NOVEL CARBOHYDRATE-BINDING ACTIVITY OF PANCREATIC TRYPSINS TO *N*-LINKED GLYCANS OF GLYCOPROTEINS

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Running Title: Carbohydrate binding activity of pancreatic trypsins

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How glycosylation affects the reactivity of proteins to trypsin is not well understood. Bovine and porcine pancreatic trypsins were discovered to bind to α-Man, Neu5Acα2,6Galβ1,4Glc, and α-Gal sequences by binding studies with biotinylated sugar-polymers. Quantitative kinetic studies supported that phenylmethylsulfonyl fluoride (PMSF)-treated trypsin binds to glycolipid analogues possessing α-Man or α-NeuAc but not to those possessing β-Gal or β-GlcNAc residue. ELISA showed that trypsin binds to six kinds of biotinylated glycoproteins possessing high mannose-type and complex type *N*-glycans but not to bovine submaxillary mucin, which possesses only *O*-glycans. Further, the binding of trypsin to glycoproteins was differentially changed by treatments with sequential exoglycosidases, endoglycosidase H, or *N*-glycosidase F. Quantitative kinetic studies indicated that PMSF-treated trypsin binds with bovine thyroglobulin with the affinity constant of 10^{10} M^{-1}, which was the highest among the glycoproteins examined, and that α-galactosidase treatment decreased it to 10^5 M^{-1}. PMSF-treated trypsin bound to other glycoproteins including ovomucoid, a trypsin inhibitor, with the affinity constants of 10^8-10^5 mol^{-1} and were markedly changed by glycosidase treatments in manners consistent with the sugar-binding specificities suggested by ELISA. Thus, the binding site for glycans was shown to be distinct from the catalytic site, allowing trypsin to function as an uncompetitive activator in the hydrolysis of a synthetic peptide substrate. Correspondingly the carbohydrate-binding activities of trypsin were unaffected by treatment with PMSF or soybean trypsin inhibitor. The results indicate the presence of an allosteric regulatory site on trypsin that sugar-specifically interacts with glycoproteins in addition to the proteolytic catalytic site.

Introduction

Numerous biological phenomena are mediated by recognition of specific oligosaccharide signals. This recognition implies quality control in polypeptide folding, cellular interactions, and protein targeting (1-3). In contrast, some functions of protein glycosylation seem to be widely applicable to various types of glycosylation, for example, protecting against proteolysis, stabilizing active conformations, and affording solubility to proteins (3). These functions have been attributed to ambiguous steric effects of glycosylation in the absence of clear structural specificity, but the involvement of glycan recognition in achieving these functions has not yet been elucidated. Clarification of the molecular mechanism by which glycosylation plays a role in protecting or stabilizing the active conformation of proteins would enable the use of glycosylation in molecular

engineering of recombinant products for therapeutic purposes.

Trypsin is a principal pancreatic serine protease that plays a key role in digestion in the duodenum by activating zymogens and degrading dietary proteins. Trypsin acts specifically on peptide bonds of the carboxyl side of positively charged lysine and arginine and catalyzes the activation of many pancreatic proenzymes, such as trypsinogen, chymotrypsinogen, proelastase, and carboxypeptidase, and protease-activated receptors to control digestive efficiency in the intestines (4, 5). When, however, trypsin is activated in the pancreas, the activated proteinases induce the destruction of pancreatic cells. The modulation of trypsin activity is therefore important for controlling digestive efficiency and preventing pancreatitis.

Porcine pancreatic α-amylase (PPA) is activated by interaction with glycoproteins. Previously we reported that PPA exhibits carbohydrate-binding activity toward *N*-glycans of glycoproteins (6). To further elucidate the biological functions of the carbohydrate-binding activity found in PPA, we investigated whether other pancreatic digestive enzymes possess similar carbohydrate-binding activity. In this study, we found that trypsin exhibits remarkable carbohydrate-binding activities to the sequences present in the *N*-glycans of glycoproteins with a specificity distinct from PPA. This finding provides new insights into the interaction between the proteases and glycoproteins related to protease resistance and the biological functions of carbohydrate-specific interactions in the digestive organs.

Experimental procedures

Materials

Porcine pancreatic trypsin (PPT), N-α-benzoyl-L-arginine ethyl ester (BAEE), N-α-benzoyl-DL-arginine-*p*-nitroanilide hydrochloride (BAPA), soybean trypsin inhibitor, bovine serum albumin (BSA), 3,3'-diaminobenzidine tetrahydrochloride, methyl- α-D-mannoside, and mannitol were purchased from Wako Pure Chemical Industries, Ltd. Osaka, Japan. Bovine pancreatic trypsin (BPT), bovine submaxillary gland mucin (BSM), human holotransferrin, fetuin from fetal calf serum, hen ovomucoid, human orosomucoid, bovine thyroglobulin, streptavidin-biotinylated horseradish peroxidase complex (ABC complex), and 4-nitrophenyl phosphate magnesium salt were purchased from Sigma Chemical Company, St. Louis, MO, USA. Sugar-biotinylated polyacrylamide probes (sugar-BP probes) were purchased from Lectinity Holdings, Inc. Moscow, Russia, except β-D-Gal-3-sulfate, which was purchased from Seikagaku Corporation, Tokyo, Japan. Porcine thyroglobulin and *Galanthus nivalis* lectin were purchased from Cosmo Bio Co., Ltd, Tokyo, Japan. Neuraminidase from *Vibrio cholerae,* *N*-glycosidase F from *Flavobacterium meningosepticum,* and *O*-glycosidase were purchased from Roche Diagnostics Corporation, Inc. (Indianapolis, IN, USA). *Psathyrella velutina* lectin was prepared in our laboratory (7). β-Galactosidase and β-*N*-acetylhexosaminidase from jack bean and α-galactosidase from *Mortierella vinacea* were purchased from Seikagaku Corporation. EZ-Link sulfo-*N*-hydroxysuccinimide-biotin and *Sambucus nigra* bark lectin were purchased from Funakoshi Co. Ltd., Tokyo, Japan. Phenylmethylsulfonylfluoride (PMSF) and methyl-α-D-galactopyranoside were purchased from Nacalai Tesque, Inc., Kyoto, Japan. N-Heptyl-β-D-thioglucoside was purchased from Dojindo Laboratories, Kumamoto, Japan. Peanut lectin and *Ricinus communis* agglutinin I were purchased from Seikagaku Corporation. Lactose was purchased from Kanto Kagaku, Tokyo, Japan. SDS-PAGE molecular weight standards were purchased from Bio-Rad Laboratories, Hercules, CA, USA.

Preparation of glycoprotein probes

All biotinylated glycoprotein probes, their deglycosylated derivatives, and biotinyl lectins were prepared in our laboratory. Biotinylation was performed using EZ-link™ sulfo-*N*-hydroxysuccinimide-biotin according to the instruction manual. Briefly, 2 mg of each glycoprotein was dissolved in 1 ml of 50 mM sodium bicarbonate buffer (pH 8.5), and 74 μl

of sulfo-NHS-biotin (1 mg/ml) was added. After incubation for 30 min at room temperature, the reactant was dialyzed against water to remove excess biotin. Asialoglycoproteins, asialo-agalactoglycoproteins, and ahexosamino-asialoagalactoglycoproteins were prepared from biotinylated glycoproteins by sequential glycosidase treatments with neuraminidase (0.1 units/mg glycoprotein) in 20 mM acetate-buffered saline (pH 5.5), β-galactosidase (0.14 units/mg glycoprotein) in 50 mM sodium-citrate buffer (pH 3.5) overnight, and then β-N-acetylhexosaminidase (1.43 units/mg glycoprotein) in 50 mM sodium-citrate buffer (pH 5.0) at 37°C overnight. The glycan structures and carbohydrate concentrations of the glycoproteins used in this study are summarized in Scheme 1. Besides the sequential treatments described above, biotinylated bovine thyroglobulin was treated with α-galactosidase (0.14 units/mg of glycoprotein) in 20 mM acetate-buffered saline (pH 5.5) for agalactosylation of the major oligosaccharide, Galα1-3Galβ1-4GlcNAc. Fetuin was treated with *N*-glycosidase F (600 units/mg of glycoprotein) in 10 mM Tris-buffered saline (TBS) at pH 7, or de*O*-glycosylated with a mixture of neuraminidase (0.1 units/mg glycoprotein) and *O*-glycosidase (2 mU/mg of glycoprotein) in 10 mM acetate buffer of pH 6 at 37°C overnight.

Biotinylated porcine thyroglobulin (20 μg) was denatured in glycoprotein denaturing buffer (5% SDS, 10% β-mercaptoethanol) at 100℃ for 10 minutes, a 10% volume of 0.5 M sodium citrate buffer (pH 5.5) was added, and then it was incubated with 1500 units of endoglycosidase H at 37 ℃ overnight. Deglycosylation of all biotinylated glycoprotein probes was checked by ELISA for a change in reactivity with *Ricinus communis* agglutinin I for agalactosylation, *Psathyrella velutina* lectin for desialylation and ahexosaminylation, *Galanthus nivalis* lectin for endoglycosidase H treatment, and peanut lectin for de*O*-glycosylation to recognize each carbohydrate structure, and by mobility on SDS-PAGE to demonstrate the decrease in molecular weight (data not shown).

SDS-PAGE

In order to check the purity of trypsin, SDS-PAGE was performed according to the method of Laemmli (8) using a 14% gel in the presence of 2-mercaptoethanol. The bovine and porcine trypsins (10, 20, or 40 μg protein per lane) were loaded onto the gel together with a set of markers and run at 20 mA for 1.5 hrs. After electrophoresis, protein bands were visualized by Coomassie Brilliant Blue R-250.

Binding studies with sugar-BP probes or biotinylated glycoprotein probes

PPT and BPT were preincubated in the presence or absence of 0.5 mM PMSF, 0.5 mM soybean trypsin inhibitor, or 5 mM EDTA in 10 mM TBS (pH 7.5) for 1 hr and then immobilized at concentrations of 0.01-0.5 μg/100 μl in wells of a microtiter plate (Immulon 1, Dynatech Laboratories) at 4℃ overnight. All other procedures were performed at room temperature using 10 mM TBS (pH 7.5) as the dilution buffer. After immobilization, the wells were blocked with 3% BSA for 2 hrs. Aliquots (100 μl) of various sugar-BP probes (shown in Scheme 1 (A)) or biotinylated glycoprotein probes at concentrations of 10 μg/ml were added to each well, followed by incubation for 1 hr. After incubation, the wells were washed three times, and 100 μl of ABC complex (1 μg/ml) was added and incubated for 1 hr. After washing three times, color was developed by adding 200 μl of *o*-phenylenediamine/H_2O_2, and then 50 μl of 2.5 M H_2SO_4 was added to stop the reaction. Absorbance was measured with a microplate reader (Bio-Rad MPR-80) at 490 nm.

Quantification of interactions between trypsins and glycolipid analogues by surface plasmon resonance (SPR)

For binding studies between trypsins and glycolipid analogues or various glycoproteins, a BIAcore 2000 SPR apparatus (BIACORE AB, Uppsala, Sweden) was used. Structure of glycolipid analogues used in this study was illustrated in Scheme 2 (B) and the synthesis of them will be described elsewhere. Glycolipid analogues were immobilized on a HPA sensor chip (BIACORE AB) by preparing liposomes

containing each glycolipid analogue/phosphatidylchoine at a molar ratio of 40/60 as described previously (9, 10). PMSF-treated PPT was injected onto the sensor chip at various concentrations in 10 mM TBS buffer (pH 7.5) at a flow rate of 20 μl/min at 25°C using a BIAcore biosensor. The reference cell was prepared by immobilizing phosphatidylcholine and used to correct for bulk effect. The chip was regenerated each time by injection of 20 μl of 0.1 M phosphoric acid.

Quantification of interactions between trypsins and various glycoproteins by SPR

After equilibration of a CM5 sensor chip (BIACORE AB) with HEPES-buffered saline, the surface of the sensor chip was activated with an amine coupling kit. BPT or PPT (each 1.8 μM) in 10 mM sodium acetate buffer (pH 6) containing 0.1 mM PMSF and 0.2 M methyl α-D-mannoside was injected onto the activated surface, and then the remaining *N*-hydroxysuccinimide esters were blocked with 1.0 M ethanolamine hydrochloride (pH 8). Each step was performed for 14 min at a constant flow rate of 10 μl/min at 25℃. The reference flow cell was prepared with BSA as a ligand.

To determine the pH dependency of the binding, fetuin, or porcine thyroglobulin were dissolved at 30 μg/ml in buffers of various pH, 10 mM acetate (pH 4.5, 5.5, and 6.5), 10 mM TBS (pH 7.0, 7.5 and 8.0), or 10 mM bicarbonate buffer (pH 9 and 10), and injected onto the trypsin-immobilized sensor chip. To measure binding curves, various glycoproteins in 10 mM TBS (pH 7.5) were separately injected onto the trypsin-immobilized sensor chip at concentrations of 1, 0.5, 0.25, 0.125, and 0.0625 μM for 150 s at a flow rate of 20 μl/min at 25℃. The chip was regenerated each time by injection of 20 μl of 10 mM HCl. To assay inhibition, a trypsin-immobilized sensor chip was equilibrated with TBS containing 50 mM or 0.2 M methyl α-mannoside, methyl α-galactoside, or lactose for 15 min, and then the glycoprotein dissolved in the same buffer was injected. Kinetic parameters were calculated mainly by global analysis, or affinity analysis when necessary, using the BIAevaluation software version 3.1.

Measurement of enzyme activity of trypsin

Enzyme activity was measured in a test tube according to the method previously described using BAEE (11) or BAPA (12) as the substrate. To estimate the effect of sugar on the BAEE-hydrolytic activity, it was measured after preincubation of PPT in 100 μl of 1 mM HCl (0.02 mg/ml) with 100 μl of 0.4 M methyl-α-D-mannoside, 0.4 M methyl-α-D-galactopyranoside, or 0.4 M lactose in 20 mM TBS (pH 7.6) for 10 min at 25℃. A control experiment was done by preincubating PPT without sugar. After preincubation, the PPT solution was added to 500 μl of 0.025 mM BAEE in 10 mM TBS (pH 7.6) and incubated at 25°C for 1 min. Absorbance was immediately measured at 253 nm, and trypsin activity that increased absorbance by 0.003 at 25°C for 1 min was regarded as 1 USP unit of trypsin.

To analyze the effect of sugar by a double reciprocal Lineweaver-Burk plot, the initial rates of the enzyme-catalyzed reaction were measured using BAPA as the substrate. The substrate stock solution was prepared by dissolving 0.0217 g BAPA in 1.5 ml dimethylsulfoxide and then diluted to final concentrations of 0.1-0.5 mM with 100 mM TBS (pH 7.5) in the presence or absence of 0.2 M methyl α-mannoside, methyl α-galactoside, or lactose. The substrate solutions were heated for 5 min at 37°C. The enzyme stock solution was prepared by dissolving 2.5 mg of PPT in 3 ml of 1 mM HCl containing 13 mg of $CaCl_2$-$2H_2O$. A 10 μl aliquot of the enzyme solution was added to 3 ml of the substrate solution, and absorbance was measured at 410 nm every 30 seconds.

Results

Interaction between trypsins and sugar BP-probes

The carbohydrate-binding activities of BPT and PPT were analyzed using synthetic sugar-BP probes (Scheme 2 (A)), and specificities toward sugar residues and oligosaccharides were determined. As shown in Fig. 1, both BPT and PPT exhibited high binding activity toward α-Man-,

α-Man-6-phosphate-, NeuAcα2,6Galβ1,4Glc-, α–Gal-, and β-Glc-BP probes among the 17 kinds of sugar-BP probes tested. Both trypsins bound to NeuAcα2,3Galβ1,4Glc- and NeuAc-BP to a lesser extent than to NeuAcα2,6Galβ1,4Glc-BP, indicating a preference for sialyl linkages. On the contrary, neither trypsin bound with α-GalNAc- or mucin core 2-type BP probes or with β-Gal, LacNAc, Lac, β-GlcNAc, or β-Gal3-sulfate-BP probes. None of the carbohydrate-binding activities of the trypsins was affected by preincubation with PMSF and EDTA or soybean trypsin inhibitor, suggesting that binding is independent of the catalytic site. The bound sugar residues other than β-D-Glc are components of *N*-glycans, demonstrating basic specificities toward monosaccharides or short sequences that include linkages for trypsin binding.

Interaction between trypsin and glycolipid analogues analyzed by SPR

To verify the carbohydrate-binding specificity of trypsin by quantitative measurement, interaction analyses were performed by SPR using five kinds of synthetic high sensitivity glycolipid analogues (Scheme 2 (B)). The total amounts of immobilized glycolipid analogues containing α-Man, α-NeuAc, and β-Lac were 1593, 1560, and 1680 BIAcore resonance units (RU, 1000 RU = 1 ng/mm^2), respectively. As shown in Fig. 2 (A)-(C), PPT concentration-dependently bound to immobilized glycolipid analogues. The differential binding of PPT to the analogues clearly indicates its relative binding affinity toward sugar residues: PPT binds best with the analogues containing α-Man, then α-NeuAc, and to a lesser extent β-Lac. The binding and dissociation occurred rapidly at the start and end of injection of the glycolipid analogues except the α-Man derivative, demonstrating the specific binding of PPT to those glycolipid analogues with quick association and dissociation rates. PPT did not bind to other analogues containing β-Gal or β-GlcNAc even at 2 μM. The association constants (K_A) were calculated to be 10^6-10^5 (M^{-1}) for glycolipid analogues containing α-Man and α-NeuAc (Figure 2 (D)), which are comparable to the K_A obtained for the interaction between ricin and the glycolipid analogues containing β-Gal (our unpublished result) and higher than that obtained between Con A and α-Man-derivatized glycolipid containing phosphatidylethanolamine aglycon (13). The carbohydrate-binding specificity indicated by SPR corresponded with that obtained by using sugar-BP probes (Fig. 1) demonstrating that the affinity of trypsin for specific carbohydrates is comparable to those of known plant lectins. Therefore, the binding activity of trypsin for glycoproteins was examined.

Purity of BPT and PPT on SDS-PAGE

The carbohydrate-binding activities shown in Fig. 1 and Fig. 2 have never been reported for trypsin. To eliminate the suspicion that some contaminant in the trypsin preparation might exhibit such an activity, we analyzed the purity of the trypsin preparations used in this study by SDS-PAGE. As shown in Fig. 3, both BPT and PPT showed only a single band without any detectable contamination even if 40 μg of trypsin preparation was applied per lane to the polyacrylamide gel. Therefore, the carbohydrate-binding activities observed in this study were attributed to the trypsins.

Interaction between trypsins and biotinylated glycoprotein probes

Interactions between the glycoprotein probes and PPT or BPT were studied by ELISA at pH 7.5, which is the physiological pH in the duodenum. Because the amount of biotin incorporated into each glycoprotein probe was almost equal, as judged by the color intensity of each probe developed with the ABC complex being within a 10% error, the value of A490 corresponds to the amount of probe bound. As shown in Fig. 4(A) and (B), BPT and PPT were found to bind to various glycoproteins with very similar binding patterns. The trypsins bound best to bovine thyroglobulin, and to a lesser extent to fetuin, porcine thyroglobulin, ovomucoid, orosomucoid, and transferrin, in that order, but not to BSM. All the bound glycoproteins contain 5-30% (w/w) *N*-linked oligosaccharides while BSM possesses up to 60% (w/w) *O*-linked glycans, which are

mainly sialyl Tn and core 3-type (Scheme 1). Combined with the finding that trypsins did not bind with α-GalNAc- and β-GlcNAc (Fig. 1), this indicates that trypsins do not interact with *O*-linked glycans.

The involvement of the *N*-glycan structure in the binding with PPT and BPT was shown by deglycosylating the glycoprotein probes with endo-type glycosidases. As shown in Fig. 5(C), de*N*-glycosylation of fetuin by *N*-glycosidase F treatment markedly decreased the reactivity toward both trypsins (data not shown for PPT), showing that their binding was mostly due to the affinity for the sialylated complex-type *N*-glycans of fetuin. The reactivity of trypsins for porcine thyroglobulin (Fig. 5 (B)), which contains almost equal amounts of high Man-type and complex-type glycans (Scheme 1), was decreased to about half that of intact porcine thyroglobulin by endoglycosidase H treatment as well as asialoagalactoahexosaminylation, indicating that trypsins bind with high Man-type *N*-glycans as well as the sialylated complex-type.

As shown in Fig. 5, the effects of exo-type glycosidase treatments of the glycoprotein probes illustrate the contribution of each sugar residue to the interaction with BPT. Remarkably, binding of BPT with bovine thyroglobulin was found to be diminished by α-galactosidase treatment (Fig. 5(A)), clearly indicating that the α-galactosyl residue at the nonreducing terminal, which is unique to the *N*-glycan of bovine thyroglobulin (Scheme 1), is an epitope for BPT binding. Other exoglycosidase treatments of bovine thyroglobulin did not affect the binding.

On the other hand, neuraminidase treatment of other glycoproteins that possess sialylated complex-type *N*-glycans, fetuin, ovomucoid, orosomucoid, and porcine thyroglobulin, considerably decreased the binding, as shown in Fig. 5(B)-(E). For these glycoprotein probes β-galactosidase treatment subsequent to desialylation did not significantly change the binding, but exposure of α-mannosyl residues of the trimannosyl core of *N*-glycans by β-hexosaminidase treatment subsequent to degalactosylation restored the binding to trypsin. These results strongly indicate that α-NeuAc and α-mannosyl residues of complex-type multiantennary *N*-glycans contribute to the binding of trypsins, but β-Gal and β-GlcNAc residues of the lactosamine sequence do not. The biantennary complex type of transferrin did not show significant affinity for trypsins (Fig. 5F). As a whole, the sugar-binding specificities of BPT and PPT indicated in Fig. 1 coincide with and account for the binding specificities toward the glycoprotein probes.

Preincubation of PPT and BPT with PMSF and EDTA or soybean trypsin inhibitor before the binding studies did not affect the binding activities toward glycoproteins (data not shown). Moreover, the binding of trypsin to ovomucoid, a natural inhibitor that blocks the catalytic site of trypsin, was found to be significantly affected by glycan trimming (Fig. 5D). The observations indicate that the trypsin binding to glycoproteins is independent of their catalytic activity.

Interaction between trypsins and various glycoproteins analyzed by BIAcore

The total amounts of immobilized PPT, BPT, and BSA were 4,012, 4,028, and 4,031 RU, 1000 RU, respectively. The responses are expressed as the change of resonance units induced by the binding of analytes to each flow cell, which was corrected for bulk effect by subtracting the change on the BSA-immobilized reference cell.

A. PH-dependency of interaction between trypsin and glycoproteins

Fetuin or porcine thyroglobulin was injected onto a trypsin-immobilized chip at pH 4.5-10. As shown in Fig. 6, the amounts of the glycoproteins bound to immobilized PPT and BPT changed within 30% in the pH range examined, showing a maximum at around pH 7.5-8.0. The weakly alkaline pH coincides with the enteric pH indicating that the carbohydrate-binding activity of trypsin is optimal in the milieu of the intestine. Based on this observation, 10 mM TBS at pH 7.5 was thereafter used for the binding studies.

B. Effect of sugars on binding of trypsin to glycoproteins

Fig. 7 shows the effect of monosaccharide trypsin binding to

glycoproteins. Me α-Man and Me α-Gal which showed the highest binding to trypsin (Fig. 1) were used as inhibitors in comparison with Lac, which showed relatively lower binding in the binding study with BP-sugars. The binding of both trypsins to fetuin and porcine thyroglobulins was decreased by 30-44% in 50 mM Me α-Man and 56-64% in 0.2 M Me α-Man, and binding to bovine thyroglobulin was decreased by 44-50% and 66-70% in 50 mM and 0.2 M Me α-Gal, respectively. While the binding of trypsins was decreased by only 10-18% even at 0.2 M Lac, indicating the weak inhibitory activity of Lac compared to those of Me α-Man and Me α-Gal coinciding with the relative affinity of sugars shown by BP-sugar binding studies. The results strongly support the hypothesis that trypsins bind glycoproteins by sugar-specific interaction.

C. Kinetic parameters for binding between trypsins and glycoproteins

The sensorgrams are shown in Fig. 8 (A) and (B), and the binding parameters were calculated for each glycoprotein. The binding of all glycoproteins except BSM fit best a 1:1 binding model among the fitting models in global analysis. The interaction between bovine thyroglobulin and trypsins was analyzed at concentrations lower than 0.25 μM (Fig. 8 (A)-e and (B)-o) because bovine thyroglobulin gave fluctuating, irregular-shaped binding curves at concentrations higher than 0.5 μM. The interaction between trypsins and BSM showed box-shaped binding curves suggesting high association and dissociation rates (Fig. 8 (A)-j and (B)-t) and was analyzed using affinity analysis. The kinetic data of the binding are summarized in Table 1.

Trypsin bound to the glycoproteins possessing *N*-glycans with significantly high affinity, K_A ranging from 10^{10}-10^6 M^{-1}. In contrast, the K_A for BSM was as low as 1-8 x 10^4 M^{-1}, indicating very weak interaction with trypsins. The K_A for bovine thyroglobulin binding to both PPT and BPT was 10^{10} M^{-1}, which is the strongest among glycoproteins and equal to that of high affinity antibodies, followed by the K_A of porcine thyroglobulin, 4-5 x 10^7 M^{-1}. The high K_A of trypsin for bovine thyroglobulin is attributable to the extremely low dissociation rate constants (k_d) (10^{-7}-10^{-6} s^{-1}) compared to those of other glycoproteins (10^{-4}-10^{-3} s^{-1}), suggesting that thyroglobulins hardly dissociate from trypsin. The K_A of trypsin for bovine thyroglobulin was markedly decreased from 10^{10} to 10^5 (M^{-1}) by α-galase treatment, indicating that α-Gal residues are essential for high affinity binding to trypsin. On the other hand, the K_A of trypsin for porcine thyroglobulins (4-5 x 10^7 M^{-1}) was decreased to 15-20% by treatment with endoglycosidase H or neuraminidase, showing that high-Man types as well as sialyl residues of complex types contribute to the binding. The K_A for fetuin was decreased by *N*-glycosidase F treatment by about 10^{-3}-fold but not by *O*-glycosidase treatment, indicating that the sialylated complex-type *N*-glycans of fetuin contributed absolutely to the binding, but *O*-glycans did not, even if they are sialylated. The results correlated well with the reactivities of trypsin toward intact and glycosidase-modified glycoprotein probes by ELISA.

Effect of sugars on enzyme activity of PPT

As shown in Fig. 9 (A), the sugars that bound to trypsins enhanced the enzyme activity to various degrees, as detected using BAEE and BAPA as substrates. The hydrolytic activity of PPT for BAEE was enhanced by 1.4-fold in 0.2 M methyl α-D-mannoside and 1.2-fold in methyl α-D-galactoside, but not enhanced in 0.2 M lactose. When we used a slowly hydrolyzable BAPA as the substrate, PPT was activated with 0.2 M methyl α-D-mannoside and methyl α-D-galactoside to about 1.2-1.4-fold at 300-600 sec (Fig. 9 (B)). As shown in Fig. 9 (C)-(E) and Table 1, the Lineweaver-Burk plots indicate that the binding of Meα·Man, and Meα·Gal uncompetitively activates PPT with increasing Vmax by 2.5-fold and Km by 2- to 2.5-fold, while binding of lactose slightly inhibited PPT noncompetitively and uncompetitively, indicating that the binding of carbohydrates activates the hydrolytic activity to various degree.

Discussion

This study demonstrates that mammalian pancreatic trypsin commonly binds to glycoproteins possessing *N*-linked glycans by carbohydrate-specific interaction. The sugar-binding specificity of trypsin was shown by the binding with sugar-BP probes and glycolipid analogues to be α-galactosyl, oligomannosyl, and nonreducing terminal α2,6-NeuAc residues (Fig. 1). Trypsin bound to glycoproteins possessing *N*-glycans with very high affinity, reaching 10^{10}-10^{6} M^{-1}, whereas it did not bind to BSM (Fig. 4 and Table 1). The binding of glycoprotein probes with trypsin was changed by glycosidase treatments on ELISA and SPR analyses, which coincided well with the sugar-binding specificity indicated by sugar-BP probes. The specificity of the interaction between trypsin and the glycoproteins was proven by inhibition studies with monosaccharides using SPR (Fig. 7), and conclusively demonstrated to be due to the affinity of trypsin for component saccharide residues of the *N*-linked glycans but not by protein-protein interaction.

Treatment of trypsin with soybean trypsin inhibitor and PMSF did not affect the binding to sugar-BP, glycolipid analogues, and glycoprotein probes, and trypsin was noncompetitively and uncompetitively activated toward synthetic substrates, BAEE and BAPA, by the binding of specific sugars (Figs. 9 and Table 2). Therefore, the *N*-glycan recognition of trypsin must be exhibited at a site different from its catalytic site, and activation would be caused by an allosteric effect to make the substrate binding site more accessible to the substrate and/or by a conformational effect that stabilizes the trypsin molecule against autodegradation, like the stabilizing effect of Ca^{2+} binding (14).

The coating of oligosaccharides on glycoproteins can serve to protect the polypeptide chain from degradation by proteases (3). The contributions of sialylation to the stabilization of glycoprotein against tryptic hydrolysis have been reported for several glycoproteins including orosomucoid (15), and vitronectin (16). The de*N*-glycosylation of ovomucoid with trifluoromethanesulfonic acid has been reported to interfere with the inhibitory activity against trypsin and make ovomucoid easily hydrolyzable with trypsin (17). Although the relationship between oligosaccharide structure and the protective function against preoteases has been explored for several glycoproteins (18-20), the protecting mechanism achieved by the oligosaccharides have remained unclear. Because the removal of oligosaccharides from a mature protein does not always drastically alter its sensitivity to proteolysis, some specific interaction between protease and glycoproteins may be involved in regulating protease attack. We found that trypsin sugar-specifically interacts with *N*-linked glycoproteins. The binding of trypsin to the *N*-glycans of glycoprotein would protect the carrier glycoprotein from hydrolysis, at least partially, by topologically restricting the substrate-binding site of trypsin. Deglycosylation of glycoproteins, which diminishes the carbohydrate-specific binding, makes trypsin interact with the peptide moiety of the glycoprotein through the substrate-binding site to hydrolyze it. In this hypothesis, glycosylation at even one site of the polypeptide can significantly affect the proteolysis of the carrier glycoprotein. It is necessary to define the relationship between the structure and position of glycosylation that affects the susceptibility to trypsin to examine the hypothesis.

The binding specificity of trypsin toward carbohydrates was different from that of PPA on the point that trypsin bound little to *N*-acetyllactosamine and α-GalNAc, which bound well to PPA, and bound to fetuin better than to transferrin (Fig. 4) while PPA bound to transferrin better than to fetuin (6). The differences may suggest that the endogenous receptors for trypsin and α-amylase are not identical.

The carbohydrate-binding activity of trypsin was exhibited at a broad pH range with the optimum at pH 8.0, the slightly alkaline pH similar to the pancreatic fluid in the intestinal lumen. Therefore trypsin may interact with glycoligands in the epithelial surface of the duodenum and intestine in vivo because it is extensively glycosylated with *N*-glycans (21-23) containing α-Gal residues (24). The *N*-glycan-binding activity would play a role in

targeting trypsin and concentrating it on the brush border membrane. Such immobilization of trypsin would enhance the activity and/or elongate the short life span of trypsin by stabilizing it against autodegradation. Because the ability of the duodenum to digest proteins increases rapidly in the cascade of enzyme activations following trypsin activation, the enhancement of trypsin activity would be amplified to increase digestive efficiency exponentially, therefore the 140% enhancement of trypsin activity measured by using BAEE would be amplified in the duodenum to increase more than 5-fold after the sixth stage. In addition, the binding of trypsin to intestinal epithelium makes the product peptides spatially available as a substrate for the exo-type peptidases that are naturally anchored to the intestinal brush border membrane. The activated proteinases cooperatively break down dietary proteins to peptides that are subsequently degraded to amino acids by other exo-type peptidases either secreted or expressed in the brush border membrane of epithelial cells in the duodenum and small intestine. Rat aminopeptidase N (EC 3.4.11.2) is one of such glycoproteins with 20% (w/w) carbohydrates that possess unsialylated tri- and tetraantennary complex types as major *N*-glycans (25), which are very similar to the glycans of ovomucoid. A major part of dipeptidylpeptidase IV (EC 3.4.14.-) (26) and peptide transporter-1 (PEPT1), a H+/peptide cotransporter responsible for the uptake of small peptides(27), are among the *N*-glycosylated glycoproteins in the small intestine, too. The association of trypsin with this exopeptidase or transporter would enhance the rate of degradation of substrate proteins and peptide absorption by increasing the catalytic efficiency both allosterically and with mass action after. The binding of trypsin to intestinal glycoreceptors may also stimulate exocrine secretion of digestive tract hormones or pancreatic proteins as reported for exogenously administered plant lectins (28). The carbohydrate binding may regulate the reactivity of trypsin with the glycosylated protease-activated receptor 2 depending on the glycosylation state(29) and influence intestinal inflammation, cytoprotection, and cellular motility.

Together with our previous findings on pancreatic □-amylase, carbohydrate-binding activities of macromolecule-degrading enzymes might play essential roles in localization, activation, and stabilization of pancreatic enzymes to achieve efficient digestion. Considering the biological significance of trypsin in the activation of other proteinases and its degradative role in various tissues, the mechanism of modulating tryptic susceptibility by glycosylation of proteins must be elucidated.

References

1. Varki,A., Esko, J. R. C., Freeze, H., Hart, G., Marth, J. (1999) in *Essentials of Glycobiology*, Coldspring Harbor Laboratory Press, Woodbury, NY
2. Helenius, A., and Aebi, M. (2001) *Science* **291**, 2364-2369
3. Varki, A. (1993) *Glycobiology* **3**, 97-130
4. Chen, J. M., and Ferec, C. (2000) *Pancreas* **21**, 57-62
5. Phillips, M.A., and Fletterick, R. J. (1992) *Curr. Opin. Struct. Biol*. **2**, 713-720
6. Matsushita, H., Takenaka, M., and Ogawa, H. (2002) *J. Biol. Chem.* **277**, 4680-4686
7. Ueda, H., Kojima, K., Saitoh, T., and Ogawa, H. (1999) *FEBS Lett*., **448**, 75-80.
8. Laemmli, U. K. (1970) Nature 227, 680-685
9. Azefu, Y., Tamiaki, H., Sato, R., and Toma, K. (2002) *Bioorg. Med. Chem*., **10**, 4013-4022
10. Sato, R., Toma, K., Nomura, K., Takagi, M., Yoshida, T., Azefu, Y., and Tamiaki, H. (2004) *J. Carbohyd. Chem.*, **23**, 375-388.
11. Schwert, G. W. and Takenaka, Y. (1955) *Biochim. Biophys. Acta*, **16**, 570-575

12. Erlanger, B. F., Kokowsky, N., and Cohen W. (1961) *Arch. Biochem. Biophys.*, ***95,*** 271-278
13. Mann, D.A., Kanai, M., Maly, D. J., and Kiessling L. L. (1998) *J. Amer. Chem. Soc.*, **120**, 10575-10582.
14. Abbott, F., Gomez, J. E., Birnbaum, E. R., and Darnall, D. W. (1975) *Biochemistry* **14**, 4935-4943
15. Sharon, N. (1975) *Complex Carbohydrates: Their Chemistry, Biosynthesis and Functions*, pp. 109-117, Addison-Wesley Publishing, MS
16. Uchibori-Iwaki, H., Yoneda, A., Oda-Tamai, S., Kato, S., Akamatsu, N., Otsuka, M., Murase, K., Kojima, K., Suzuki, R., Maeya, Y., Tanabe, M., and Ogawa, H. (2000) *Glycobiology* **10**, 865-874
17. Gu, J. X., Matsuda, T., Nakamura, R., Ishiguro, H., Ohkubo, I., Sasaki, M., and Takahashi, N. (1989) *J. Biochem. (Tokyo)* **106**, 66-70
18. Gentile, F., and Salvatore, G. (1993) *Eur. J. Biochem.* **218**, 603-621
19. Arnold, U., Schierhorn, A., and Ulbrich-Hofmann, R. (1998) *J. Protein Chem.* **17**, 397-405
20. Ashida, H., Yamamoto, K., and Kumagai, H. (2000) *Biosci. Biotechnol. Biochem.* **64**, 2266-2268
21. Roth, J. (1993) *Histochem. J.* **25**, 687-710
22. Roth, J. (1987) *Biochim. Biophys. Acta* **906**, 405-436
23. Pusztai, A., Ewen, S. W., Grant, G., Peumans, W. J., Van Damme, E. J., Coates, M. E., and Bardocz, S. (1995) *Glycoconj. J.* **12**, 22-35
24. Oriol, R., Barthod, F., Bergemer, A.M., Ye, Y., Koren, E., and Cooper, D.K. (1994) *Transpl. Int.*, **7**, 405-413
25. Takasaki, S., Erickson, R. H., Kim, Y. S., Kochibe, N., and Kobata, A. (1991) *Biochemistry* **30**, 9102-9110
26. Erickson, R. H., and Kim, Y. S. (1983) *Biochim. Biophys. Acta* **743**, 37-42
27. Shen, H., Smith, D. E., and Brosius, F. C., 3rd. (2001) Pediatr. Res. 49, 789-795
28. Pusztai, A. a. B., S. (1996) *Trends Glycosci.Glycotechnol.* **8**, 149-165
29. Hollenberg, M. D., and Compton, S. J. (2002) *Pharmacol. Rev.* **54**, 203-217
30. Yamashita, K., Kamerling, J. P., and Kobata, A. (1982) *J. Biol. Chem,* **257**, 12809-12814
31. van Dijk, W., Havenaar, E. C., and Brinkman-van der Linden, E. C. (1995) *Glycoconj. J.* **12**, 227-233
32. Thall, A., and Galili, U. (1990) *Biochemistry* **29**, 3959-3965
33. Ito, S., Yamashita, K., Spiro, R. G., and Kobata, A. (1977) *J. Biochem. (Tokyo)* **81**, 1621-1631
34. Kamerling, J. P., Rijkse, I., Maas, A. A., van Kuik, J. A., and Vliegenthart, J. F. (1988) *FEBS Lett.* **241**, 246-250
35. Tsuji, T., Yamamoto, K., Irimura, T., and Osawa, T. (1981) *Biochem. J.* **195**, 691-699
36. Yamamoto, K., Tsuji, T., Irimura, T., and Osawa, T. (1981) *Biochem. J.* **195**, 701-713
37. Fu, D., and van Halbeek, H. (1992) *Anal. Biochem.* **206**, 53-63

38. Takasaki, S., and Kobata, A. (1986) *Biochemistry* **25**, 5709-5715
39. Berman, E. (1987) *Magn. Reson. Chem.* **25**, 784-789
40. Tsuji, T., and Osawa, T. (1986) *Carbohydr. Res.* **151**, 391-402
41. Toba, S., Tenno, M., and Kurosaka, A. (2000) *Biochem. Biophys. Res. Commun.* **271**, 281-286

Footnotes

This work was supported in part by Grants-in-Aid for Scientific Research (C) 14580622 and 17570109 (HO) from the Japan Society for the Promotion of Science and Grants-in-aid for Scientific Research on Priority Areas 15040209 and 17046004 (HO) from the Ministry of Education, Culture, Sports, Science, and Technology.

Abbreviations. PPA, porcine pancreatic α-amylase; BPT, bovine pancreatic trypsin; PPT, porcine pancreatic trypsin; BAEE, N-α-benzoyl-L-arginine ethyl ester; BAPA, N-α-benzoyl-DL-arginine-*p*-nitroanilide hydrochloride; BSA, bovine serum albumin; BSM, bovine submaxillary mucin; ABC complex; streptavidin-biotinylated horseradish peroxidase complex; sugar-BP probe, sugar-biotinylated polyacrylamide probe; PMSF, phenylmethylsulfonyl fluoride; EDTA, ethylenediamine tetraacetic acid; TBS, Tris-buffered saline; K_a, affinity constant; k_a, association rat constant; k_d, dissociation rate constant.

Legends to Figures

Figure 1. Reactivities of PPT (A) and BPT (B) toward sugar BP-probes by ELISA. PPT and BPT (100 μl) were coated onto the wells of a microtiter plate and reacted with various sugar BP-probes as described in the text. The bound sugar BP-probes were detected with ABC complex and 4-chloro-1-naphthol/H_2O_2 by ELISA. Symbols used are: (◆) α-Man-BP, (◇) α-Man-6-phosphate-BP and Neu5Ac α2-6Galβ1-4Glc-BP, (□) α-Gal-BP, (×) β-Glc-BP, (△) β-GalNAc-BP, (▲) Neu5Ac α2-3Galβ1-4Glc-BP, (△) α-Neu5Ac-BP, (◈) α-Glc-BP, (■): GlcNAcβ1-4GlcNAc-BP, (▣) GlcNAcβ1-6(Galβ1-3)GalNAc (core2)-BP, α-GalNAc-, β-Gal-, LacNAc-, Lac-, β-GlcNAc- and β-Gal-3-sulfate-BP. The label "core 2*" stands for the seven sugar BP-probes that bound very little with trypsin.

Figure 2. Quantification of interaction between PPT and glycolipid analogues by SPR. Glycolipid analogues were immobilized on a HPA sensor chip as described in the text. PPT was pretreated with 0.1 mM PMSF and injected onto the sensor chip at various concentrations in 10 mM TBS buffer (pH 7.5) at a flow rate of 20 μl/min at 25°C using BIAcore. Binding curves of PPT on the sensor chip immobilized with glycolipid analogues containing (A) α-Man, (B) α-NeuAc, and (C) α-Gal are shown. The response is expressed as the change in the number of resonance units induced by the binding of PPT to the glycolipid analogue-immobilized flow cell, which was corrected for bulk effect by subtracting the change on the phosphatidylcholine-immobilized

reference cell. (D) Kinetic parameters for the interaction between PPT and glycolipid analogues. Kinetic parameters were calculated by global analysis for α-Man and affinity analysis for α-NeuAc and α-Gal. *ka* shows association rate constant; *kd*, dissociation rate constant; K_A, association constant.

Figure 3. SDS-PAGE of BPT and PPT. Bovine and porcine trypsin (10, 20, or 40 μg protein per lane) were loaded under reduced condition onto a 14% polyacrylamide gel. SDS-PAGE was performed as described in the text, and protein bands were visualized by Coomassie Brilliant Blue R-250. The migration positions of molecular weight markers are shown in the left side of the gel.

Figure 4. Reactivities of PPT (A) and BPT (B) to biotinylated glycoproteins by ELISA. PPT or BPT (each 100 μl) was coated onto the wells of a microtiter plate and reacted with various glycoprotein probes as described in the text. The bound glycoprotein probes were detected with ABC complex and 4-chloro-1-naphthol/H_2O_2 by ELISA. Symbols used are: (◆) bovine thyroglobulin, (◇) porcine thyroglobulin, (▲) fetuin, (■) ovomucoid, (□) orosomucoid, (×) transferrin, and (▩) BSM.

Figure 5. Reactivities of BPT to biotinylated glycoprotein probes before and after glycosidase-treatment by ELISA. Biotinylated glycoprotein probes were pretreated with various exoglycosidases as described in the text. BPT (100 μl) was coated onto the wells of a microtiter plate and reacted with biotinylated glycoprotein probes: bovine thyroglobulin (A), porcine thyroglobulin (B), fetuin (C), ovomucoid (D), orosomucoid (E), and transferrin (F). The bound glycoprotein probes were detected by ELISA as described in the text. Symbols used are: (--■--) intact, (○) asialo-, (△) asialoagalacto-, (□) asialoagalactoahexosamino-, (×) α-galactosidase-treated, (✳) endoglycosidase H-treated-, and (+) de*N*-glycosylated glycoproteins.

Figure 6. Binding of trypsin to fetuin and porcine thyroglobulin at various pH by SPR. PPT and BPT were immobilized on a CM5 sensor chip, and each glycoprotein was injected onto the sensor chip at various pH, as described in the text. Fetuin (■) or porcine thyroglobulin (○) was dissolved at concentrations of 1 μM or 0.5 μM, respectively, in 10 mM acetate buffer (pH 4.5-6.5), 10 mM TBS (pH 7-8), or 10 mM bicarbonate buffer (pH 9-10) and injected onto the sensor chip. The bound amounts of glycoprotein are expressed as relative response (%) by taking the response at pH 7.5 as 100%. (A) Relative response on immobilized PPT; (B) relative response on immobilized BPT.

Figure 7. Effect of sugars on interaction between trypsins and glycoproteins. Trypsins were immobilized on the sensor chip and preincubated with 50 mM or 0.2 M methyl α-D-mannoside, lactose, or methyl α-D-galactoside, and then the glycoprotein solution in 10 mM TBS (pH 7.5) or TBS containing each sugar at a concentration of 50 mM or 0.2 M was injected onto the

immobilized trypsins. (A), the binding curves of glycoproteins to PPT, and (B), the binding curves of glycoproteins to BPT. Lines used are: ——— , control without sugar; - - - , 50 mM methyl α-D-mannoside; — — , 0.2 M methyl α-D-mannoside; ····· , 50 mM methyl α-D-galactoside; ▪▪▪▪ , 0.2 M methyl α-D-galactoside; and - · - , 50 mM Lac.

Figure 8. Quantification of interaction between trypsins and glycoproteins by SPR.
PPT and BPT were immobilized on a CM5 sensor chip as described in the text. Glycoproteins were injected onto a trypsin-immobilized sensor chip in 10 mM TBS (pH 7.5) for 150 s at a flow rate of 20 ml/min at 25℃. The response was expressed as the change of resonance units induced by the binding of fetuin to the trypsin-immobilized flow cell, which was corrected for bulk effect by subtracting the change on the BSA-immobilized reference cell. Binding curves of glycoproteins on the sensor chip immobilized with PPT (A), and BPT (B).

Figure 9. Effect of various sugars on enzyme activity of PPT. (A) Aliquots (100 μl) of 0.2 M methyl α-mannoside, methyl α-galactoside, or lactose, or buffer for the control were added to PPT (2 μg) in the same volume, and the enzyme activity was measured against BAEE as described in the text. Relative activity was expressed as %, taking the control as 100%. (B) Time course of PPT activity in the presence of various sugars. The enzyme activity was measured against BAPA as described in the text in the presence or absence of 0.2 M methyl α-mannoside (■), methyl α-galactoside (□), lactose (◇) and control (×). (C-E) Lineweaver-Burk plots of PPT. PPT activity was measured in the presence (———), or absence (– – – –) of 0.2 M concentrations of various sugars as described in the text and analyzed by a double reciprocal Lineweaver-Burk plot.

Table 1. Binding parameters for interaction between trypsins and glycoproteins. Interactions between trypsin and glycoproteins were measured in 10 mM TBS (pH 7.5) using BIAcore. Kinetics parameters were calculated by global analysis for most glycoproteins and affinity analysis for BSM. k_a shows association rate constant; k_d, dissociation rate constant; K_A, association constant. $K_A = k_a/k_d$

		k_a ($M^{-1}s^{-1}$)	k_d (s^{-1})	K_A (M^{-1})
(A) PPT	**Bovine thyroglobulin**	**3.97×10^{3}**	**2.47×10^{-7}**	**1.61×10^{10}**
	α-Galase-treated bovine thyroglobulin	**7.23×10**	**5.67×10^{-5}**	**1.28×10^{5}**
	Porcine thyroglobulin	**3.05×10^{4}**	**7.27×10^{-4}**	**4.19×10^{7}**
	Asialo-porcine thyroglobulin	**8.52×10^{3}**	**1.35×10^{-3}**	**6.30×10^{6}**
	Endo H-treated thyroglobulin	**1.04×10^{4}**	**1.36×10^{-3}**	**7.68×10^{6}**
	Fetuin	**5.07×10^{4}**	**6.20×10^{-3}**	**8.17×10^{6}**
	Asialo-fetuin	**1.26×10^{4}**	**6.04×10^{-3}**	**2.09×10^{6}**
	De*O*-glycosylated fetuin	**4.57×10^{4}**	**5.46×10^{-3}**	**8.38×10^{6}**
	De*N*-glycosylated fetuin	**9.71×10**	**4.67×10^{-3}**	**2.08×10^{4}**
	BSM			**1.08×10^{4}**
(B) BPT	**Bovine thyroglobulin**	**1.55×10^{4}**	**1.45×10^{-6}**	**1.07×10^{10}**
	α-Galase-treated bovine thyroglobulin	**3.19×10**	**9.07×10^{-5}**	**3.51×10^{5}**
	Porcine thyroglobulin	**3.06×10^{4}**	**6.38×10^{-4}**	**4.79×10^{7}**
	Asialo-porcine thyroglobulin	**4.28×10^{3}**	**6.08×10^{-4}**	**7.04×10^{6}**
	Endo H-treated thyroglobulin	**3.49×10^{2}**	**5.33×10^{-5}**	**6.55×10^{6}**
	Fetuin	**2.43×10^{4}**	**5.67×10^{-3}**	**4.30×10^{6}**
	Asialo-fetuin	**9.13×10^{3}**	**7.13×10^{-3}**	**1.28×10^{6}**
	De*O*-glycosylated fetuin	**1.79×10^{4}**	**5.40×10^{-3}**	**3.32×10^{6}**
	De*N*-glycosylated fetuin	**1.09×10^{2}**	**1.86×10^{-2}**	**5.87×10^{3}**
	BSM			**8.09×10^{4}**

Table 2. Km value and Vmax of PPT activity on effect of various sugars. The enzyme activity was measured in the presence of various sugars (0.2 M) and analyzed by the Lineweaver-Burk plot.

Sugars or Glycoprotein	Vmax ($\times 10^{-3}$ M/sec)	Km ($\times 10^{-3}$ M)	Mode of effect
control	8.08	1.26	
Meα-Man	20.7	3.20	uncompetitive activation
Meα-Gal	18.1	2.81	uncompetitive activation
Lac	4.70	0.85	non- and uncompetitive inhibition

Fig. 1

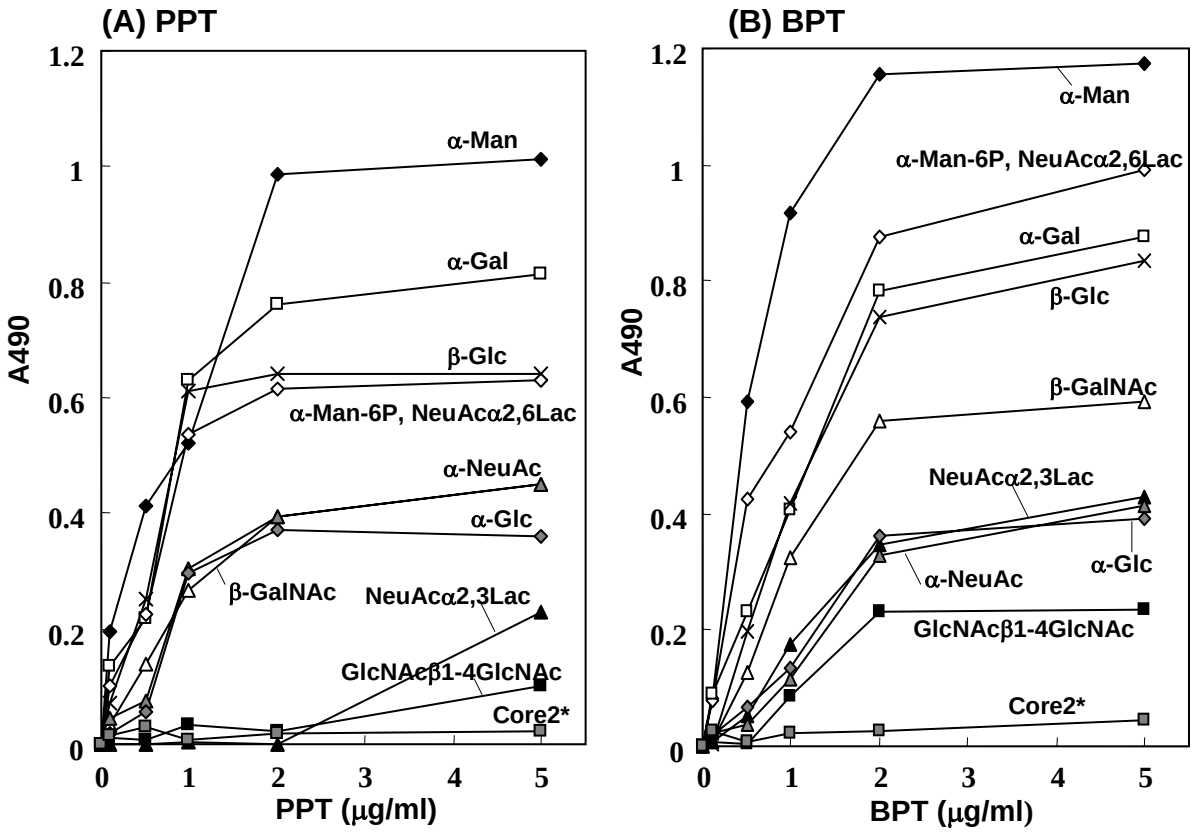
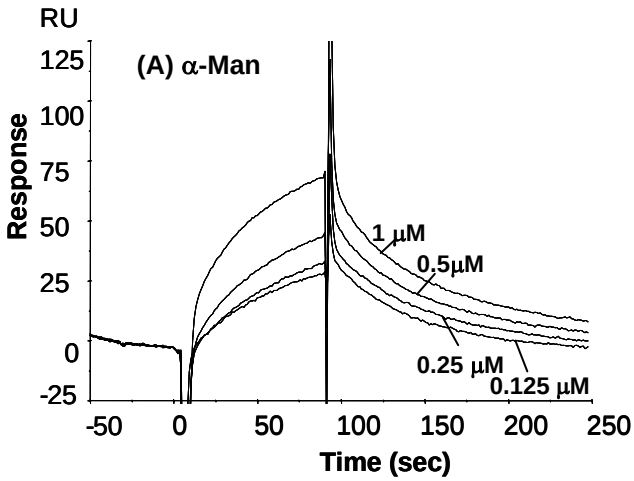
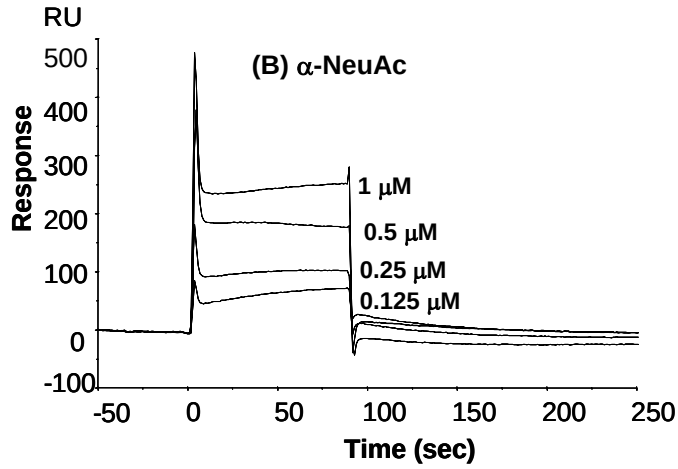
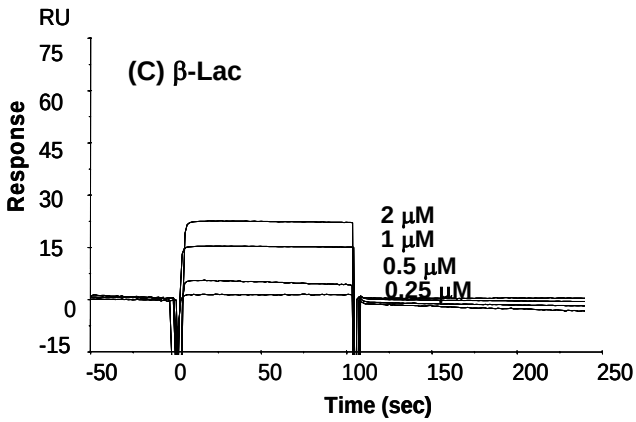

(A) PPT
A490
PPT (μg/ml)
α-Man
α-Gal
β-Glc
α-Man-6P, NeuAcα2,6Lac
α-NeuAc
α-Glc
β-GalNAc
NeuAcα2,3Lac
GlcNAcβ1-4GlcNAc
Core2*
(B) BPT
A490
BPT (μg/ml)
α-Man
α-Man-6P, NeuAcα2,6Lac
α-Gal
β-Glc
β-GalNAc
NeuAcα2,3Lac
α-Glc
α-NeuAc
GlcNAcβ1-4GlcNAc
Core2*

Fig. 2







(D)

Glycolipid analogue	k_a ($M^{-1}s^{-1}$)	k_d (s^{-1})	K_A (M^{-1})
α-Man	5.6×10^{4}	1.6×10^{-2}	3.6×10^{6}
α-NeuAc			1.1×10^{5}
β-Lac			2.1×10^{4}

Fig. 3

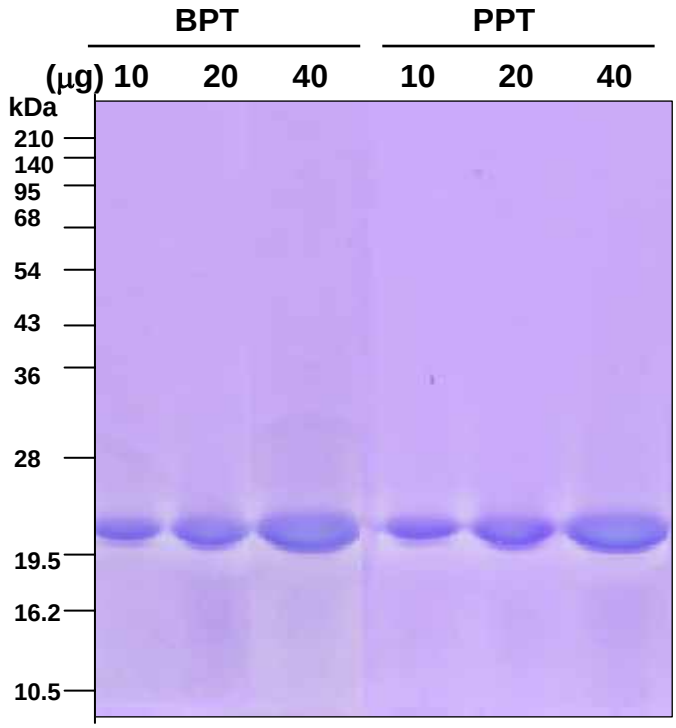

BPT
PPT
(μg) 10 20 40 10 20 40
kDa
210
140
95
68
54
43
36
28
19.5
16.2
10.5

Fig 4.

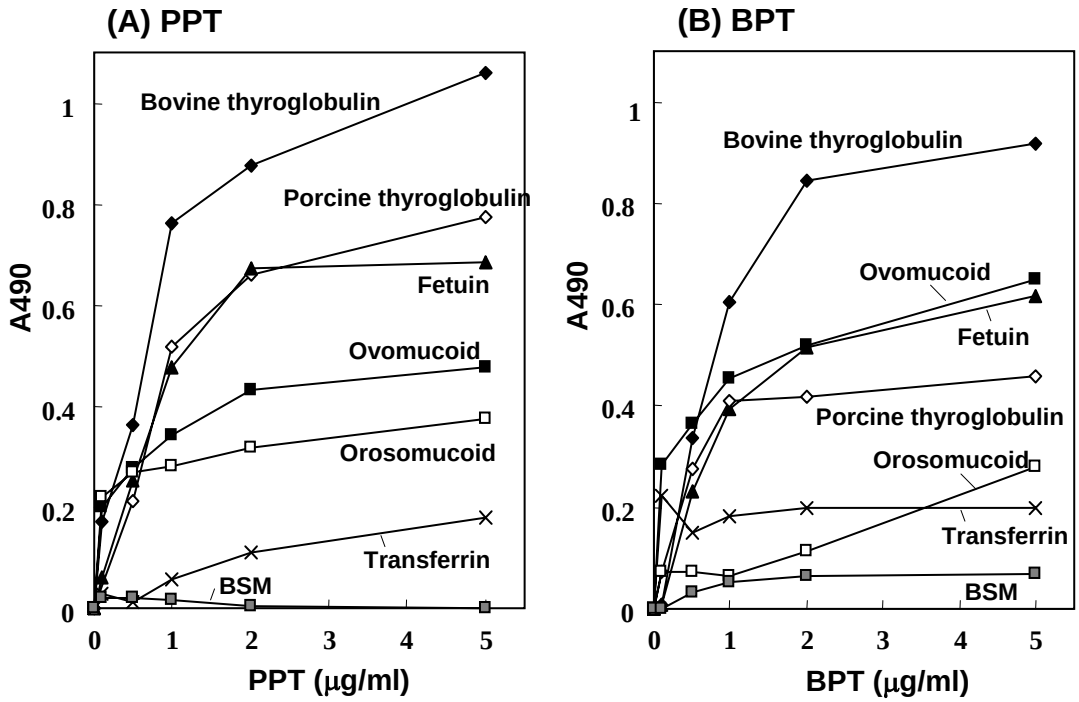

(A) PPT
Bovine thyroglobulin
Porcine thyroglobulin
Fetuin
Ovomucoid
Orosomucoid
Transferrin
BSM
A490
PPT (μg/ml)
(B) BPT
Bovine thyroglobulin
Ovomucoid
Fetuin
Porcine thyroglobulin
Orosomucoid
Transferrin
BSM
A490
BPT (μg/ml)

Fig. 5

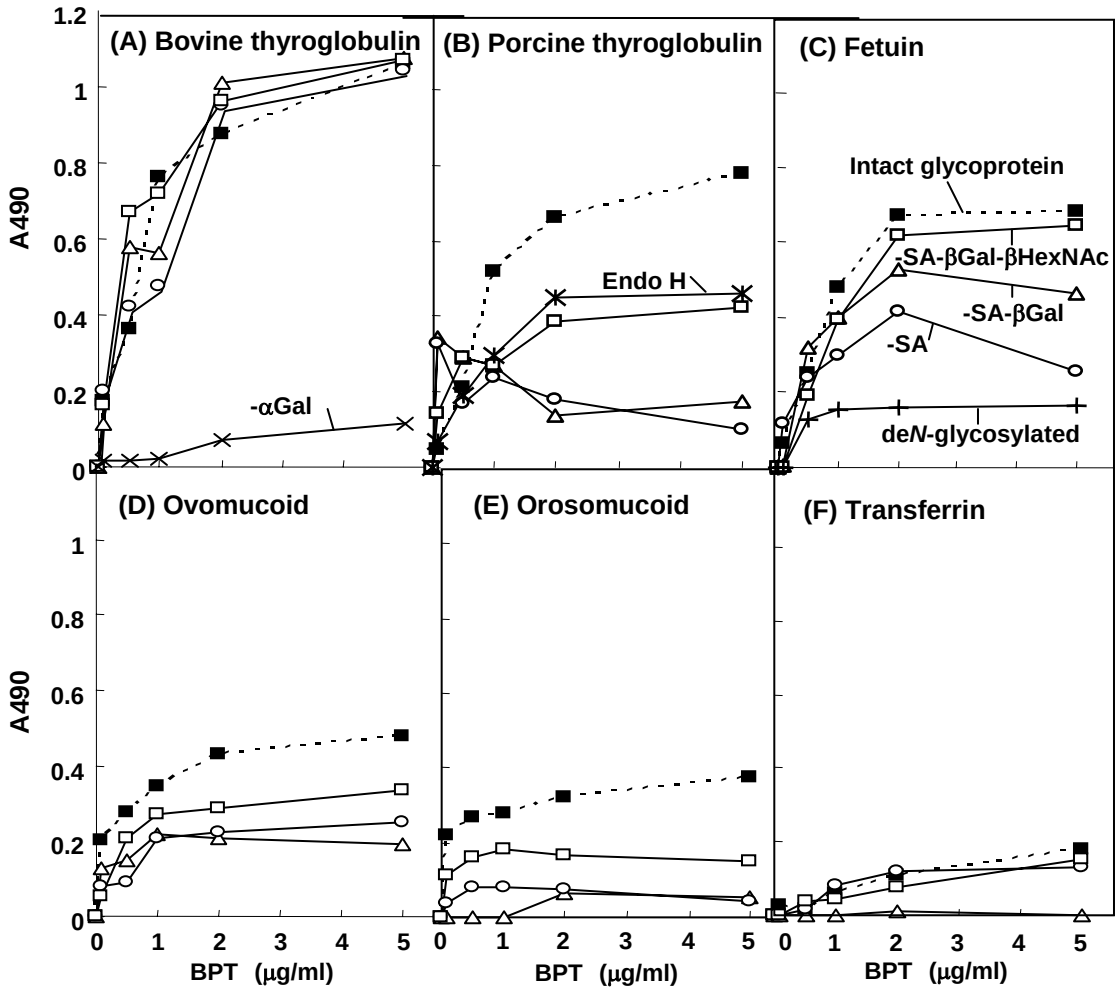

(A) Bovine thyroglobulin
(B) Porcine thyroglobulin
(C) Fetuin
(D) Ovomucoid
(E) Orosomucoid
(F) Transferrin
A490
BPT (μg/ml)
-αGal
Endo H
Intact glycoprotein
-SA-βGal-βHexNAc
-SA-βGal
-SA
de*N*-glycosylated

Fig. 6

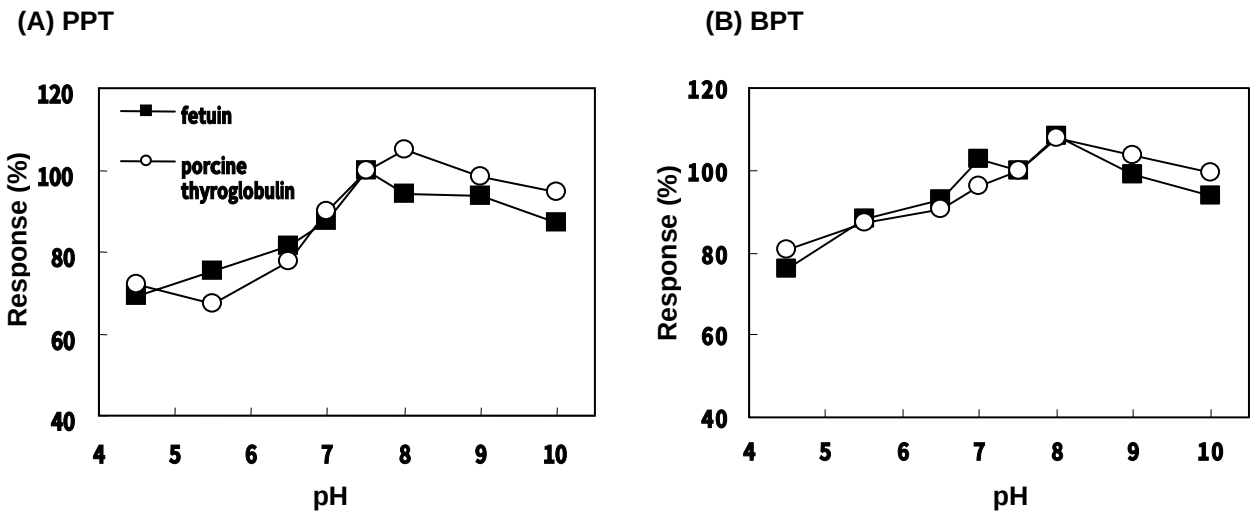

(A) PPT
(B) BPT
Response (%)
pH
fetuin
porcine thyroglobulin
120
100
80
60
40
4
5
6
7
8
9
10

Fig. 7

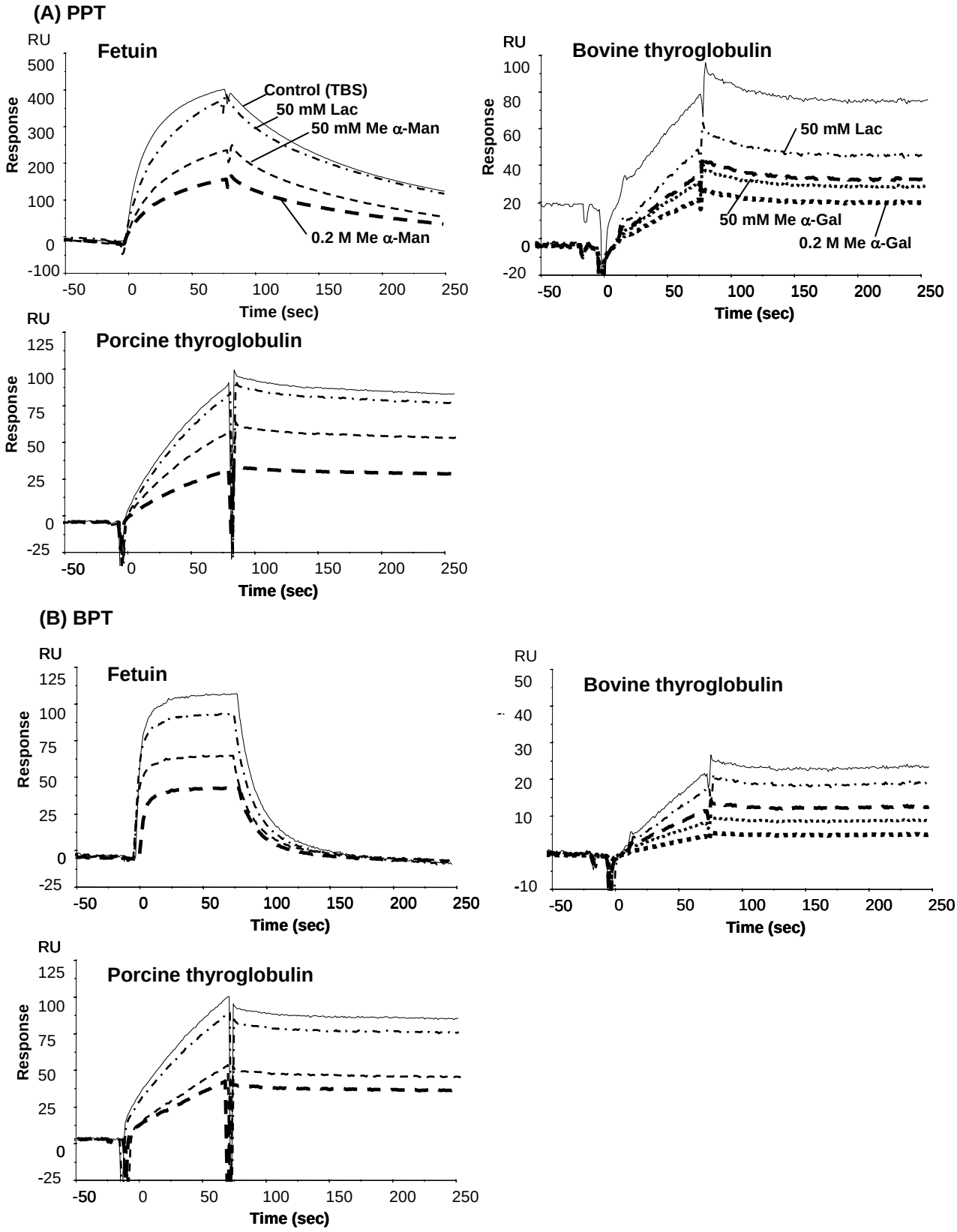
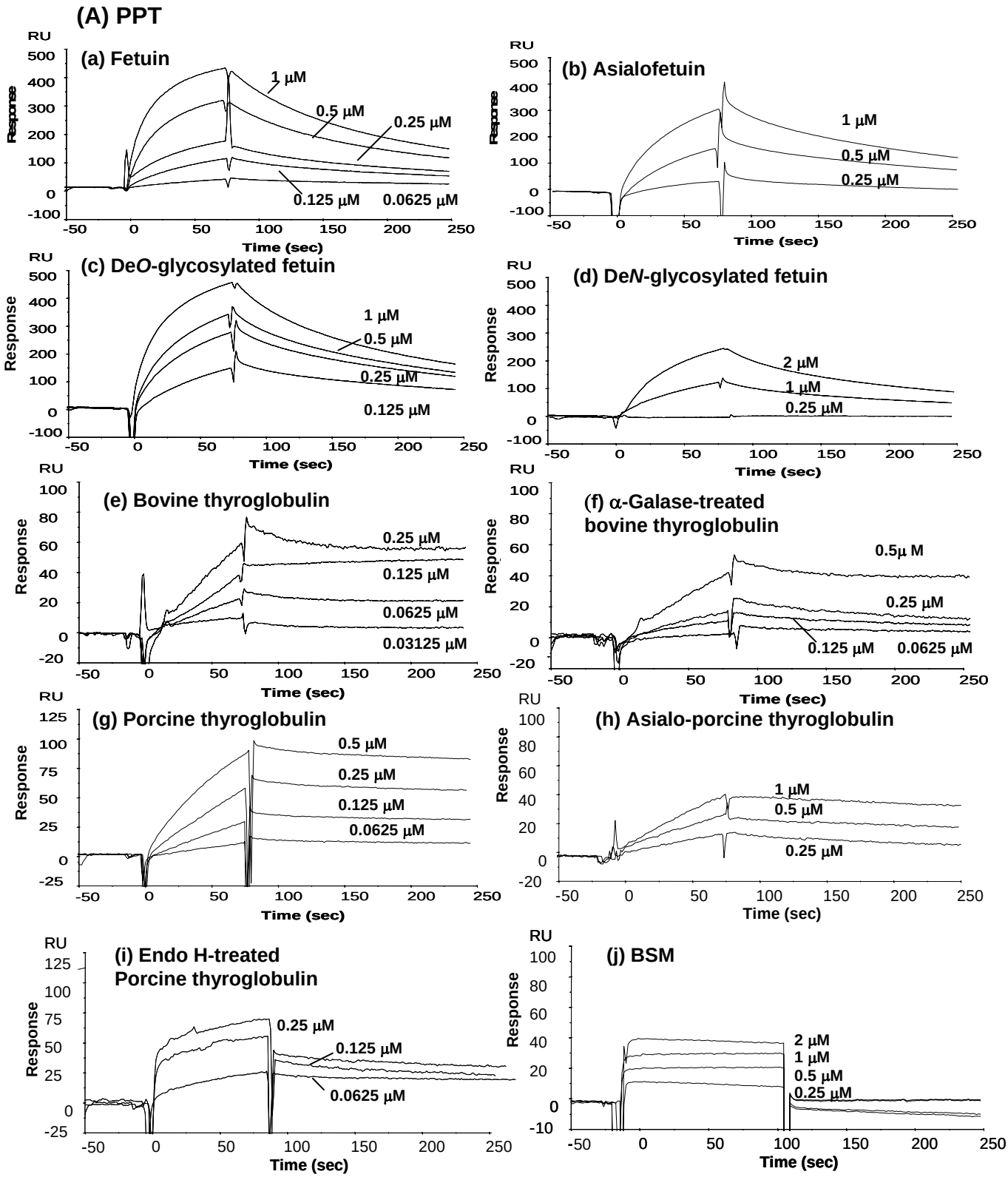
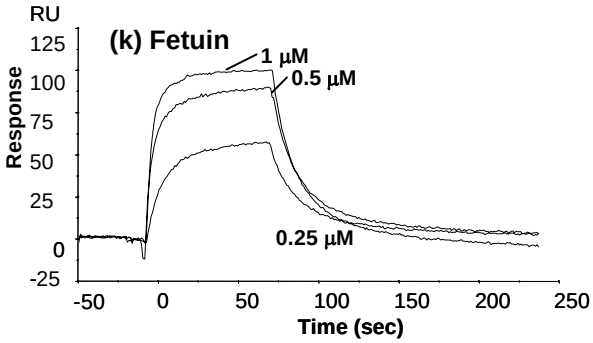

(A) PPT
Fetuin
RU
Response
Control (TBS)
50 mM Lac
50 mM Me α-Man
0.2 M Me α-Man
Time (sec)
Bovine thyroglobulin
50 mM Lac
50 mM Me α-Gal
0.2 M Me α-Gal
Porcine thyroglobulin
(B) BPT
Fetuin
Bovine thyroglobulin
Porcine thyroglobulin

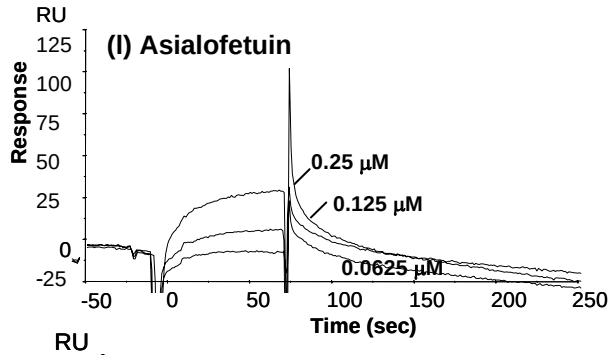
Fig. 8 *(to be continued)*

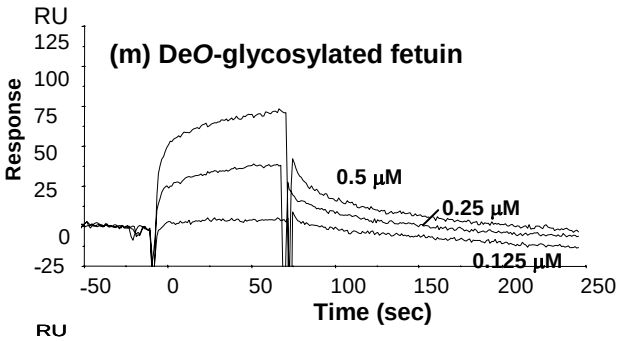


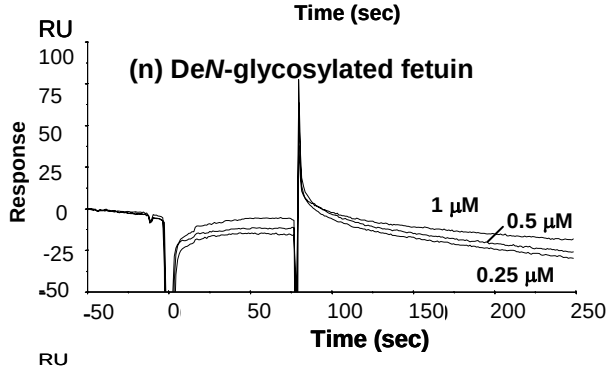
(continued)

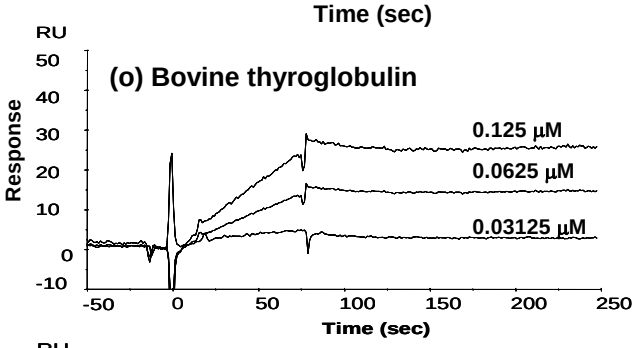
(B) BPT

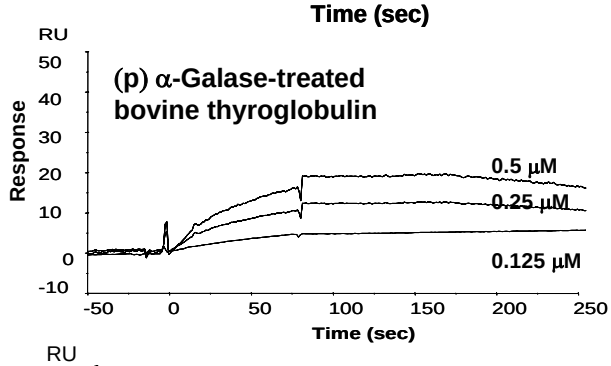


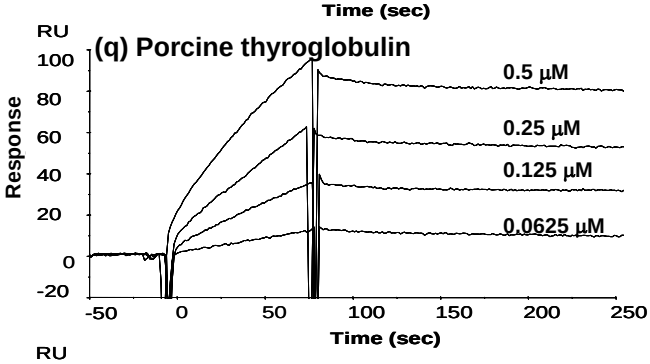


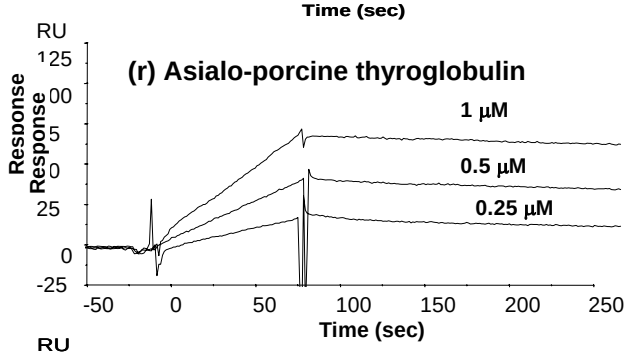


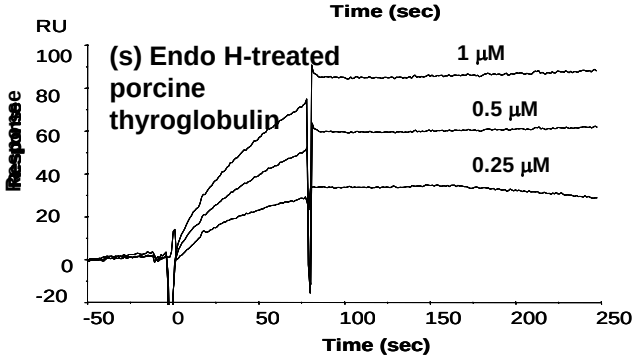












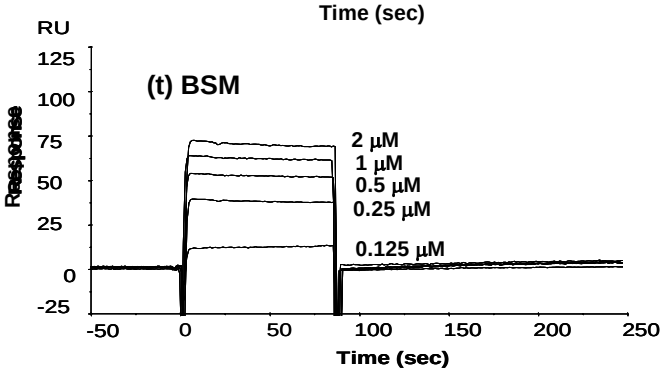
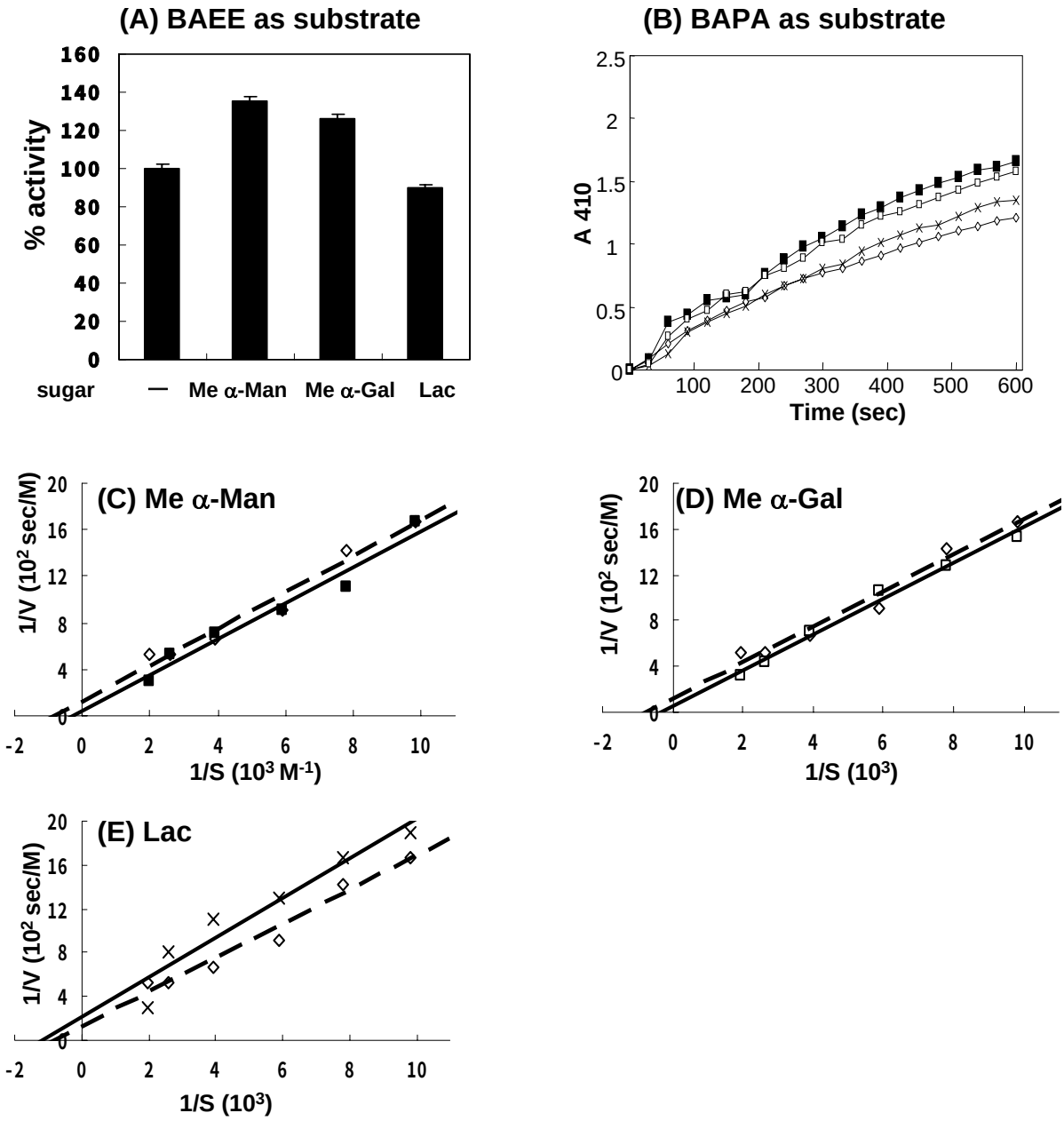
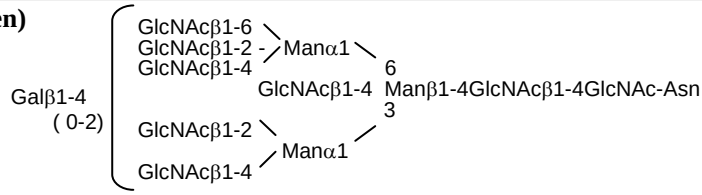
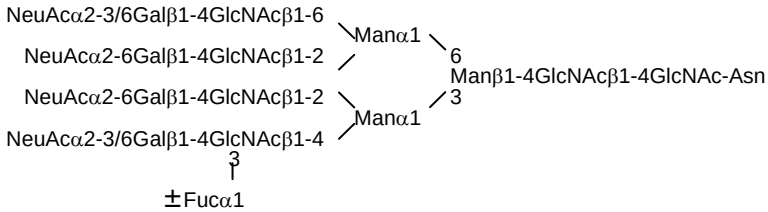
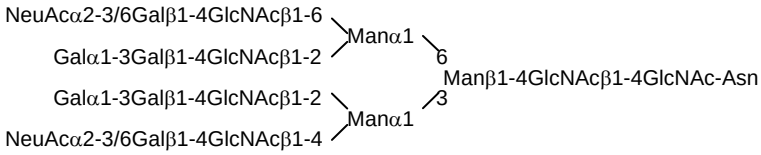
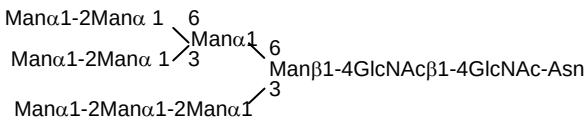
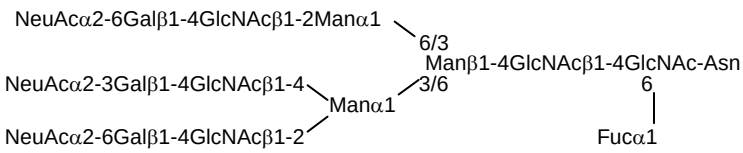
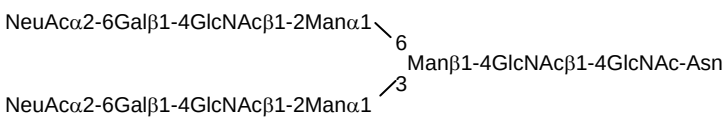
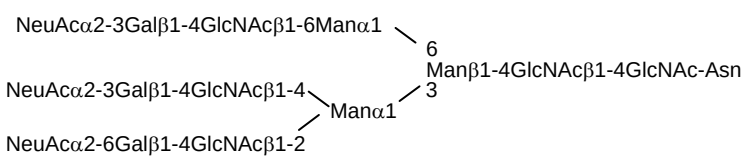
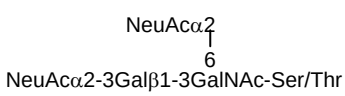


Fig. 9

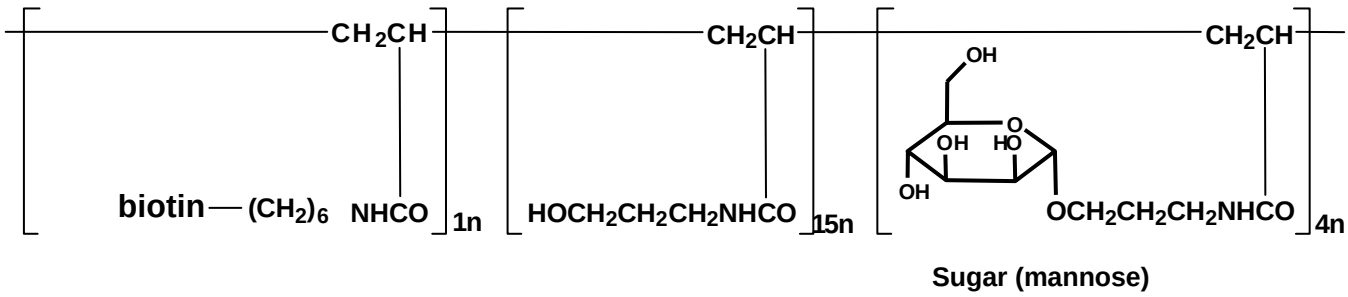

(A) BAEE as substrate
% activity
160
140
120
100
80
60
40
20
0
sugar
—
Me α-Man
Me α-Gal
Lac
(B) BAPA as substrate
A 410
2.5
2
1.5
1
0.5
0
100
200
300
400
500
600
Time (sec)
(C) Me α-Man
1/V (10² sec/M)
20
16
12
8
4
0
-2
0
2
4
6
8
10
1/S (10³ M⁻¹)
(D) Me α-Gal
1/V (10² sec/M)
1/S (10³)
(E) Lac
1/V (10² sec/M)
1/S (10³)

Scheme 1. Major oligosaccharide structures of glycoproteins used in this study

		Total carbohydrate contents (%, w/w)	Reference
Ovomucoid (hen)		25~30%	(30)
Orosomucoid (human)		36%	(31)
Bovine thyroglobulin		10%	(32, 33)
Porcine thyroglobulin		10%	(34-36)
			
Transferrin (human)		5%	(37)
Fetuin (bovine)		22%	(38)
			(39)
BSM		57%	(40, 41)

Scheme 2 Structures of sugar-BP probes and glycolipid analogues used in this study

(A) Sugar-BP probe



(B) Glycolipid Analogue