used for sample injection. An Agilent 1100 binary pump (Agilent technologies,
594 Palo Alto, CA) delivered a flow of 250 µl/min, which was split down in an 1/16" microvolume-T (0.15 mm
595 bore) (Vici AG International, Schenkon, Switzerland) by a 50 cm x 50 µm i.d. fused silica capillary before the
596 injector of the autosampler, allowing approximately 2-3 µl/min through the column. Samples were eluted with
597 an aqueous gradient (A:100% acetonitrile to B: 10 mM ammonium bicarbonate). The gradient (0-50% B) was
598 eluted for 40 min, followed by a wash step with 100% B, and equilibration of the column for 20 min. The
599 samples were analyzed in negative ion mode on a LTQ linear quadropole ion trap mass spectrometer (Thermo
600 Electron, San José, CA), with an IonMax standard ESI source equipped with a stainless steel needle kept at –
601 3.5 kV. Compressed air was used as nebulizer gas. The heated capillary was kept at 270 °C, and the capillary
602 voltage was –50 kV. Full scan (*m/z* 500-1800, two microscans, maximum 100 ms, target value of 30,000) was
603 performed, followed by data-dependent MS^2 scans (two microscans, maximun 100 ms, target value of 30.000)
604 with normalized collision energy of 35%, isolation window of 2.5 units, activation q= 0.25 and activation time
605 30 ms). The threshold for MS^2 was set to 500 counts. Data acquisition and processing were conducted with
606 Xcalibur software version 2.0.7 (Thermo Fisher Scientific). Manual assignment of glycosphingolipid
607 sequences was done with the assistance of the Glycoworkbench tool (Version 2.1), and by comparison of
608 retention times and MS^2 spectra of reference glycosphingolipids.

609

610 **Endoglycoceramidase digestion and LC-ESI/MS**

611 Endoglycoceramidase II from *Rhodococcus* spp. (Ito) (Takara Bio Europe S.A., Gennevilliers, France)
612 was used for hydrolysis of glycosphingolipids. Briefly, 50 µg of glycosphingolipids were resuspended in 100
613 µl 0.05 M sodium acetate buffer, pH 5.0, containing 120 µg sodium cholate, and sonicated briefly. Thereafter,

614 1 mU of enzyme was added, and the mixture was incubated at 37°C for 48 h. The reaction was stopped by
615 addition of chloroform/methanol/water to the final proportions 8:4:3 (by volume). The oligosaccharide-
616 containing upper phase thus obtained was separated from detergent on a Sep-Pak QMA cartridge (Waters).
617 The eluant containing the oligosaccharides was dried under nitrogen and under vacuum.

618 The glycosphingolipid-derived oligosaccharides were resuspended in 50 µl of water and analyzed by
619 LC-ESI/MS as described (20). The oligosaccharides were separated on a column (200 x 0.180 mm) packed in-
620 house with 5 µm porous graphite particles (Hypercarb, Thermo-Hypersil, Runcorn, UK). An autosampler,
621 HTC-PAL (CTC Analytics AG, Zwingen, Switzerland) equipped with a cheminert valve (0.25 mm bore) and
622 a 2 µl loop, was used for sample injection. An Agilent 1100 binary pump (Agilent technologies, Palo Alto,
623 CA) delivered a flow of 250 µl/min, which was split down in an 1/16" microvolume-T (0.15 mm bore) (Vici
624 AG International, Schenkon, Switzerland) by a 50 cm x 50 µm i.d. fused silica capillary before the injector of
625 the autosampler, allowing approximately 2-3 µl/min through the column. The oligosaccharides (3 µl) were
626 injected on to the column and eluted with an acetonitrile gradient (A: 10 mM ammonium bicarbonate; B: 10
627 mM ammonium bicarbonate in 80% acetonitrile). The gradient (0-45% B) was eluted for 46 min, followed by
628 a wash step with 100% B, and equilibration of the column for 24 min. A 30 cm x 50 µm i.d. fused silica
629 capillary was used as transfer line to the ion source.

630 The oligosaccharides were analyzed in negative ion mode on an LTQ linear quadrupole ion trap mass
631 spectrometer (Thermo Electron, San José, CA). The IonMax standard ESI source on the LTQ mass
632 spectrometer was equipped with a stainless-steel needle kept at –3.5 kV. Compressed air was used as nebulizer
633 gas. The heated capillary was kept at 270 °C, and the capillary voltage was –50 kV. Full-scan (*m/z* 380-2 000,
634 2 microscans, maximum 100 ms, target value of 30 000) was performed, followed by data dependent MS^2
635 scans of the three most abundant ions in each scan (2 microscans, maximum 100 ms, target value of 10 000).
636 The threshold for MS^2 was set to 500 counts. Normalized collision energy was 35%, and an isolation window
637 of 3 u, an activation q = 0.25, and an activation time of 30 ms, was used. Data acquisition and processing were
638 conducted with Xcalibur software (Version 2.0.7).

639 Manual assignment of glycan sequences was done on the basis of knowledge of mammalian biosynthetic
640 pathways, with the assistance of the Glycoworkbench tool (Version 2.1), and by comparison of retention times
641 and MS^2 spectra of oligosaccharides from reference glycosphingolipids (20).
642

643 **S. suis cell binding assay**

644 EA.hy926 cells were maintained and grown in DMEM, 10 % FCS medium at 37°C, 5 % CO_2. For
645 bacterial binding assay the cells were detached with Trypsin-EDTA, counted and 15 000 cells/well added into
646 round glass coverslips in 24 well-plates. Cells were grown for 24 - 48 h to subconfluency.
647 *S. suis* D282 WT strain and D282-Δ*sadP* were grown in THY overnight at 37°C, 5 % CO_2. Bacteria
648 were diluted 1/20 into prewarmed 37°C THY and were grown to OD550 of 0.2 and were diluted 1/100 into
649 prewarmed DMEM, 10 % FCS without antibiotics. 500 µl of bacterial dilution was pipetted into the wells
650 (MOI 100:1) and the plate was centrifuged with 800 x g, 15 min at 20°C.
651 The plate was incubated at 37°C for 1 h. The wells were washed 4 x 1000 µl of PBS. The cells were
652 stained with DiffQuick kit, washed and the coverslips were mounted on glass slides with Permount.
653 The bacterial binding was quantitated by microscopy with 100 x objective with immersion oil. The
654 bound bacteria were enumerated by counting two wells for each sample. The results were expressed as average
655 of bacteria / optical field.
656 For flow cytometry, N-terminal domain of SadP was labelled with FITC (Sigma-Aldrich) in 0.2 M
657 borate buffer, pH 8.0, 0.16 M NaCl (50:1 molar ratio of FITC/SadP, 83 nmol of SadP and 1.7 µmol of FITC)
658 and the labelling was stopped with Tris-buffer. The labelled SadP was purified from the free FITC with PD-
659 10 (GE Healthcare) desalting column. The EA.hy926 cells were seeded into 6 well culture dishes (1 x 10^5
660 cells/well) and were grown for 48 h. The cells were washed with DMEM and were incubated with 400 ng/ml
661 of labelled SadP with or without 10 µg/ml pigeon ovomucoid. After binding, the wells were washed with
662 phosphate Buffered Saline (PBS, 0.15 M NaCl, 2.7 mM KCl, 8.1 mM Na_2HPO_4, 1.5 mM KH_2PO_4). and were
663 fixed with 2 % (w/v) paraformaldehyde in PBS for 15 min. The cells were washed twice with PBS and the
664 cells were scraped of the wells and suspended into the PBS. 10 000 cells were analyzed for SadP binding with
665 FACSCalibur.

666

667 **Amplified luminescent proximity homogeneous assay (AlphaScreen)**

668 The AlphaScreen assay was optimized as described before (19). Briefly, the assay was performed using
669 AlphaScreen Streptavidin Donor beads and NiNTA Acceptor beads (PerkinElmer). The molar concentrations
670 of galabiose-containing biotinylated ovomucoid (receptor) and adhesin were optimized by finding the hook
671 point for the interaction by setting up a matrix of proteins in 96 well AlphaPlates (Perkin Elmer) in 10 mM
672 Tris-HCl, pH 7.5, 0.15 M NaCl, 0.2% BSA, 0.05 % Tween 20 0.2% (TBST-0.2%BSA). For the optimized
673 assay dilutions of 5 µl of the His-tagged adhesin and 5 µl of biotinylated ovomucoid were pipetted into the
674 wells and the plates were centrifuged for 1 min, 1000 x g. The plates were incubated at +25°C for 1 hr. This
675 was followed by addition of Ni-NTA- beads (20 µg/ml) and incubation for 1.5 hrs. Finally, streptavidin donor
676 beads were added (20 µg/ml) and the mixtures were incubated for 30 mins and were then measured with the
677 Ensight multimode reader (Perkin Elmer) using excitation wavelength of 680 nm with donor beads and
678 measurement of emission wavelength of 615 nm from AlphaLISA anti-HIS acceptor beads. For inhibition
679 assays the oligosaccharides, whose structures have been described before (25) or depicted in Figure 4 for
680 TMSEt- glycosides of GalNAcβ1–3Galα1–4Gal and 3Galα1–4Gal, were diluted into TBST-0.2%BSA buffer
681 and were mixed with the His-tagged adhesin and biotinylated ovomucoid. The binding was measured as
682 described above. The binding inhibition data was fitted using Prism with settings of log(inhibitor) vs. response
683 slope (four parameters).

684

685 **Isothermal titration calorimetry**

686 SadP-D282(31-328) (P_N), SadP-6107(31-328) (P_O), SadP(125-329) type P_N and site-specific mutant
687 SadP(125-328)N285D were desalted into PBS using PD-10 desalting column (GE Healtcare). The synthetic
688 oligosaccharides were diluted to the same buffer. 0.1 - 0.2 µM of SadP proteins in a 350 µl vessel was titrated
689 with 1.5 - 2 mM solutions of galabiose oligosaccharides using MicroCal (Malvern). The protein solution was
690 stirred with 750 rpm at 25°C and 16 injections of a volume of 2.49 µl were injected at 180 s intervals. The data
691 from single determinations was analyzed with Origin.

692

693 **Preparation of liposomes and SadP binding assay**

694 Vesicles were prepared as described before (45). Briefly, POPC (1-palmitoyl-2-oleoyl-glycero-3-
695 phosphocholine, Avanti Polar lipids), cholesterol and glycolipids were dissolved and mixed into the
696 chloroform : methanol (2:1, vol/vol) to contain 30 % cholesterol and 2 mM glycolipids. The solvent was
697 evaporated and the lipid film was suspended for 30 min at 60 °C in 10 mM Tris-Cl, 140 mM NaCl buffer. The
698 lipid-buffer suspension was briefly vortexed followed by the extrusion procedure (Avanti mini extruder using
699 0.1 µm polycarbonate membranes filter, (Avanti Polar Lipids, Alabaster, AL, USA)) to form large unilamellar
700 vesicles.

701 PVDF membrane was wetted (wetting in 100 % MeOH, washing 4 x 5 min MilliQ water) and was
702 overlaid onto wet Whatman filter paper. Liposomes were serially diluted 1/10 into Tris-buffered saline and 2
703 µl of liposomes containing 2 mM, 0.2 mM and 0.02 mM of glycolipid was pipetted onto the membrane and
704 the membrane was not allowed to dry during the pipetting. The membrane was saturated with 2 % BSA (w/v)
705 in TBS for 1 h at 20°C and was incubated with 10 µg/ml recombinant SadP for 2 h at 20°C. The membrane
706 was washed 4 x 5 min with TBS and the bound SadP was detected with 1:10000 dilution of anti-His primary
707 antibody (Sigma) and 1:20000 dilution of HRP-labelled secondary rabbit anti-mouse antibody
708 (DakoCytomation). The membrane was incubated with ECL substrate (WesternBright Quantum, Labtech) and
709 the SadP binding was imaged with Fuji LAS-4000.

710

711 **STD-NMR**

712 STD-NMR measurements were carried out on a Bruker AVANCE III HD spectrometer (Bruker BioSpin
713 GmbH, Rheinstetten, Germany) operating at 600.13 MHz, equipped with a nitrogen-cooled triple-channel TCI
714 inverse CryoProbe™. The pulse sequence used for the experiments was the stddiffesgp provided by Bruker.
715 A 1x PBS buffer with a pH of 7.45 with 10% D_2O, containing 50 µM protein and 2500 µM Gb3 trisaccharide
716 was used for the experiments. The on-resonance pulse was set to the methyl groups at 0.9 ppm and the off-
717 resonance pulse was set at 20 ppm. A saturation time of 2 s was used and the experiments were carried out at

718 313 K to somewhat improve the weak signals, likely resulting from slow k_{off}. A blank experiment with only
719 Gb3 and no protein was done to rule out any self-STD.
720

721 **Molecular dynamics simulations**

722 Molecular dynamics simulations were performed with the OPLS3 force field in Desmond (Schrödinger
723 Release 2019-4: Desmond Molecular Dynamics System, D. E. Shaw Research, New York, NY, 2017;
724 Maestro-Desmond Interoperability Tools, Schrödinger, New York, NY, 2017) using default settings except
725 for the length of the simulation. Simulations were performed with periodic boundary conditions using
726 orthorhombic simulation boxes with SPC water model. Counter ions were used to neutralize each other.
727 Starting conformations of ligands in complex with SadP (pdb id 5BOA) were built by manually placing ligand
728 galabiose residues in an identical position to that in the crystal structure (pdb id 5BOA). Complexes with the
729 mutants were generated by exchanging N285 for D285. The complexes were then subjected to 100 ns
730 molecular dynamics simulations. The complex of the phenylurea derivative with the N285D mutant was not
731 stable during the 100 ns simulations. Therefore, light constraints (1 $kcal \cdot mol^{-1} \cdot Å^{-1}$) on the protein secondary
732 structures were applied. Molecular images were generated using PyMOL v2.30 (Schrodinger LLC).
733

734 **Author contributions**

735 MMJ and ST purified, characterized the glycolipids and performed TLC overlay experiments. TK and
736 JC performed the bioinformatic analysis. EB and SH purified recombinant WT and site-specifically mutated
737 SadP proteins, optimized and performed AlphaScreen analysis and competitive inhibition assays. SH
738 performed the cell binding and flow cytometry analysis. SM and TN prepared Gb3 and Gb4 containing
739 liposomes. ACP performed the structural analysis and modelling of SadP. APS and UJN did the molecular
740 dynamics calculations. JR and RL performed the STD-NMR experiments. JK and SH did the ITC experiments.
741 JF, ST and SH planned the project. APS, UJN, JF and JC contributed to the editing of the article. ST and SH
742 wrote the manuscript.
743

744

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Tables

Table 1.

Table 1. Binding of SadP to glycosphingolipids on thin-layer chromatograms

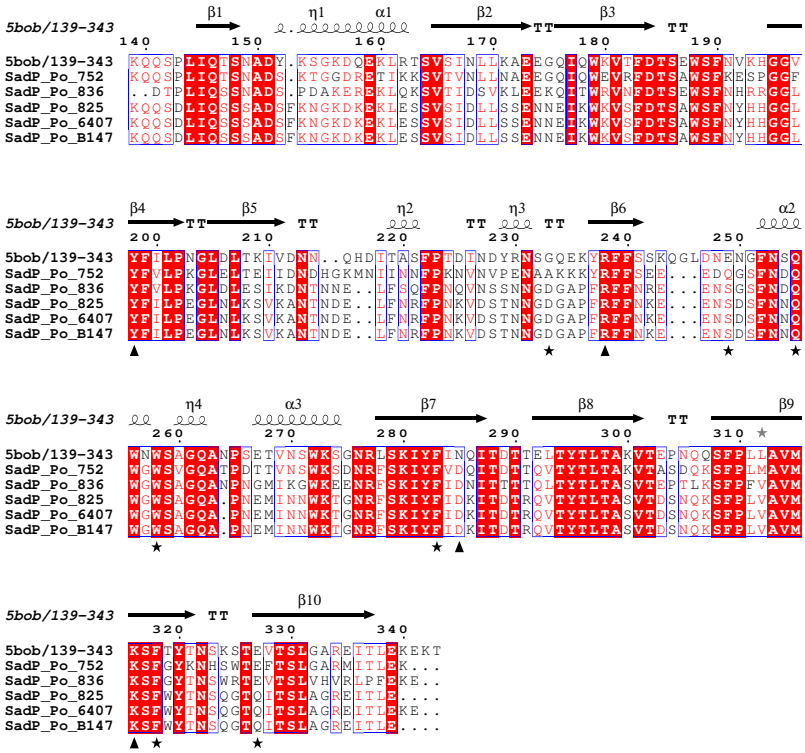
No. Trivial name	Structure	SadP type P_N/P_O	Source
1. Galabiaosylcer (Gb2)	Galα1–4Galβ–O–Cer	-	Human meconium
2. Galabiaosylcer (Gb2-S)	Galα1–4Galβ1–O–*bis*–$(SO_2\text{-}C_{16}H_{33})_2$	-	Synthetic
3. Isoglobotri (iGb3)	Galα1–3Galβ1–4Glcβ1–O–Cer	+/-	Cat intestine
4. Globotri (Gb3)	Galα1–4Galβ1–4Glcβ1–O–Cer	+++/+++	Human erythrocytes
5. Globotetra (Gb4)	GalNAcβ1–3Galα1–4Galβ1–4Glcβ1–O–Cer	+/-	Human erythrocytes
6. Forssman	GalNAcα1–3GalNAcβ1–3Galα1–4Galβ1–4Glcβ1–O–Cer	+/-	Dog intestine
7. para-Forssman	GalNAcβ1–3GalNAcβ1–3Galα1–4Galβ1–4Glcβ1–O–Cer	-	Human erythrocytes
8. P1	Galα1–4Galβ1–4GlcNAcβ1–3Galβ1–4Glcβ1–O–Cer	+++/+++	Human erythrocytes
9. H type 4/Globo H hexa	Fucα1–2Galβ1–3GalNAcβ1–3Galα1–4Galβ1–4Glcβ1–O–Cer	-	Pig intestine
10. H type 2 penta	Fucα1–2Galβ1–4GlcNAcβ1–3Galβ1–4Glcβ1–O–Cer	-	Pig lung
11. Galili penta	Galα1–3Galβ1–4GlcNAcβ1–3Galβ1–4Glcβ1–O–Cer	-	Pig lung
12. Le^b hexa	Fucα1–2Galβ1–3(Fucα1-4)GlcNAcβ1–3Galβ1–4Glcβ1–O–Cer	-	Pig lung
13. Le^y hexa	Fucα1–2Galβ1–4(Fucα1-3)GlcNAcβ1–3Galβ1–4Glcβ1–O–Cer	-	Pig lung
14. A type 2 hexa	Galα1–3(Fucα1–2)Galβ1–4GlcNAcβ1–3Galβ1–4Glcβ1–O–Cer	-	Pig erythrocytes
15. A type 4/Globo A hepta	GalNAcα1-3(Fucα1-2)Galβ1-3GalNAcβ1–3Galα1-4Galβ1-4Glcβ1–O–Cer	-	Pig intestine

[a] Binding is defined as follows: +++ denotes a highly reproducible binding of SadP type P_N/P_O when 4 μg of the glycosphingolipid was applied on the thin-layer chromatogram, while + denotes an occasional binding, and - denotes no binding even at 4 μg.

Figures

Fig 1.

A.



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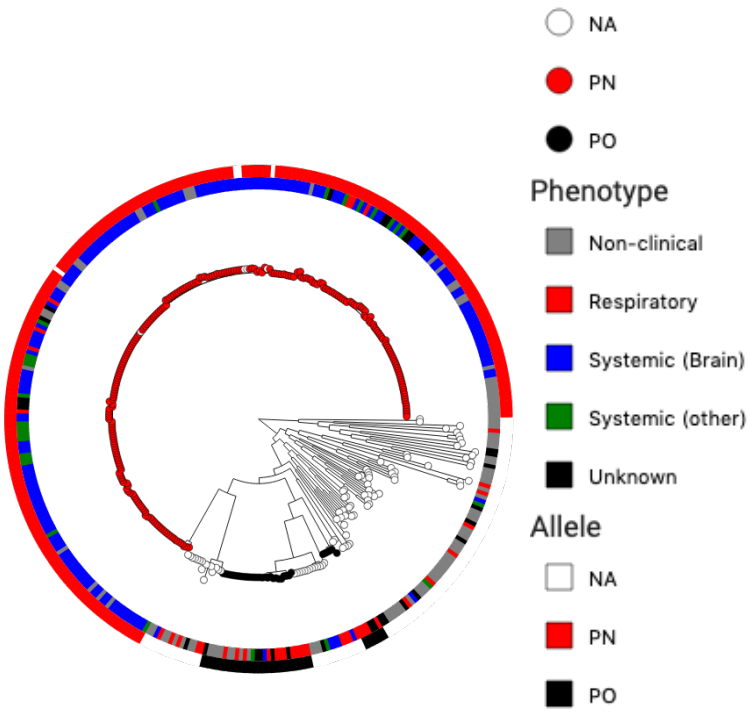

Fig 2.

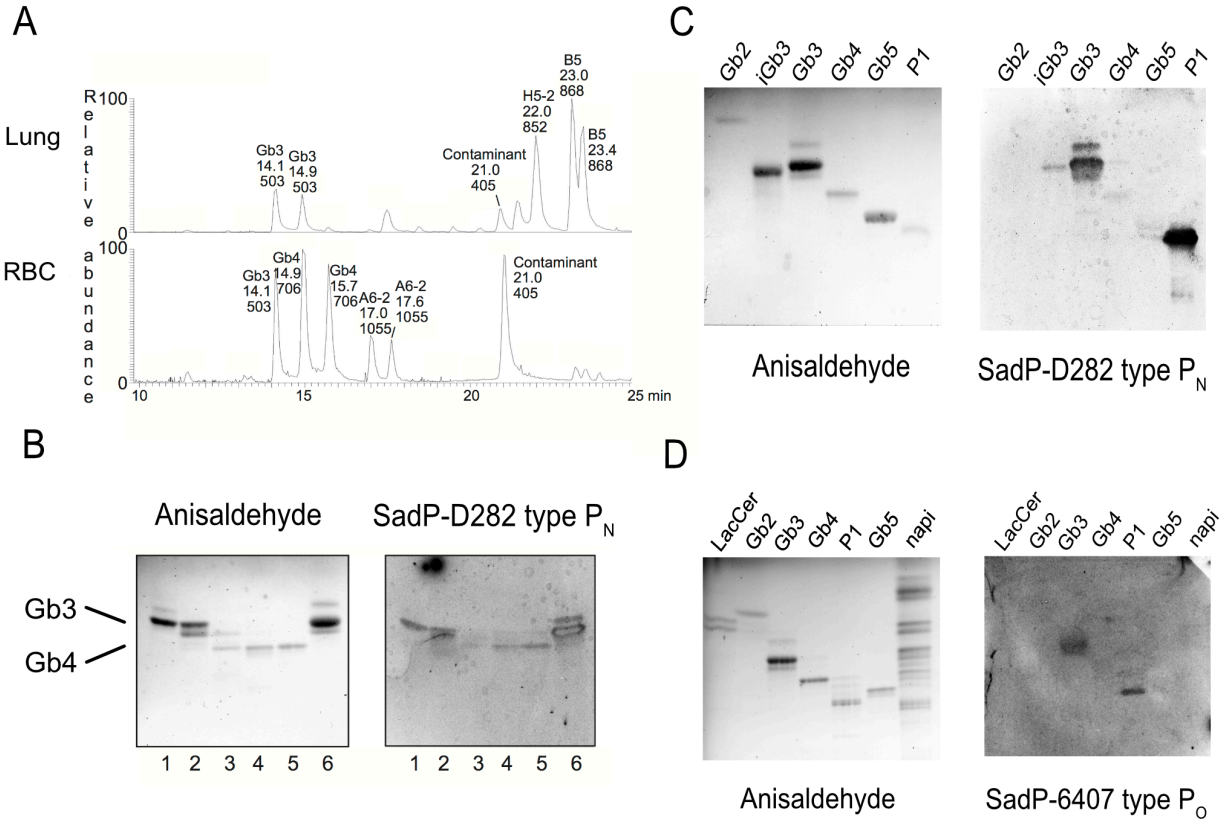
A
Lung
RBC
Relative abundance
100
0
Gb3 14.1 503
Gb3 14.9 503
Contaminant 21.0 405
H5-2 22.0 852
B5 23.0 868
B5 23.4 868
Gb4 14.9 706
Gb4 15.7 706
A6-2 17.0 1055
A6-2 17.6 1055
10
15
20
25 min
B
Anisaldehyde
SadP-D282 type P_N
Gb3
Gb4
1 2 3 4 5 6
C
Gb2 iGb3 Gb3 Gb4 Gb5 P1
Anisaldehyde
SadP-D282 type P_N
D
LacCer Gb2 Gb3 Gb4 P1 Gb5 napi
Anisaldehyde
SadP-6407 type P_O

Fig. 3.

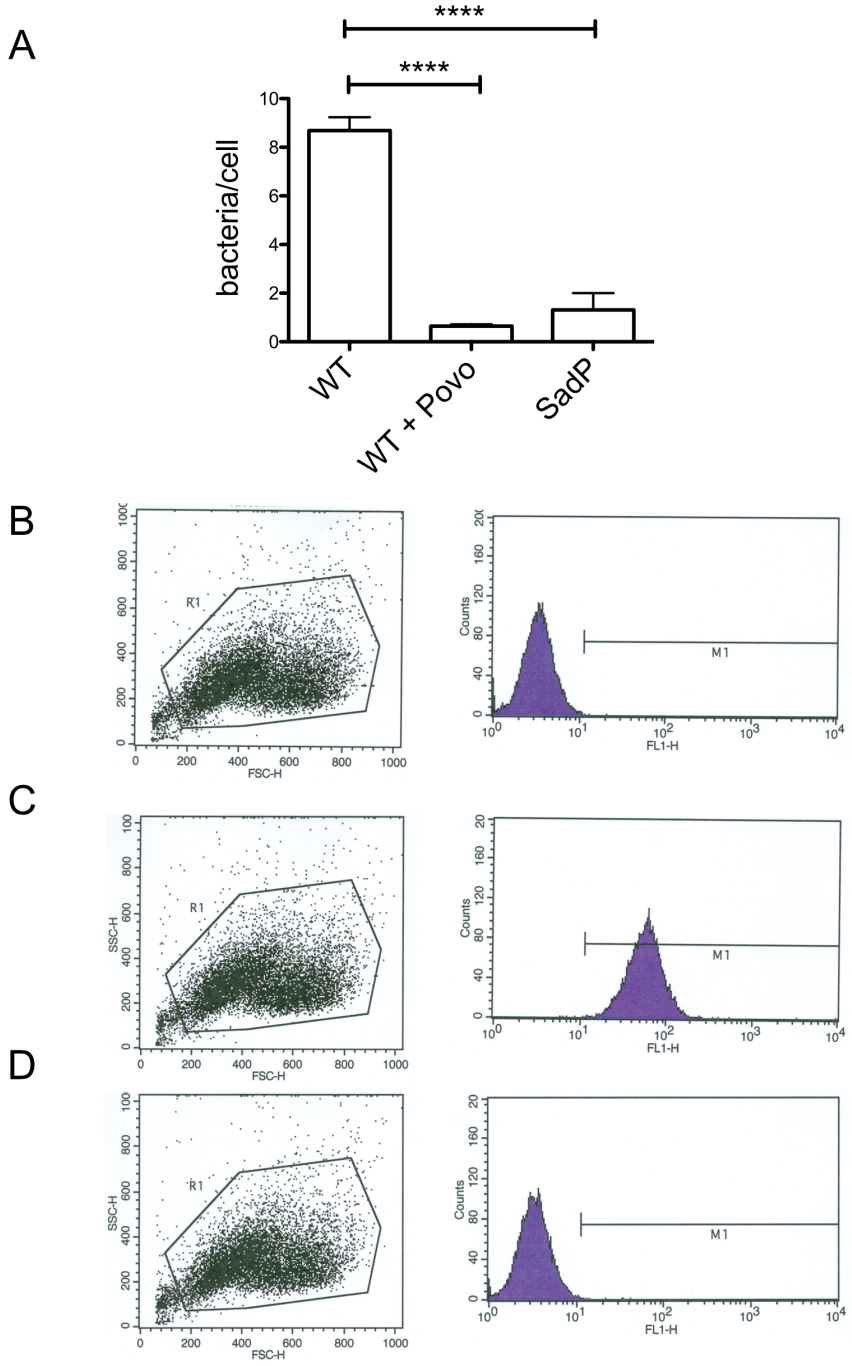
A
****
****
bacteria/cell
10
8
6
4
2
0
WT
WT + Povo
SadP
B
C
D
R1
FSC-H
SSC-H
Counts
M1
FL1-H

Fig 4.

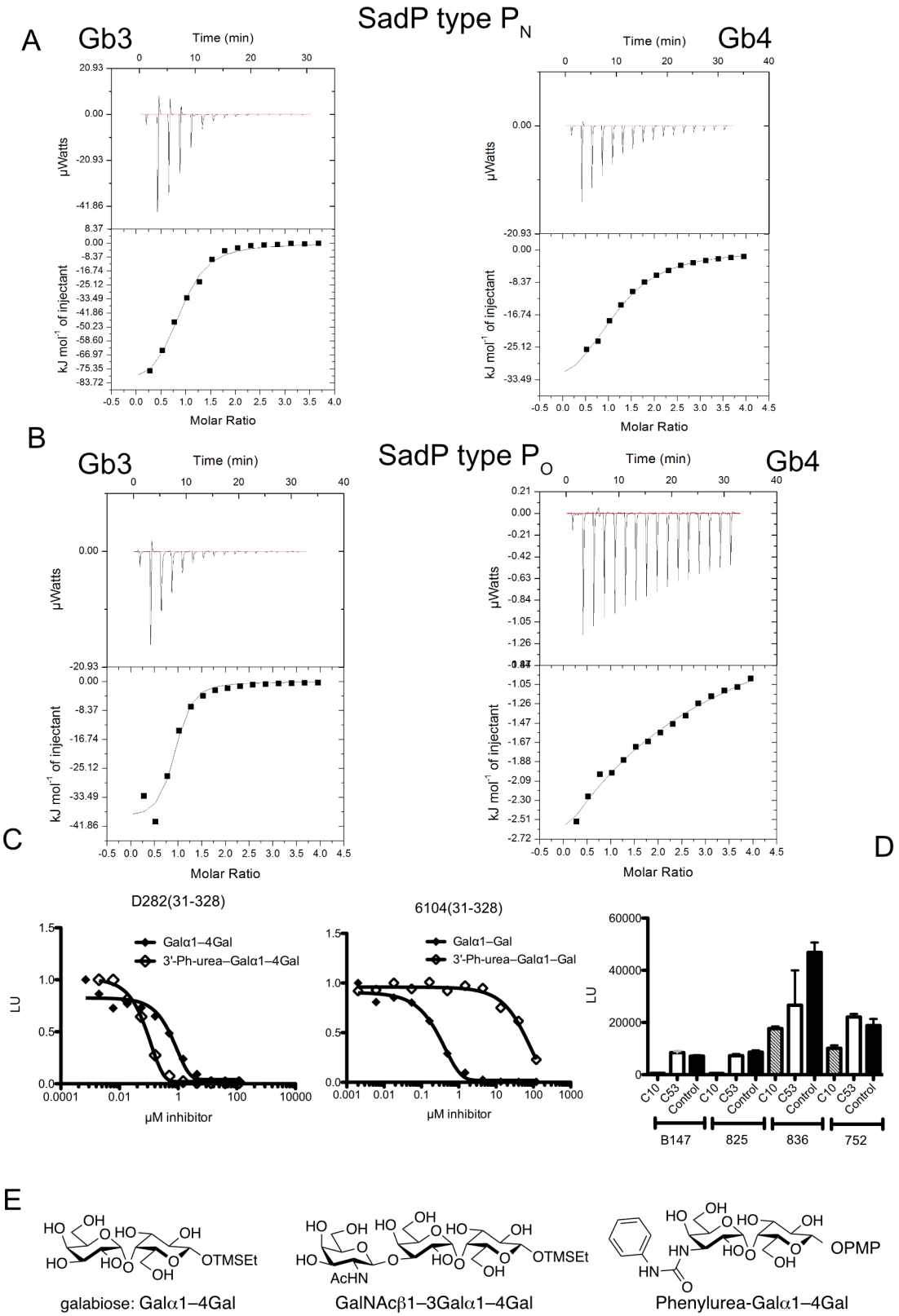
SadP type P_N
A
Gb3
Gb4
Time (min)
µWatts
kJ mol⁻¹ of injectant
Molar Ratio
B
SadP type P_O
C
D
D282(31-328)
6104(31-328)
Galα1–4Gal
3'-Ph-urea–Galα1–4Gal
Galα1–Gal
3'-Ph-urea–Galα1–Gal
LU
µM inhibitor
C10
C53
Control
B147
825
836
752
E
galabiose: Galα1–4Gal
GalNAcβ1–3Galα1–4Gal
Phenylurea-Galα1–4Gal
OTMSEt
OPMP
AcHN

Fig 5.

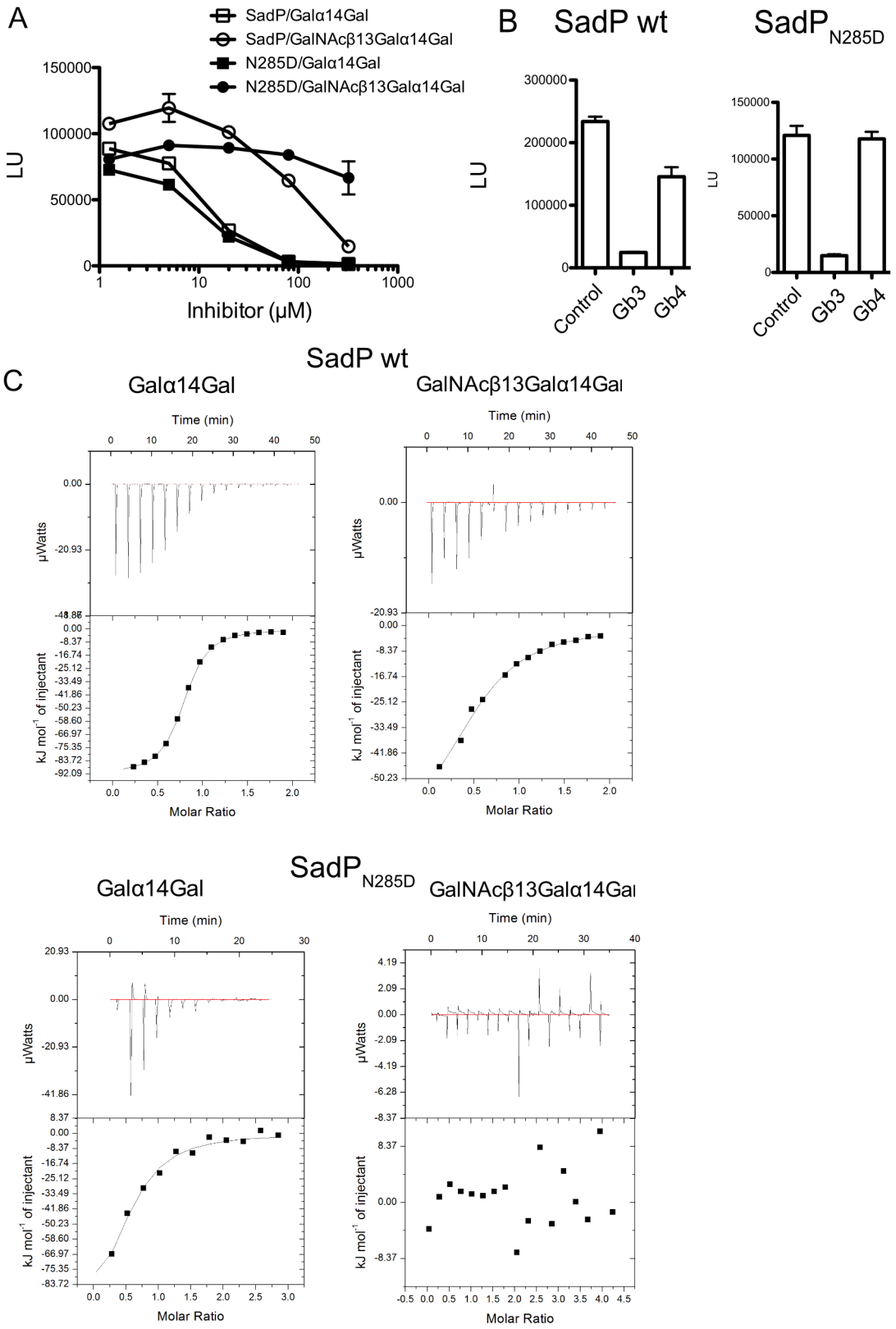
A
SadP/Galα14Gal
SadP/GalNAcβ13Galα14Gal
N285D/Galα14Gal
N285D/GalNAcβ13Galα14Gal
LU
Inhibitor (μM)
B
SadP wt
SadP N285D
Control
Gb3
Gb4
C
SadP wt
Galα14Gal
GalNAcβ13Galα14Gal
SadP N285D
Time (min)
μWatts
kJ mol-1 of injectant
Molar Ratio

Fig 6.

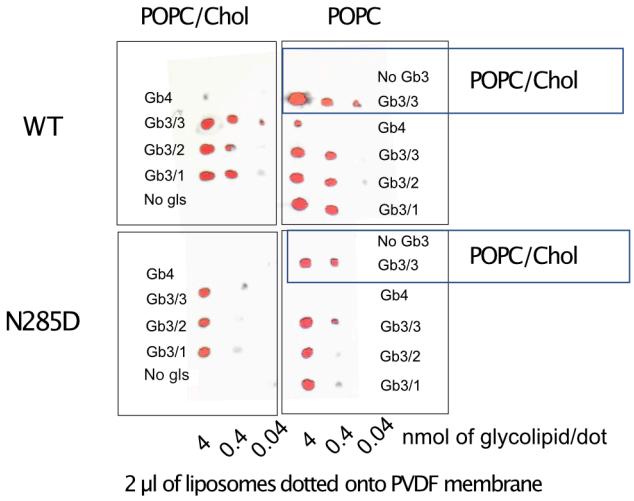
POPC/Chol
POPC
WT
N285D
Gb4
Gb3/3
Gb3/2
Gb3/1
No gls
No Gb3
Gb3/3
Gb4
Gb3/3
Gb3/2
Gb3/1
POPC/Chol
POPC/Chol
4
0.4
0.04
4
0.4
0.04
nmol of glycolipid/dot
2 µl of liposomes dotted onto PVDF membrane

Fig 7.

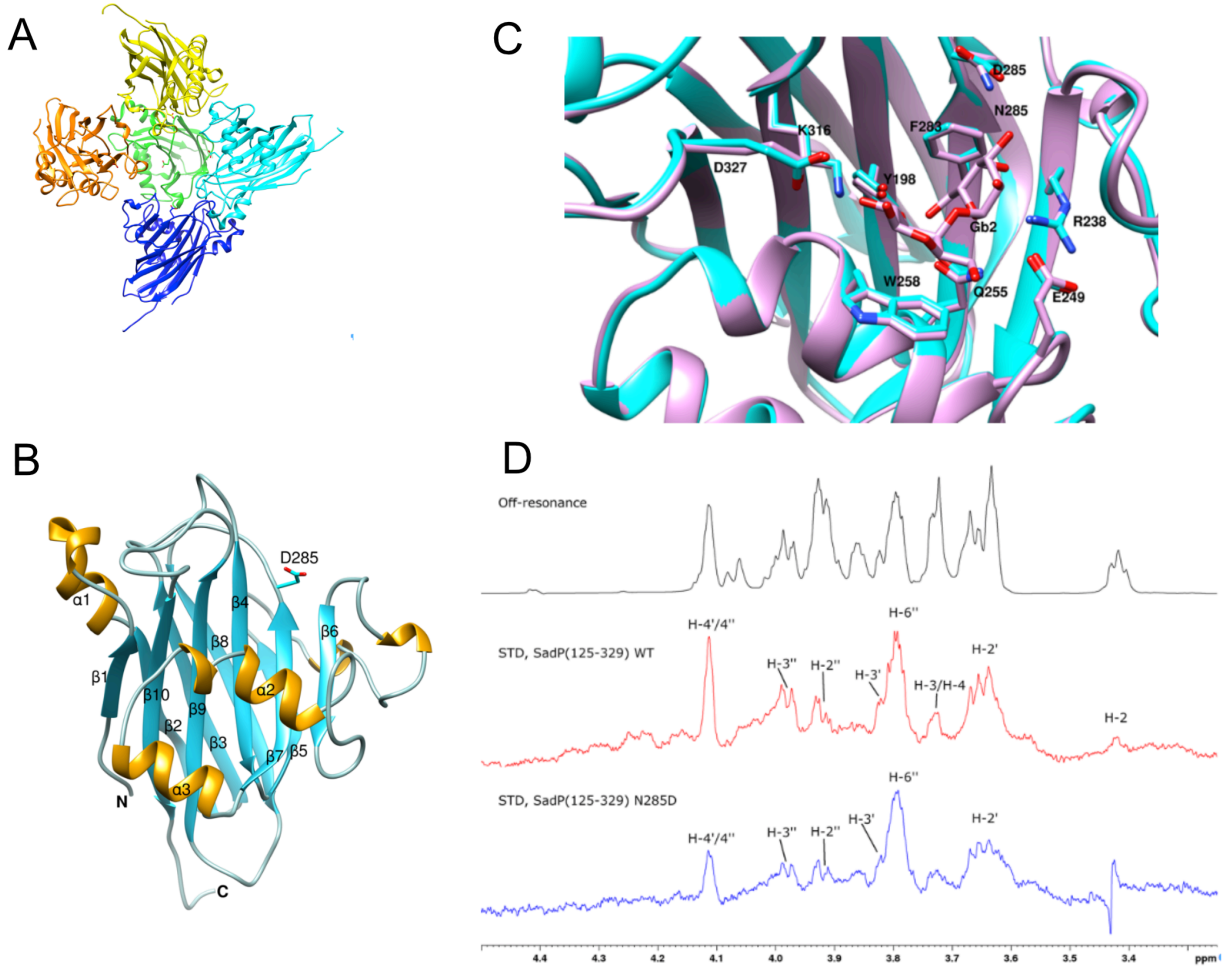
A
B
C
D
D285
N285
K316
F283
D327
Y198
Gb2
R238
W258
Q255
E249
α1
β1
β10
β2
β9
β3
β8
β4
β6
α2
β7
β5
α3
N
C
Off-resonance
STD, SadP(125-329) WT
STD, SadP(125-329) N285D
H-4'/4''
H-3''
H-2''
H-3'
H-6''
H-3/H-4
H-2'
H-2
4.4
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
3.4
ppm

Fig 8.

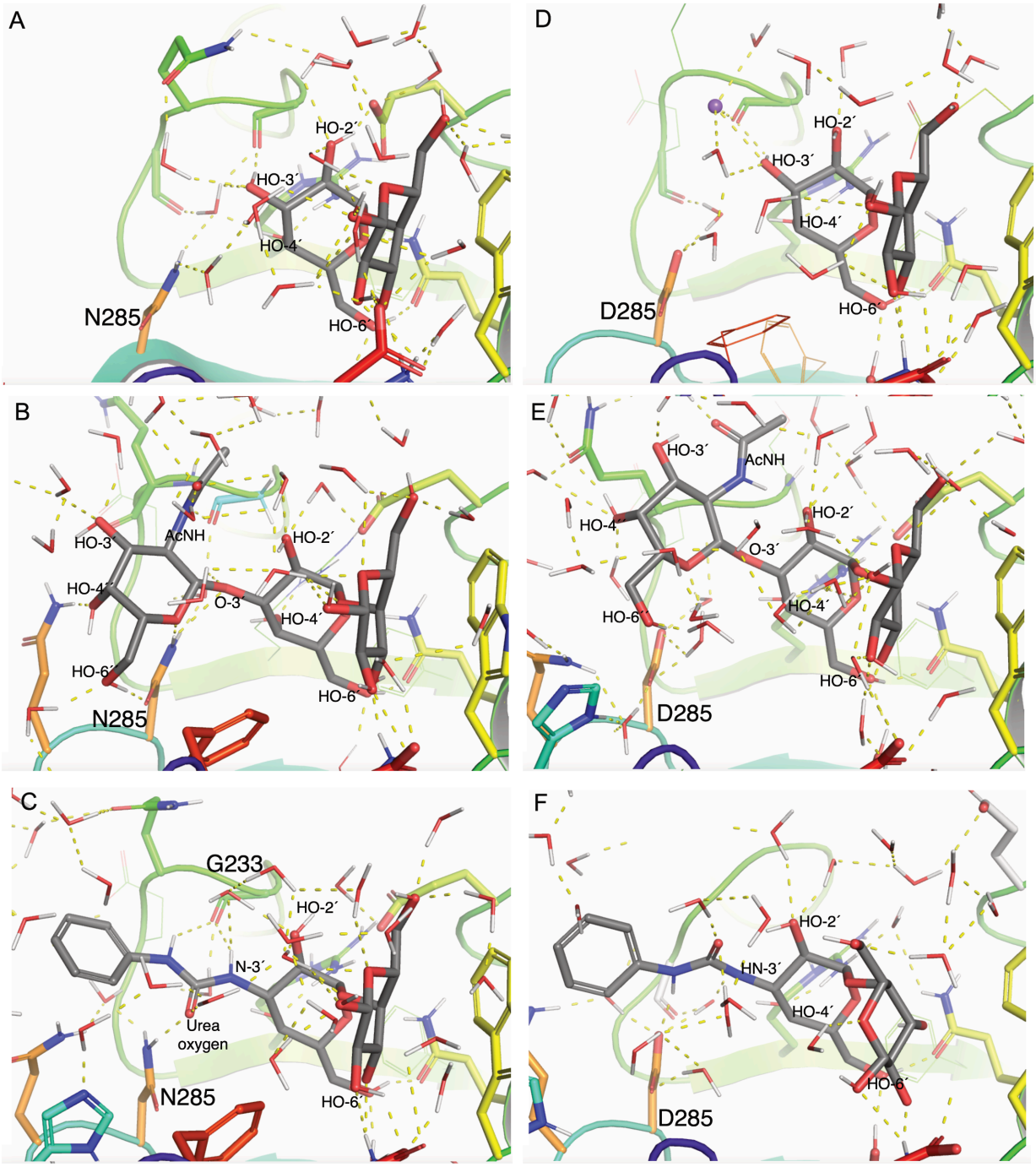
A
HO-2´
HO-3´
HO-4´
N285
HO-6´
D
HO-2´
HO-3´
HO-4´
D285
HO-6´
B
HO-3´
AcNH
HO-2´
HO-4´
O-3´
HO-4´
HO-6´´
HO-6´
N285
E
HO-3´
AcNH
HO-4´´
HO-2´
O-3´
HO-6´´
HO-4´
HO-6´
D285
C
G233
HO-2´
N-3´
Urea
oxygen
N285
HO-6´
F
HO-2´
HN-3´
HO-4´
HO-6´
D285

Fig 9.

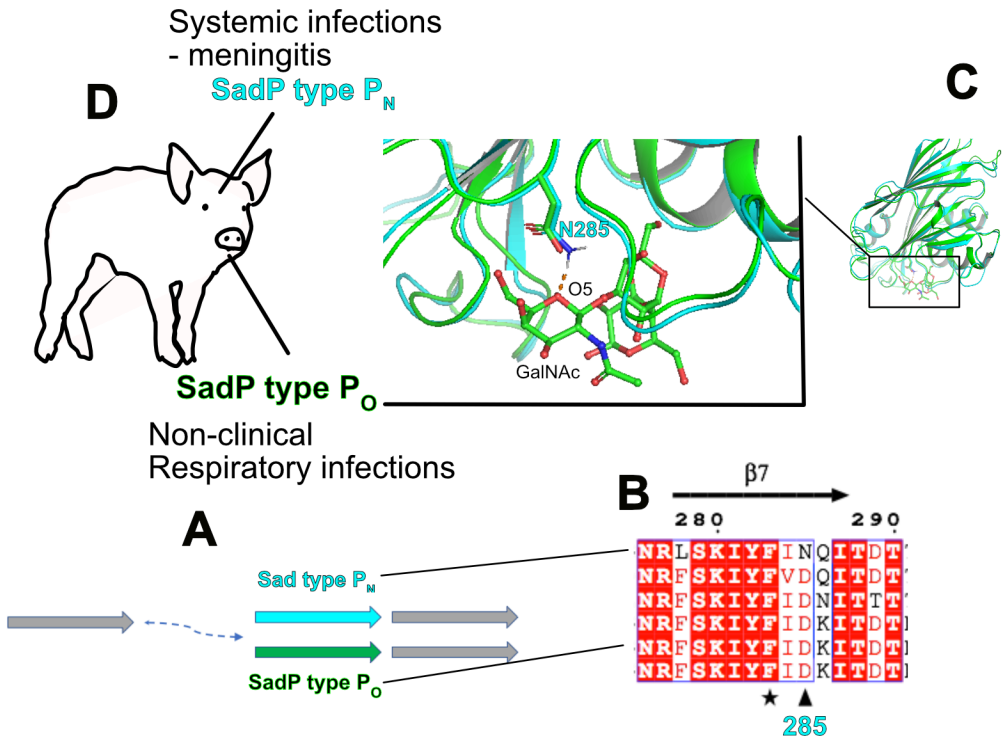
Systemic infections
- meningitis
SadP type P_N
D
C
N285
O5
GalNAc
SadP type P_O
Non-clinical
Respiratory infections
A
B
β7
280
290
Sad type P_N
SadP type P_O
285

Figure legends

Fig 1. Homology of SadP types P_N and P_O galabiose-binding domains and their distribution in systemic, respiratory and non-clinical *S. suis* isolates. A. Multiple alignment of SadP galabiose binding domains of type P_N and type P_O strains. Conserved amino acids are shown in shaded red rectangles and white letters. Residues with >70% similarity according to their physicochemical properties are framed in white background and shown with red letters. Residues involved in hydrogen-bond formation with galabiose (Galα1–4Gal) are shown with (▲) and those involved in hydrophobic interactions with a star (★). Residues 139-343 of SadP are included as found in the crystal structure (pdb id 5BOB). Secondary structure elements are shown on the top. Figure was created with ESpript (46). **B. Distribution of SadP type P_N and P_O alleles in *S. suis* clinical and non-clinical isolates.** Maximum-likelihood core genome phylogeny of 374 *S. suis* isolates from Weinert et al. 2015. The phylogeny was run with RAxML using SNP sites. The nucleotide substitution model used was GTR GAMMA. Tips of the tree are coloured according to the SadP allele detected with SRST2. NA means that with the default parameters neither allele was detected. The inner circle shows the phenotype according to Weinert et al. 2015. Grey non-clinical, red respiratory, blue systemic (brain), green systemic (other) and black unknown. The outer circle is coloured according to the SadP allele detected with SRST2 with the same colours as the tree tips. White NA, red P_N and black P_O.

Fig 2. Different glycolipid binding specificities of SadP type P_N from systemic *S. suis* strains and type P_O SadP from respiratory strains towards pig lung glycolipids and purified globo series glycolipids . A. Comparison of the total non-acid glycosphingolipid fractions from porcine lung and erythrocytes. Base peak chromatogram from LC-ESI/MS of the oligosaccharides derived the total non-acid glycosphingolipid fraction from porcine lung by digestion with *Rhodococcus* endoglycoceramidase II. B. Base peak chromatogram from LC-ESI/MS of the oligosaccharides derived the total non-acid glycosphingolipid fraction from porcine erythrocytes by digestion with *Rhodococcus* endoglycoceramidase II. The identification of individual glycosphingolipid-derived oligosaccharides was based on their determined molecular masses and subsequent MS^2 sequencing. The oligosaccharides identified in the chromatograms are: Gb3, Galα1–4Galβ1–4Glc; H5-2, Fucα2–3Galβ1–4GlcNAcβ1–3Galβ1–4Glc; B5, Galα1–3Galβ1–4GlcNAcβ1–3Galβ1–4Glc;

Gb4, GalNAcβ1–3Galα1–4Galβ1–4Glc; A6-2, GalNAcα1–3(Fucα2–3)Galβ1–4GlcNAcβ1–3Galβ1–4Glc. **B. SadP binding tri- and tetraglycosylceramides isolated from porcine lung.** Thin-layer chromatogram after detection with anisaldehyde (A), and autoradiograms obtained by binding of SadP (B), followed by autoradiography for 12 h, as described under "Methods". The solvent system used was chloroform/methanol/water (60:35:8, by volume). The lanes were: Lane 1, fraction PL-1 isolated from pig lung, 1 μg; Lane 2, fraction PL-2 isolated from pig lung, 1 μg; Lane 3, fraction PL-3 isolated from pig lung, 1 μg; Lane 4, fraction PL-4 isolated from pig lung, 1 μg; Lane 5, reference globotetraosylceramide (GalNAcβ1–3Galα1–4Galβ1–4Glcβ1Cer), 2 μg; Lane 6, reference globotriaosylceramide (Galα1–4Galβ1–4Glcβ1Cer), 2 μg. **C. TLC overlay assay with purified glycolipids**, **SadP-D282 type P_N** 1. Gb2, galabiaosylceramide 2 μg, 2. iGb3, isoglotriosylceramide 4 μg, 3 Gb3, globotriosylceramide 4 μg , 4. Gb4, globotetraosylceramide 4 μg, 5. Gb5, Forssman 4 μg, 6. P1 pentaosylceramide 4 μg. **D. SadP-6407 type P_O** 1. Lactosylceramide 4 μg, 2. Galabiaosylceramide 4 μg, 3. Globotriaosylceramide 4 μg, 4. Globotetraosylceramide 4 μg, 5. P1, pentaosylceramide 4 μg, 6. Forssman pentaosylceramide 4 μg, 7. Non-acid glycosphingolipids of porcine small intestine (blood group O) 40 μg.

Fig 3. SadP binding to EA.hy926 cell line. A. Binding of S. suis D282 wild type serotype 2 strain and the SadP insertion mutation to EA.hy926 cells grown on coverslips. The binding of the wild type bacteria was inhibited with 10 μg/ml of pigeon ovomucoid. Flow cytometry analysis of SadP(31-328) type P_N binding to EA.hy926 cells. **B.** Buffer control. **C.** SadP adhesin (0.4 μg/ml) and **D.** SadP adhesin in the presence of 10 μg/ml of pigeon ovomucoid.

Fig 4. Oligosaccharide specificity of SadP from systemic (type P_N) and respiratory (type P_O) *S. suis* strains analyzed with glycans representing the terminal saccharide structure of Gb3 and Gb4. A. and B. ITC of SadP type P_N and type P_O with Galα1–4Galβ1– and GalNAcβ1–3Galα1–4Galβ1– TMSEt derivatives **C.** AlphaScreen inhibition assay with Galα1–4Galβ1– and 3'Phenylurea-Galα1–4Galβ1– methoxyphenyl (-PMP = 4-methoxyphenyl). **D**. AlphaScreen inhibition assay of Galα1–4Galβ1– (compound

C10) and 3'Phenylurea-Galα1–4Galβ1– methoxyphenyl (compound C53) with recombinant N-terminal domains cloned from 4 different type P_O *S. suis* strains **E**. Structures of the ligands in this study.

Fig 5. A. Single amino acid site-specific mutation N285D of SadP from systemic strains changes its Gb4 binding specificity to type P_O Gb3 binding specificity of respiratory strains. A. Inhibition of WT SadP(125-329) and its site-specific mutant SadP(125-329)N285D with the dilutions series (1.25 to 320 μM, duplicate determinations) of TMSEt (2-trimethylsilylethyl) glycosides of Galα1–4Gal and GalNAcβ1–3Galα1–4Gal representing the Gb3 and Gb4 oligosaccharides. **B.** Inhibition assay with 5 μM of Galα1–4Gal and GalNAcβ1–3Galα1–4Gal TMSEt glycosides. **C.** ITC measurements of WT SadP and N285D mutant with the TMSEt glycosides of Galα1–4Gal and GalNAcβ1–3Galα1–4Gal representing the Gb3 and Gb4 oligosaccharides.

Fig 6. SadP and $SadP_{N285D}$ binding to liposomes. POPC/glycolipid liposomes (4, 0.4 and 0.04 nmol/dot) and POPC/cholesterol/globosylceramide liposomes (4, 0.4 and 0.04 nmol/dot) were applied onto PVDF membrane. WT, His-tagged SadP(125-329) type P_N; N285D, site-specific mutant of SadP(125-329); Replicate membranes containing dotted liposomes with or without cholesterol (see Methods) were probed with **SadP and $SadP_{N285D}$**. The bound proteins were detected with anti-His and HRP-labelled antibodies as described in the methods and membrane was imaged with FujiLAS-4000. The globo series glycolipids used were: Gb4, d18:1-24:0 + d18:1 – 16:0; Gb3/1, Gb3 d18:1-24:0; Gb3/2, Gb3 d18:1-16:0; Gb3/3, Gb3 d18:1-h16:0.

Fig 7. A. Arrangement of the five site-specifically mutated SadP(125-329)N285D molecules in the crystallographic asymmetric unit. Each molecule is shown as ribbon and colored differently. **B.** Ribbon diagram of SadP(125-329)N285D structure. α-Helices are shown in yellow color and β-strands in cyan. D285 is depicted as sticks. **C.** Structural superposition of Galα1–4Gal -bound Fhc (PDB 5BOA) structure (identical to SadP type P_N (pink) onto $SadP(125\text{-}329)_{N285D}$ (cyan). Residues involved in binding interactions are shown

in stick representation. **D.** STD-NMR of binding of wild type SadP(125-329) type P_N and its site-specific mutant N285D. Peaks in the STD spectra indicate hydrogens (C-H) that are in close proximity to the protein.

Fig 8. Molecular dynamics of SadP type P_N binding to Gb4 saccharide and glycomimetic phenylurea-galabiose inhibitor. Representative MD snapshots (at 90 ns) of SadP. WT in complex with **A**. Galα1–4Gal, **B**. GalNAcβ1–3Galα1–4Galβ, and **C.** C3´-phenylurea-Galα1–4Galβ. Representative MD snapshots of SadP N285D in complex with **D.** Galα1–4Gal, **E.** GalNAcβ1–3Galα1–4Galβ, and **F.** C3´-phenylurea-Galα1–4Galβ.

Fig 9. Summary of the results. A. SadP type P_N (cyan) and type P_O (green) are putative duplicates of the downstream SadP homolog (grey). **B.** Conservative change of type P_N SadP asparagine-285 to aspartic acid of SadP type P_O. **C.** This study has shown the mechanism how N285 contributes to the binding of terminal GalNAcβ1- saccharide of Gb4 by a specific interaction with GalNAc hexose ring oxygen (orange dashed line). The 3D-structure of SadP type P_O from type 4 *S. suis* 6407 was obtained by homology modelling (Swiss Prot) and superimposed structures of type P_N (cyan) in complex with GalNAcβ1–Galα1–4Gal and type P_O (green) were created with Pymol. The structures suggest that the abolishment of Gb4 binding is based on the same mechanism as shown with N285D mutant. **D.** The results of the binding mechanisms of SadP type P_N with Gb4 and the distribution of SadP subtypes in *S. suis* clinical and non-clinical strains suggest that SadP Gb4 binding is associated with strains causing systemic disease. Therefore, the molecular mechanism of SadP type P_N binding to Gb4 could be targeted to prevent *S. suis* systemic diseases.

Supporting information

S1 Fig. LC-ESI/MS of the native fraction PL-1 from pig lung. (A) Base peak chromatogram from LC-ESI/MS of fraction PL-2 from pig lung. (B) MS^2 of the ion at *m/z* 1132 (retention time 14.1 min). The interpretation formula shows the deduced glycosphingolipid structure.

S2 Fig. LC-ESI/MS of the native fraction PL-2 from pig lung. (A) Base peak chromatogram from LC-ESI/MS of fraction PL-2 from pig lung. (B) Mass chromatogram of *m/z* 1022. (C) Mass chromatogram of *m/z* 1132. (D) MS^2 of the ion at *m/z* 1022 (retention time 13.1 min). (E) MS^2 of the ion at *m/z* 1132 (retention time 12.5 min). (F) Interpretation formulas showing the deduced glycosphingolipid structures.

S3 Fig. LC-ESI/MS of the oligosaccharides obtained by digestion of fraction PL-1, PL-2, reference globotriaosylceramide, and reference isoglobotriaosylceramide with *Rhodococcus* endoglycoceramidase II. A. Base peak chromatogram from LC-ESI/MS of the oligosaccharides derived from fraction PL-1. B. Base peak chromatogram from LC-ESI/MS of the oligosaccharides derived from fraction PL-2. C. Base peak chromatogram from LC-ESI/MS of the oligosaccharides derived from reference globotriaosylceramide (Galα1–4Galβ1–4Glcβ1–O–Cer). D. Base peak chromatogram from LC-ESI/MS of the oligosaccharides derived from reference isoglobotriaosylceramide (Galα1–3Galβ1–4Glcβ1–O–Cer). E. MS^2 of the ion at *m/z* 503 (retention time 18.4 min) in (A). F. MS^2 of the ion at *m/z* 503 (retention time 17.7 min) in (B). G. MS^2 of the ion at *m/z* 503 (retention time 17.4 min) in (C). H. MS^2 of the ion at *m/z* 503 (retention time 20.2 min) in (D). The interpretation formula shows the deduced oligosaccharide structure. The identification of oligosaccharides was based on their retention times, determined molecular masses and subsequent MS^2 sequencing.

S4 Fig. LC-ESI/MS of the oligosaccharides obtained by digestion of fraction PL-4, and reference globotetraosylceramide with *Rhodococcus* endoglycoceramidase II. A. Base peak chromatogram from LC-ESI/MS of the oligosaccharides derived from fraction PL-4. B. MS^2 of the ion at *m/z* 706 (retention time 18.4 min) in (A). C. MS^2 of the ion at *m/z* 706 (retention time 18.6 min) from LC-ESI/MS of the oligosaccharides

derived from reference globotetraosylceramide (GalNAcβ1–3Galα1–4Galβ1–4Glcβ1–O–Cer). D. MS^2 of the ion at *m/z* 998 (retention time 19.4 min) in (A). E. MS^2 of the ion at *m/z* 998 (retention time 21.4 min) in (A). The interpretation formula shows the deduced oligosaccharide structure. The identification of oligosaccharides was based on their retention times, determined molecular masses and subsequent MS^2 sequencing.

S5 Fig. SadP types P_N and P_O glycolipid binding specificity analysed with TLC overlay analysis and microwell binding assay: A. Decreasing glycolipid dilutions from 2 to 0.2 µg per lane probed with SadP type P_N full length and it's N-terminal domain SadP(31-328). **B.** Microwell binding assay with radiolabelled SadP type P_N to 250 ng of glycolipids, Gb2 galabiosylceramide, Gb2-S Galα1–4Galβ1–O-*bis*-$(SO_2\text{-}C_{16}H_{33})_2$, Gb3 non-OH globotriaosylceramide with non-hydroxy ceramide, Gb3 OH globotriaosylceramide with hydroxy ceramide, iGb3 isoglobotriaosylceramide, Gb4, globotetraosylceramide, P1 pentaosylceramide. Leb Lewis b hexaosylceramide.

S6 Fig. SDS-PAGE of the type P_N WT SadP(125-329) and the site-specific mutants N285D and E292Q, deletion Δ244-246 and N285D&Δ244-246 mutants were constructed into the type P_N SadP(125-328) cloned into the plasmid pET28a. In addition, the 28 amino acid long region H216-D246 of the type P_N was replaced by the corresponding region of type P_O.

S7 Fig. A. Binding of SadP wild type and site-specific mutants to Galα1–4Gal analysed with AlphaScreen**. B - F.** Inhibition assay for the binding of site-specific mutants of PSAD1-5 (PSAD-1 Δ244-246, PSAD-2 N285D, PSAD-3 E292Q, PSAD-4 N285D&Δ244-246 and PSAD-5 H216-D246delinsDELFNRFPNKVDSTNNGDGAPFRFFNKE (replacement of aa 216-242 into corresponding sequence of type P_O of strain 6107).

S8 Fig. Structure analysis of TMSEt (2-trimethylsilylethyl) glycosides

S9 movie. MD simulation of type P_N WT SadP(125-329) and Galα1–4Gal

S10 movie. MD simulation of N285D SadP(125-329) and Galα1–4Gal

S11 movie. MD simulation of of type P_N WT SadP(125-329) and GalNAcβ1–3Galα1–4Gal

S12 movie. MD simulation of of type P_N WT SadP(125-329) and 3'-phenylurea- Galα1–4Gal

S13 movie. MD simulation of N285D SadP(125-329) and GalNAcβ1–3Galα1–4Gal

S14 movie. MD simulation of N285D SadP(125-329) and 3'-phenylurea- Galα1–4Gal