Interaction of triosephosphate isomerase from the cell surface of *Staphylococcus aureus* and α-(1→3)-mannooligosaccharides derived from glucuronoxylomannan of *Cryptococcus neoformans*

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The glycolytic enzyme triosephosphate isomerase (TPI; EC 5.3.1.1) of *Staphylococcus aureus* is a candidate adhesion molecule for the interaction between the bacterium and the fungal pathogen *Cryptococcus neoformans*. TPI may recognize the mannan backbone of glucuronoxylomannan (GXM) of *C. neoformans*. We purified TPI from extracts of *S. aureus* surface proteins to investigate its binding by surface plasmon resonance analysis. The immobilized TPI reacted with GXM in a dose-dependent manner. Furthermore, the interactions between staphylococcal TPI and α-(1→3)-mannooligosaccharides derived from GXM were examined. The oligosaccharides exhibited binding with TPI; however, monomeric mannose did not. Differences in the slopes of the sensorgrams were observed between oligosaccharides with an even number of residues versus those with an odd number. A heterogeneous ligand-parallel reaction model revealed the existence of at least two binding sites on TPI. The enzymic activities of TPI were inhibited in a dose-dependent manner by α-(1→3)-mannooligosaccharides larger than triose. The binding of TPI and α-(1→3)-mannotriose near the substrate-binding site was predicted in silico (AutoDock 3.05). An oligosaccharide of size equal to or greater than triose could bind to the site, affecting enzymic activities. Moreover, affinities were indicated, especially for biose and tetrose, to another binding pocket, which would not affect enzymic activity. These data suggest a novel role for TPI, in addition to glycolysis, on the surface of *S. aureus*.

INTRODUCTION

The search for novel targets for the regulation of microbes has focused on interactions between micro-organisms. Diffusible signalling molecules that play essential roles in bacterial cell–cell communication have been identified (Kaper & Sperandio, 2005; Ryan & Dow, 2008; von Bodman et al., 2008). Concentrating on the fungal–bacterial interaction, we previously reported contact-mediated killing of *Cryptococcus neoformans* by *Staphylococcus aureus* (Saito & Ikeda, 2005).

*Cryptococcus neoformans*, an encapsulated yeast pathogen that causes severe meningitis, is found predominantly in avian excreta, especially that of the pigeon. This fungus is characterized by a capsule composed mainly of the acidic heteropolysaccharide glucuronoxylomannan (GXM), which has a backbone consisting of α-1,3-mannan with a single branch of β-1,2-xylose or glucuronic acid per mannose residue. *C. neoformans* enters the human body via the respiratory pathway (Casadevall & Perfect, 1998). *S. aureus* is found in the nasal cavities of a large percentage of normal healthy subjects (Kluytmans et al., 1997). In *S. aureus* infection, nasal colonization is a risk factor for invasive infection (von Eiff et al., 2001; Foster, 2004; Park et al., 2008), and the elimination of *S. aureus* nasal carriage reduces the development of the infection. However, the presence of *S. aureus* in the nasal mucosa may also provide a defence against the entry of *C. neoformans*.

Previously, we found that cell–cell contact is required for the apoptosis-like cell death of *C. neoformans* (Ikeda & Sawamura, 2008). The cell surface adhesion molecules involved in this interaction were identified as triosephosphate isomerase (TPI) and α-(1→3)-mannooligosaccharides larger than triose in *S. aureus* and *C. neoformans*, respectively (Ikeda et al., 2007). In the present study, we purified staphylococcal TPI and examined its interactions with α-(1→3)-mannooligosaccharides derived from *C. neoformans* in order to characterize the binding affinities and predict binding models for TPI.

METHODS

Strain. *Staphylococcus aureus* RN4220 was obtained as a gift from K. Sekimizu (University of Tokyo, Japan).
Preparation of surface proteins from S. aureus. Surface protein extracts from S. aureus were prepared as previously described (Ikeda et al., 2007; Komatsuzawa et al., 1997). Briefly, S. aureus cells that had been cultured in Trypticase soy broth (TSB; Becton Dickinson) at 37 °C for 6 h were suspended in 3 M LiCl. After mixing gently on ice for 15 min, the cell extract was dialysed against 10 mM phosphate buffer (pH 6.8) and the surface proteins were collected. TPI activity was not detected in the cellular debris remaining after surface protein isolation.

**TPI activity assay.** Enzymic activity was coupled to the oxidation of NADH by glycerol-3-phosphate dehydrogenase and measured as a change in absorbance at 340 nm, according to the method of Rozacky and the method of Smith degradation product was hydrolysed with 0.4 M H2SO4 at 100 °C for 1 h. After neutralization with BaCO3, the product was applied to a Bio-Gel P-2 column (2.5 × 120 cm; Bio-Rad) and eluted with water (10 ml h−1, 2 ml fractions). Carbohydrate concentrations were determined by the phenol/sulfuric acid method. To identify mannoooligosaccharides, the NMR spectra of the oligosaccharide fractions were recorded (Ichiikawa et al., 2001; Ikeda & Maeda, 2004).

Surface plasmon resonance (SPR) analysis of the interaction between cryptococcal GXM and staphylococcal TPI. The interaction of S. aureus TPI and C. neoformans GXM was analysed using a Biacore 3000 biosensor system (GE Healthcare). The purified TPI, confirmed using SDS-PAGE followed by silver staining (Fig. 1), was diluted with 10 mM sodium acetate buffer (pH 3.48) and immobilized on a standard sensor chip CM 5 (GE Healthcare) using an amine coupling kit, according to the manufacturer’s instructions. The analyte, GXM, was diluted with HBS-EP running buffer [10 mM HEPES (pH 7.4), 150 mM NaCl, 3 mM EDTA and 0.005% (w/v) surfactant P20] and injected into the flow cell. The buffer flow rate was maintained at 10 μl min−1 for the immobilization and at 20 μl min−1 for the analysis.

**Inhibition of TPI activity by mannoooligosaccharides.** We investigated the possible inhibition of TPI activity by the mannoooligosaccharides mannose, manniobiose, mannotriose, mannotetraose and mannopentaose. TPI activity in the presence of each mannoooligosaccharide at 0, 10 and 100 μM was determined using the TPI assay described above.

**Table 1. Purification of TPI from S. aureus**

<table>
<thead>
<tr>
<th>Purification step</th>
<th>Total protein (mg)</th>
<th>Total TPI activity (units*)</th>
<th>Specific activity (units mg−1)</th>
<th>Yield (%)</th>
<th>Purification (fold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude extract</td>
<td>10.5</td>
<td>57.3</td>
<td>5.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Salting out</td>
<td>5.3</td>
<td>35.2</td>
<td>6.6</td>
<td>61</td>
<td>1.2</td>
</tr>
<tr>
<td>Hydrophobic interaction</td>
<td>5.4 × 10−2</td>
<td>66.7</td>
<td>1.2 × 104</td>
<td>116</td>
<td>220</td>
</tr>
<tr>
<td>Anion exchange</td>
<td>5.7 × 10−3</td>
<td>68.1</td>
<td>1.2 × 104</td>
<td>119</td>
<td>2200</td>
</tr>
<tr>
<td>Gel filtration</td>
<td>1.7 × 10−3</td>
<td>22.2</td>
<td>1.3 × 104</td>
<td>39</td>
<td>2400</td>
</tr>
</tbody>
</table>

*A unit is defined as the amount of enzyme required to cause a change in A340 of 0.002 in 1 min in the spectrophotometric assay utilizing glyceraldehyde 3-phosphate as substrate.*
RESULTS

Purification of TPI from *S. aureus*

As summarized in Table 1, TPI was purified from *S. aureus* surface proteins by salting out followed by hydrophobic, anion-exchange, and gel-filtration column chromatography. The purified TPI had a molecular mass of 28.5 kDa, as determined by SDS-PAGE (Fig. 1). The yield of 1.7 μg TPI reflected a 2400-fold purification.

Interaction between GXM from *C. neoformans* and TPI from *S. aureus*

Fig. 2 shows the SPR sensorgrams for the interaction between GXM and immobilized TPI. The SPR response occurred in a dose-dependent manner.

Interactions between α-(1→3)-mannooligosaccharides and TPI

The SPR analyses revealed that the α-(1→3)-mannooligosaccharides derived from *C. neoformans* interacted with TPI from *S. aureus* in a dose-dependent manner (Fig. 3). The rate at which the response increased (expressed in response units) over the injection time (0–60 s) for each mannoooligosaccharide decreased in the following order: mannopentaose, mannotetraose, mannotriose and mannobiose; mannose did not display interaction with TPI. However, from 60 to 600 s, the rate of increase in the response was greater for mannotetraose and mannobiose than for mannopentaose and mannotriose. The sensorgrams of the TPI interactions showed steeper slopes for oligosaccharides containing an even number of residues than for those with an odd number of residues, suggesting a difference in the mode of binding between the two types of oligosaccharides.

Analysis and evaluation of the interactions between TPI and α-(1→3)-mannooligosaccharides

The association and dissociation kinetics of each mannoooligosaccharide were evaluated using BiAevaluation version 4.1. Based on the sensorgrams, a 1:1 Langmuir binding model was not considered for the interaction between TPI and α-(1→3)-mannooligosaccharides. Instead, we used a heterogeneous ligand-parallel reaction model (Smith *et al.*, 2003; Yaqub *et al.*, 2003; Mader *et al.*, 2004) and a two-state reaction model to study the binding kinetics. As shown in Table 2, the heterogeneous ligand-parallel reaction model indicated two binding sites. Similar affinity constants (Kd1) were calculated for the α-(1→3)-mannooligosaccharides at the first binding site, although the order depended on size (mannopentaose<mannotetraose<mannotriose<mannobiose); however, the second parallel reaction affinity (Kd2) clearly increased according to the order mannotetraose, mannobiose, mannopentaose and mannotriose. The differences among these affinities might have contributed to the variation in the sensorgrams. In contrast, the two-state reaction model gave similar affinity constants (Kd) among the oligosaccharides, with values and an order similar to those of Kd1.

Docking simulation for mannotriose from *C. neoformans* and TPI from *S. aureus*

We performed docking simulation analyses for *S. aureus* TPI (253 amino acids) with AutoDock 3.05 using a PDB file for TPI from *S. aureus* obtained by homology modelling. Several possible conformations were obtained, and the interaction between TPI and mannotriose near the substrate binding site was suggested (Fig. 4).
Inhibition of TPI activity by $\alpha$-(1→3)-mannooligosaccharides

The $\alpha$-(1→3)-mannooligosaccharides larger than mannotriose demonstrated inhibitory effects on TPI activity (Fig. 5). Furthermore, dose-dependent inhibition was observed with mannotriose, mannolactose and mannopentaose (Fig. 6).

**DISCUSSION**

Glycolytic enzymes have been found on the cell surfaces of certain bacteria and fungi. In addition to their roles in glycolysis, some glycolytic enzymes, such as D-glyceraldehyde-3-phosphate dehydrogenase, that occur both on the cell surface and in a secreted form have been shown to possess multi-functional properties, including adhesion and nutrient uptake (Modun & Williams, 1999; Bergmann et al., 2004; Gatlin et al., 2006; Terao et al., 2006; Antikainen et al., 2007; Egea et al., 2007). Furthermore, interactions have been reported between glycolytic enzymes and human bioactive proteins, such as fibrinogen, plasminogen and fibronectin, and glycolytic enzymes expressed on microbial cell surfaces have become targets for the regulation of bacteria and fungi (Pancholi & Fischetti, 1992; Gil-Navarro et al., 1997; Pancholi & Fischetti, 1998; Bergmann et al., 2001).

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**Table 2. Affinities of $\alpha$-(1→3)-mannooligosaccharides to TPI from S. aureus**

<table>
<thead>
<tr>
<th>Oligosaccharide*</th>
<th>Heterogeneous ligand-parallel reaction $K_{D1}$ (M)</th>
<th>Heterogeneous ligand-parallel reaction $K_{D2}$ (M)</th>
<th>Two-state reaction $K_{D}$ (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>$4.77 \times 10^{-3}$</td>
<td>$5.37 \times 10^{-6}$</td>
<td>$4.45 \times 10^{-3}$</td>
</tr>
<tr>
<td>M3</td>
<td>$2.02 \times 10^{-3}$</td>
<td>$1.24 \times 10^{-4}$</td>
<td>$1.44 \times 10^{-3}$</td>
</tr>
<tr>
<td>M4</td>
<td>$3.14 \times 10^{-4}$</td>
<td>$1.46 \times 10^{-8}$</td>
<td>$5.17 \times 10^{-4}$</td>
</tr>
<tr>
<td>M5</td>
<td>$2.08 \times 10^{-4}$</td>
<td>$1.86 \times 10^{-5}$</td>
<td>$2.31 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

* M2, mannobiose; M3, mannotriose; M4, mannolactose; M5, mannopentaose.
Previously, we found that the bacterium *S. aureus* adheres to and kills the fungal pathogen *C. neoformans* (Saito & Ikeda, 2005). We identified TPI as a candidate adherence molecule on *S. aureus* that recognizes the mannose backbone in GXM, a major component of the capsule of *C. neoformans* (Ikeda et al., 2007). The glycolytic enzyme TPI, which catalyses the reversible reaction between D-glyceraldehyde 3-phosphate and dihydroxyacetone phosphate, is located on the cell surface, although it is not as abundant as the cell surface glyceraldehyde-3-phosphate dehydrogenases. TPI is also thought to play a role in adhesion with the fungal pathogen *Paracoccidioides brasiliensis* (Pereira et al., 2007).

In this study, we purified TPI from *S. aureus* and characterized its interaction with a series of α-(1→3)-mannooligosaccharides, with various degrees of polymerization, obtained from *C. neoformans*. TPI was purified from *S. aureus* surface proteins by salting out and hydrophobic, anion-exchange and gel-filtration column chromatography. The purified TPI yielded a single band in SDS-PAGE. SPR analysis of the interaction between TPI from *S. aureus* and GXM from *C. neoformans* showed that purified TPI interacted with GXM in a dose-dependent manner, providing evidence that staphylococcal TPI and cryptococcal GXM participate in the adherence between these two organisms. Subsequently, we examined the interactions between purified TPI and α-(1→3)-mannooligosaccharides derived from the backbone of GXM. Mannose did not display specific binding. During the first 60 s after injection, the SPR responses of mannobiose and mannopentaose were lower than those of mannotriose and mannopentaose, respectively. However, between 60 and 600 s, the responses of mannobiose and mannopentaose were greater than those of mannotriose and mannopentaose, respectively. For the kinetic analyses, two fitting models were selected: the heterogeneous ligand-parallel reaction model and the two-state reaction model. Two binding affinities, *K*<sub>d1</sub> and *K*<sub>d2</sub>, were calculated from the former model; the *K*<sub>d1</sub> values were similar among the oligosaccharides, whereas the second reaction appeared to occur with significantly different affinities for the oligosaccharides. This suggests that TPI has at least two binding sites with different affinities. In the two-state reaction model, binding is followed by a conformational change (A + B→AB→ABx). The affinity increased slightly with increasing number of mannose residues. The sensorgrams showed an increasing response according to the order mannopentaose, mannobiose, mannopentaose and mannotriose. We considered the heterogeneous ligand-parallel reaction model to be a better fit for the interaction of α-(1→3)-mannooligosaccharides, especially even-numbered oligosaccharides, and TPI from *S. aureus*.

The values for *K*<sub>d2</sub> were higher for odd-numbered compared to even-numbered oligosaccharides. Based on the *K*<sub>d2</sub> and the shape of the sensorgrams, the participation of the second affinity may be less significant for the odd-numbered oligosaccharides. Previously, we proposed three-dimensional models of the oligosaccharides (Ikeda et al., 2007). The characteristic structure with a curve appeared in oligosaccharides larger than mannotriose. From the curved chemical structures, we inferred that common binding sites within oligosaccharides of a size equal to or greater than that of triose could be postulated. In the docking simulation, a conformation was suggested that included the formation of hydrogen bonds to Lys<sup>11</sup>, Asn<sup>13</sup>, Gly<sup>175</sup>, Ser<sup>215</sup> and Lys<sup>217</sup>. Furthermore, other binding pockets, which would not affect enzyme activity, could be predicted for biosse and tetraose. In particular, mannobiose may bind TPI in a multiple-binding manner; therefore, the affinity of mannobiose was higher than that of mannopentaose or...
mannotriose. Comparing mannobiose and mannotetraose, mannotetraose displayed a higher affinity ($K_d 1.46 \times 10^{-8}$) than mannobiose ($K_d 5.37 \times 10^{-9}$). Overall, mannotetraose showed the highest affinity among the oligosaccharides tested.

The results of computational docking and inhibition assays for TPI activity revealed the possibility that mannoooligosaccharides larger than mannotriose may bind to $S. aureus$ TPI near the substrate-binding site. The structural model of TPI suggests that this enzyme may have multiple binding pockets and that they bind to mannos residues.

It is important to characterize the binding of TPI proteins to $C. neoformans$ cells, including their localization. For this purpose, it is necessary to prepare anti-TPI antibodies. The preparation of sufficient TPI, including recombinant TPI, should be helpful.

Since mannose plays an important role in recognizing molecules involved in infection and innate immunity (van de Wetering et al., 2004; Dommett et al., 2006), the presence of unknown substances that interact with TPI is expected. Therefore, TPI may be a multifunctional protein that binds with eukaryotic glycoproteins. The use of carbohydrates as anti-adhesion drugs for the regulation of pathogens has also been reported (Liu et al., 2000; Sharon, 2006). The elucidation of the role of TPI as a virulence factor of $S. aureus$ may prove valuable for screening novel anti-infective agents.

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REFERENCES


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