Characterization of 4,6-α-glucanotransferase enzymes and their functional role in Lactobacillus reuteri
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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2016

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Chapter 3

Biochemical characterization of *Lactobacillus reuteri* Glycoside Hydrolase family 70 GtfB type of 4,6-α-glucanotransferase enzymes that synthesize soluble dietary starch fibers

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*Applied and Environmental Microbiology* (2015), 81:7223-7232
Abstract

4,6-\(\alpha\)-Glucanotransferase (4,6-\(\alpha\)-GTase) enzymes, such as GtfB and GtfW of \textit{Lactobacillus reuteri} strains, constitute a new reaction specificity in Glycoside Hydrolase Family 70 (GH70) and are novel enzymes that convert starch or starch hydrolysates into isomalto/malto-polysaccharides (IMMPs). These IMMPs still have linear chains with some \(\alpha_1\rightarrow4\) linkages but mostly (relatively long) linear chains with \(\alpha_1\rightarrow6\) linkages, and are soluble dietary starch fibers. 4,6-\(\alpha\)-GTase enzymes and their products have significant potential for industrial applications. Here we report that an N-terminal truncation (1-733 amino acids) strongly enhances the soluble expression level of fully active GtfB-\(\Delta\)N (approx. 75 fold compared to full-length wild type GtfB) in \textit{Escherichia coli}. In addition, quantitative assays based on amylose V as substrate are described, allowing accurate determination of both hydrolysis (minor) activity (glucose release, reducing power) and total activity (iodine staining), and calculation of the transferase (major) activity of these 4,6-\(\alpha\)-GTase enzymes. The data shows that GtfB-\(\Delta\)N is clearly less hydrolytic than GtfW, which is also supported by NMR analysis of their final products. Using these assays, the biochemical properties of GtfB-\(\Delta\)N were characterized in detail, including determination of kinetic parameters and acceptor substrate specificity. The GtfB-\(\Delta\)N enzyme displayed high conversion yields at relatively high substrate concentrations, a promising feature for industrial application.
Introduction

Starch is the second most abundant carbohydrate on earth and a major dietary carbohydrate for humans; as storage carbohydrate it is present in seeds, roots and tubers of plants (1). It consists of α-glucan polymers with (α1→4) linkages and a low percentage of (α1→6) linkages, in the form of amylase and branched amylopectin (2). Starches are applied in various industrial products such as food, paper, and textile, often after processing by physical, chemical or enzymatic treatment (3-6).

Dietary fibers and low glycemic index (GI) food are considered healthy food contributing to our long-term well-being (7, 8). Of all the nutritional types of starch, slowly digestible starch (SDS) with low GI has drawn strongest interest. Annealing/heat-moisture treatment, recrystallization and enzymatic treatment are recognized approaches to obtain SDS (9-11). SDS materials prepared by physical processing suffer losses upon boiling, therefore structural modifications through enzymatic treatment of starch are more desirable. In the human digestive system, the (α1→6) linkages in starch are hydrolyzed at a lower rate than (α1→4) linkages (12, 13). Branching enzymes, alone or in combination with β-amylase, are used to increase the percentage of (α1→4,6) branches in starches (12-14).

The 4,6-α-Glucanotransferase (4,6-α-GTase) enzymes such as GtfB, GtfW and GtfML4 of Lactobacillus reuteri strains constitute a subfamily of Glycoside Hydrolase Family 70; GH70 mainly consists of glucansucrases (GSes) (http://www.cazy.org). Unlike GSes, 4,6-α-GTases are not sucrose-acting enzymes but starch-converting enzymes, capable of converting (1→4)-α-D-glucose oligosaccharides into dietary fiber isomalto/malto-polysaccharides (IMMPs). Conversion has been proposed to occur mainly by the step-wise addition of single glucose moieties onto the non-reducing end of an α-glucan, introducing linear chains with (α1→6) linkages (15-18). The 4,6-α-GTase enzymes have strong potential for SDS or soluble dietary fiber production in the starch industry (19).

The expression yields of all three studied 4,6-α-GTase enzymes in E. coli are rather low and most of the protein accumulates in inclusion bodies (18, 20); to obtain more active protein, strategies to use denatured refolded GtfB protein, or non-classical inclusion body preparations have been tested. The biochemical and
Chapter 3

catalytic properties of these enzymes, e.g. their hydrolysis and transferase activities, have not been characterized yet because of a lack of suitable quantitative assays. In the present study, the variable N-terminal region of the GtfB enzyme was removed (yielding construct GtfB_{734-1619}) which resulted in increased expression of soluble and active GtfB-ΔN enzyme in *E. coli*. In addition, we developed activity assays to characterize the reactions of 4,6-α-GTase enzymes with amylose. These assays were used to define the optimal reaction conditions of GtfB-ΔN and GtfW-ΔN, and to quantitatively compare their hydrolysis and transferase activities, as well as to determine key biochemical properties. The developed assays also provide a firm basis for the future characterization of other, natural and engineered, 4,6-α-GTase enzymes.

Materials and Methods

Construction of a truncated GtfB-ΔN mutant

Based on the alignment of the *L. reuteri* 121 GtfB with glucansucrase sequences, and the crystal structure of *L. reuteri* 180 Gtf180-ΔN glucansucrase (PDB entry 3KLK), the *gtfB* gene fragment encoding GtfB (Uniprot entry Q5SBM0) amino acids 734–1619 was amplified by PCR using High Fidelity PCR enzyme mix (Thermo-Scientific, Landsmeer, The Netherlands) with pET15b-GtfB as template and the primers CHisFor-dNgtfB 5′-GATGCATCCATGGGCCAGCTCATGAGAAACTTGGTTGCAAAACCTAAT A-3′ and CHisRev-dNgtfB 5′-CCTCCTTTCTAGATCTATTAGTGATGGTGATGGTGATGGTTGTTAAAGTT TAAATGAAATTGCAGTTGG-3′. A nucleotide sequence encoding a 6×His-tag was fused in-frame to the 3′ end of the *gtfB-ΔN* gene, using the reverse primer. The resulting PCR product was digested with NcoI and BglII and was ligated into the corresponding site of pET15b. The construct was confirmed by nucleotide sequencing (GATC, Cologne, Germany). Plasmid pET15b-gtfW-ΔN (with the *gtfW* gene fragment encoding GtfW-ΔN (Uniprot entry A5VL73) amino acids 458-1363) has been constructed previously (18).

Expression and purification of GtfB, GtfB-ΔN and 4,6-αGT-W (GtfW-ΔN)

The GtfB protein was produced in *E. coli* BL21 Star (DE3) carrying the plasmids pRSF-GtfB and pBAD22-GroELS (17). The bacterial inocula were prepared in
0.4 L Luria-Bertani cultures and grown at 37°C and 220 rpm until the OD_{600} had reached 0.4-0.5, followed by addition of the inducer 0.4 mM isopropyl β-D-1-thiogalactopyranoside, and L-arabinose (0.02% w/v). The cultures were subsequently incubated at 18 °C and 160 rpm for 16 h in an orbital shaker. Cells were harvested by centrifugation (26000×g, 40 min) and then washed with 20 ml buffer (20 mM Tris/HCl pH 8.0, 250 mM NaCl, 1mM CaCl$_2$). The collected cells were resuspended in 10 ml B-PER protein extraction reagent (Pierce, 100 μg/ml of lysozyme and 5 U/ml of DNase) for 30 min on a rolling device at room temperature, followed by centrifugation (10,000×g, 30 min). The encoded GtfB protein carrying a C-terminal (His)$_6$-tag was purified by His-tag affinity chromatography using a 1-ml Hitrap IMAC HP column (GE Healthcare) and anion exchange chromatography (Resource Q, GE Healthcare). The salt was removed using a 5-ml Hitrap desalting column (GE Healthcare) run with B-PER and 1 mM CaCl$_2$. Purity was checked on 8% sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) and protein concentration was measured by Bradford reagent (Bio-Rad, Hercules, CA) and bovine serum albumin as standard.

The *L. reuteri* DSM 20016 4,6-αGT-W (GtfW-ΔN) and GtfB-ΔN proteins were expressed and purified according to Leemhuis et al. with minor modification (18). *E. coli* BL21(DE3)-pET15b_gtfW-ΔN/gtfB-ΔN was grown in Luria broth containing 100 mg/l ampicillin. Protein expression was induced at an OD$_{600}$ of 0.4–0.5 by adding isopropyl β-D-1-thiogalactopyranoside to 0.1 mM, and cultivation was continued at 18°C and 160 rpm for 16 h. Cells were harvested by centrifugation, in Tris-HCl buffer (50 mM, pH 8.0), containing NaCl (250 mM), Cell-free extracts were made by sonication followed by centrifugation (10,000×g, 1 h). Purification was performed as described above.

**Preparation of amylose V substrate solution**

Amylose V was provided by AVEBE (Veendam, The Netherlands). Note that Amylose V is a slightly degraded amylose, as a result of the extraction procedure used to isolate it from regular potato starch. The degree of branching of amylose V was below 0.1 %, as reported earlier (21). Amylose V (1%, w/v) was prepared as stock solution. Amylose V (20 mg) was suspended in 1 ml ddH$_2$O, and dissolved by addition of 1 ml 2 M NaOH. The solution was homogenized until
clear. Prior to use, the stock solution was neutralized by adding an equal volume of 1 M HCl and the stock was further diluted with reaction buffer.

**Enzyme assays**

The optimal pH and temperature of 4,6-α-GTases were determined over the pH range of 3.5-7.0 (25 mM sodium acetate (NaAc) buffer, pH 3.5-5.5; 25 mM MES buffer, pH 5.5-6.5; 25 mM MOPS buffer, pH 6.5-7.0) at 40 °C, and temperature range of 30-60 °C at pH 5.0 with 0.25% (w/v) amylose V as substrate. All other reactions were performed in reaction buffer (25 mM NaAc, pH 5.0, 1 mM CaCl₂), with 0.25% (w/v) amylose V or 2.5% (w/v) maltodextrins (dextrose equivalent = 13-17, Sigma-Aldrich, US), or 10 mM maltoheptaose (Sigma-Aldrich, Missouri, US) as substrate, at 40 °C. In each reaction, 60 nM of enzyme was added. Every 5 min, 100 µl of reaction mixture was taken and the reaction was stopped by addition of 50 µl of 0.4 M NaOH. Afterwards, 50 µl 0.4 M HCl was added to neutralize the reaction mixture. These samples were stored for GOPOD (Megazyme International, Ireland) determination of glucose released, Nelson-Somogyi measurement of reducing power, and (changes in) iodine staining of amylose.

Paselli MD6 maltodextrins (partial hydrolysis product of potato starch with a dextrose equivalent between 5 and 7 and 2.9% α1→6 glycosidic linkages) was provided by AVEBE and variant concentrations (0.93-55.8% w/v) were incubated with GtfB-ΔN [1/1000 (w/w) concentration of substrate] for 72 h at 37°C and pH 5.0.

**Amylose-iodine assay**

The iodine staining method was used to quantify (remaining) amylose in the reaction mixture (22). Thus, 0.26 g I₂ and 2.6 g KI were dissolved in 10 ml distilled water to prepare the 260× concentrated stock. Prior to using the staining buffer, the stock was diluted 260× with distilled water. For each measurement, 150 µl iodine reagent was pipetted into microtiter plate wells, followed by addition of 15 µl enzyme reaction sample solution. The microtiter plate was shaken slowly for 5 min to allow color formation and the optical density was measured at 660 nm. Amylose V solutions (0-0.25%, w/v) were used to prepare a calibration curve.
Reducing sugar measurement

The Nelson-Somogyi assay adapted to microtiter plates was used to measure the reducing power released through hydrolysis activity of the enzymes with amylose V (23). Thus, 40 µl Somogyi copper reagent, consisting of 4 parts KNa tartrate: Na₂CO₃:Na₂SO₄:NaHCO₃ (1 : 2 : 12 : 1.3) and 1 part CuSO₄·5H₂O:Na₂SO₄ (1 : 9) and 40 µl enzyme reaction sample were mixed and incubated at 90 °C for 30 min, after which the mixture was cooled to room temperature. After shaking the microtiter plate for 1 min to remove CO₂, 160 µl arsenomolybdate (25 g ammonium molybdate in 450 ml H₂O + 21 ml 98% H₂SO₄ + 3 g Na₂HAsO₄·7H₂O dissolved in 25 ml H₂O) was added and mixed by vortexing. Optical densities were read at 500 nm. A calibration curve was made using 0-200 µg/ml glucose solutions as standard.

Glucose measurement

Glucose was measured using the GOPOD kit which was adapted for microtiter plates. Five µl enzyme reaction sample was added to wells containing 195 µl GOPOD reagent, followed by incubation at 40 °C for 30 min. Optical densities were read at 510 nm. A calibration curve was made using 0-200 µg/ml glucose solutions as standard.

Definitions of hydrolysis (H) and total activities, and calculation of transferase (T) activities

One unit of hydrolysis activity (H) is defined as the release of 1 mg glucose from amylose V per min in the GOPOD assay mixture.

One unit of total activity is defined as the decrease of 1 mg amylose V per min in the assay mixture (as determined by the amylose-iodine staining method).

Amylose V is either converted into free glucose via H or modified by transferase activity (T) introducing linear α1→6 linked glucose chains, losing ability to bind iodine. \( T = \frac{\text{Total activity}}{\text{mg}} - \frac{\text{Hydrolysis activity}}{\text{mg}} \). Also \( T/H \) activity ratios can be calculated subsequently.
Nuclear Magnetic Resonance (NMR) Spectroscopy

The reaction products were exchanged twice with D₂O (99.9 atm% D, Cambridge Isotope Laboratories, Inc.) with intermediate lyophilization and then dissolved in 0.6 ml D₂O. Resolution-enhanced 500-MHz 1D ¹H NMR spectra were recorded with a spectral width of 4500 Hz in 16k complex data sets and zero filled to 32k in D₂O on a Varian Inova Spectrometer (NMR Center, University of Groningen) at a probe temperature of 335 K. Suppression of the HOD signal was achieved by applying a WET1D pulse sequence. All spectra were processed using MestReNova 5.3.

Results

Improving expression of soluble GtfB protein

Heterologous expression of L. reuteri 4,6-α-GTase enzymes in E. coli is relatively poor. Optimization of the growth and induction conditions did not improve the soluble expression level of these enzymes and most of the GtfB and GtfW proteins accumulated in inclusion bodies. Improvement of soluble expression of these enzymes appeared essential, also in view of their potential industrial application. The 4,6-α-GTase enzymes constitute a subfamily of GH70, showing high similarity with glucansucrases in amino acid sequences. As previously reported, deletion of the N-terminal variable region of GH70 glucansucrases, such as GtfA, did not change the glycosidic linkage types present in the products, nor the product sizes but significantly improved the expression levels of the enzymes (24-26). Therefore, we applied a similar truncation approach to GtfB. Alignment of the GtfB and glucansucrase protein sequences (27) resulted in identification of amino acids 1-733 as the GtfB N-terminal variable region (Fig. 1A). This region contains 5 RDV repeats (sequence R(P/N)DV-x₁₂-SGF-x₁₉-₂₂-R(Y/F)S, where x represents a non-conserved amino acid residue) which were also observed previously in Gtf180, GtfA and GtfML1 (28). Its deletion in GtfB resulted in expression of soluble GtfB-ΔN at a much higher level compared to the full length GtfB. Moreover, the purity of GtfB-ΔN protein was improved significantly compared to that of the full length GtfB enzyme (Fig. 1B). More than 40 mg pure GtfB-ΔN protein was obtained from 1 liter E. coli culture, improving expression 75 fold based on molar calculation. The full length GtfB and GtfB-ΔN enzymes were compared with regard to their
reaction specificity and activity using amylose V and maltoheptaose as substrates (data not shown). With maltoheptaose (10 mM) as substrate, the rate of glucose release (GOPOD) and the product profiles of both enzymes were nearly identical. While using amylose V as substrate, the total and hydrolysis activities measured by the GOPOD and iodine staining assay described below were almost the same. The N-terminally truncated GtfB and the full length GtfB thus are virtually identical in activity and products.

**Products derived from amylose V and maltodextrins by GtfB-ΔN or GtfW-ΔN treatments**

Linear (α1→4)-linked compounds are preferred substrates for 4,6-α-GTases, therefore amylose V and short chain (α1→4)-linked maltodextrins were compared as donor substrates for the GtfB-ΔN and GtfW-ΔN enzymes. 1H NMR analysis of the products of GtfB-ΔN and GtfW-ΔN incubated with amylose V [(1→4)-α-D-glucan] or maltodextrins [(1→4)-α-D-glucooligosaccharides] for 48 h revealed that both hydrolysis and transferase activities occurred. Besides the presence of (α1→4) linkages (H-1, δ ~5.40), (α1→6) linkages (H-1, δ ~4.97) were newly formed. In the product mixture derived from amylose V, the (α1→6):(α1→4) linkage ratio increased up to 90:10 (Fig. 2a1) for GtfB-ΔN and 74:26 for GtfW-ΔN (Fig. 2b1), when using identical amounts of purified protein. The spectra also showed the presence of free glucose (Glcα H-1, δ 5.225, Glcβ H-1, δ 4.637), the 4-substituted reducing glucose residues [-(1→4)-α-D-Glc\(\beta\); Rα H-1, δ 5.225, Rβ H-1, δ 4.652], and a small amount of reducing-end glucose residues which are 6-substitued [-(1→6)-α-D-Glc\(\beta\); Rα H-1, δ 5.241, Rβ H-1, δ 4.670] (32), suggesting that both GtfB-ΔN and GtfW-ΔN can use glucose as acceptor substrate, forming maltose, isomaltose and longer products in the presence of donor substrate. Comparison of the spectra Fig. 2a1 and Fig. 2b1 showed that GtfW-ΔN produced a much higher percentage of free glucose (23%) compared to GtfB-ΔN (8%) from amylose V. Conceivably, GtfW-ΔN has a higher ratio of hydrolysis versus
Fig. 1 (A) Linear schematic representation of the domain organization of full length Gtf180 of *L. reuteri* 180 and GtfB of *L. reuteri* 121 (with N-terminal variable region). Structural analysis of *L. reuteri* 180 Gtf180-ΔN protein has shown that its peptide chain follows a “U”-path and that four of its five domains are built up from discontinuous N- and C-terminal parts of the peptide chain. Only the C-domain is formed from one continuous stretch of amino acids 18). The GtfB protein has a similar organization, except that the C-terminal part of domain V is absent. The amino acid residue numbers indicate the start and end of each domain. (B) SDS-PAGE (8%, Coomassie blue stained) analysis of GtfB and GtfB-ΔN expression. Lane 1, whole cell extract of *E. coli* with pET15b-gtfB plasmid; lane 2, purified GtfB (predicted Mr: 179 kDa); Lane 3, whole cell extract of *E. coli* with pET15b-gtfB-ΔN plasmid; lane 4, purified GtfB-ΔN (predicted Mw = 99 kDa); M, marker proteins.
transferase activity compared to GtfB-ΔN, thereby initially generating more free glucose. In the reactions of both GtfB-ΔN and GtfW-ΔN with maltodextrins that possess branches (Fig. 2a2 and 2b2), lower conversions (36% for GtfB-ΔN and 32% for GtfW-ΔN) of (α1→4) linkages into (α1→6) linkages were obtained compared to the reactions using amylose V (90% for GtfB-ΔN and 74% for GtfW-ΔN) as substrate. Long chain amylose thus appears to be a more efficient substrate for conversion of (α1→4) into (α1→6) linkages, and was therefore used as the standard substrate in subsequent activity assay development and further biochemical analysis.

Measurement of the hydrolysis activity of 4,6-α-GTase enzymes
To characterize 4,6-α-GTase enzymes biochemically, assays to determine both their hydrolysis activity (H) and transferase activity (T) are required. All three characterized 4,6-α-GTases synthesize most of all (α1→6) linkages and occasionally an (α1→4) linkage (Fig. 3) (18). Whereas the 4,6-α-GTase transferase activity is dominant, hydrolysis activity also occurs resulting in glucose release (Fig. 3). Reducing power and glucose measurements are widely accepted methods to determine H of starch converting enzymes with either endo- or exo-hydrolyzing activity, such as α-amylase, α-glucosidase, and cyclodextrin glucanotransferase (33-35). In case of 4,6-α-GTases, the measurement of free glucose specifically may lead to an underestimation of H. The reducing power assay representing both free glucose and products of the transferase reaction with glucose as acceptor substrate, may give a more precise estimate of H (Fig. 3). Therefore the Nelson-Somogyi assay measuring reducing power was compared with the GOPOD assay measuring free glucose; the results were the same in the initial stage of the reaction (Fig. S1). Therefore, both assays are equally applicable for measuring the initial rates of hydrolysis activity of 4,6-α-GTase enzymes.
Fig 2. One-dimensional $^1$H NMR spectra ($D_2O$, 335 K) of the products derived from amylose V and maltodextrins via *L. reuteri* 121 GtfB-ΔN (**a1** and **a2**, resp.) and *L. reuteri* DSM 20016 GtfW-ΔN (**b1** and **b2**, resp.) treatments.
Fig. 3. Schematic diagram of the reactions catalyzed by 4,6-α-GTase as proposed by Leemhuis et al. with minor modifications (18). Reducing ends of sugar molecules are shown in light grey color. The molecules with grey frames can only be used as acceptor substrates. The grey frame with light grey fill indicates free glucose.

**Measurement of the Total Activity of 4,6-α-GTases**

The total activity of 4,6-α-GTases, which includes hydrolysis \( H \) and transferase activity \( T \), was estimated with amylose as substrate, using the iodine staining assay. This assay is based on the fact that iodine stains amylose but not linear (1→6)-α-D-glucan, as can be predicted by the theory of steric hindrance; the
corresponding molecular simulations are shown in Fig. 4. The diameter of the iodine atom is 4.2 Å measured by Raman spectroscopy (36). The linear (1→6)-α-D-glucan model is based on the results of Genin et al (37), who showed that five-glucose-units per rotation in a right-handed helix is the most stable configuration. The inner diameter of such a helix is around 4.1 Å, therefore the iodine anions cannot be trapped into the cavities of the (1→6)-α-D-glucan due to the steric hindrance. We experimentally verified that dextran does not stain with iodine, using 0.5% (w/v) dextran T10 (Mw: 9-11 kDa, Holbaek, Denmark) instead of 0.5% (w/v) amylose V in the iodine staining assay as described in Methods (data not shown). The iodine anions can be entrapped into amylose because of the larger inner diameter (13 Å) and a shorter pitch (8 Å) of each helix (38). H reduces the iodine binding capacity of the amylose substrate since glucose is released gradually from the non-reducing end (Fig. 4) (15). T also impairs the iodine binding capacity of amylose V because it converts the α1→4 linked chains at the non-reducing end into α1→6 linked chains, lacking iodine staining capacity. The iodine binding capacity of the amylose V substrate decreased linearly in time during its reaction with GtfB-ΔN (Fig. 5).

Both H and T thus influence the iodine binding capacity of the amylose substrate. Therefore, the iodine assay is applicable for measuring the total activity of 4,6-α-GTases.

**Effects of pH, temperature and metal ions on activity of GtfB-ΔN and GtfW-ΔN**

The pH optimum for H and T of both GtfB-ΔN and GtfW-ΔN with amylose V was pH 5.0 (Fig. 6). The temperature optimum for H and T of both enzymes at pH 5.0 was 55 °C. However, at temperatures of 50 and 55 °C, the half-life of both enzymes is less than 10 min (18, 20). At 40 °C, both enzymes were stable for more than 2 h. At lower temperatures, the activities of both enzymes remained relatively high (Fig. 6a and b). The transferase activity does not change significantly in the range of 40 to 55 °C. Therefore, pH 5.0 and 40 °C are the optimal conditions for both enzymes, resulting in a ratio T/H=4.3:1 for GtfB-ΔN and 1.7:1 for GtfW-ΔN.
Fig. 4. (A) Schematic diagrams of amylose and α(1→6)-glucan, and (B) the complexes of iodine with amylose and with the amylose derived products of the 4,6-α-GTase activities, hydrolysis (H) and transglycosylation (T). The round atoms represent iodine ions.
Fig. 5. Total activity of the L. reuteri 121 GtfB-ΔN (60, 90 or 120 nM) enzyme with amylose V (0.25%, w/v) was followed in time by taking samples and measuring the formation of the iodine-amylose V complex. Resulting total activities (U/mg) are indicated.

Aiming to enhance the T/H ratio with the amylose V substrate, most important for industrial application of these enzymes, further variations in incubation temperature and pH were investigated. When the incubation temperature of GtfB-ΔN was decreased from 55 to 30 °C, 82% of T and 48% of H remained, resulting in the highest T/H value of 6.0:1 (Fig. 6a). Such higher values of T/H thus result in lower yields of glucose and short-chain oligosaccharides, formed from glucose as acceptor substrate. Rather, more long-chain polysaccharides (IMMPs) are synthesized which are considered as soluble dietary fiber. Using the optimal conditions described above (pH 5.0 and 40 °C), the H, T and total activities of both GtfB-ΔN (0.6, 2.2, and 2.8 U/mg) and GtfW-ΔN (1.6, 2.3, and 3.9 U/mg) were determined. Compared to GtfB-ΔN, GtfW-ΔN has relatively high H activity, which is in agreement with the NMR results showing more products with reducing ends formed by GtfW-ΔN (Fig. 2).
Fig. 6. The effects of pH and temperature on *L. reuteri* 121 GtfB-ΔN (a) and *L. reuteri* DSM20016 GtfW-ΔN (b) activities including hydrolysis, transferase and total activities, using amylose V (0.25%, w/v) as substrate in the presence of 1 mM CaCl₂. The experiments were done in triplicate. For pH optimization, values of *H*, *T* and total activities of both GtfB-ΔN (0.6, 2.2, and 2.8 U/mg) and GtfW-ΔN (1.6, 2.3, and 3.9 U/mg) determined at pH 5.0 and 40 °C were set as 100%. For temperature optimization, values of *H*, *T* and total activities of both GtfB-ΔN (0.6, 2.3, and 2.9 U/mg) and GtfW-ΔN (1.7, 2.4, and 4.1 U/mg) determined at pH 5.0 and 55 °C were set as 100%.

Both 4,6-α-GTases and glucansucrases (GSes) belong to GH70 and share high protein sequence similarity. GSes are strongly ion-dependent and need Ca²⁺ to stimulate their transferase activity; for example, in the presence of Ca²⁺ ions, transferase activity of reuteransucrase GtfA of *L. reuteri* 121 was enhanced 8 fold (24). In the present study, different metal ions had varying effects on the hydrolysis and transferase activities of 4,6-α-GTase. As shown in Table 1, Cu²⁺, Fe²⁺ and Fe³⁺ ions strongly inhibited both activities of GtfB-ΔN and GtfW-ΔN. In the presence of Cu²⁺ ions, no transferase activities were detectable for both enzymes. K⁺, Na⁺, and Mg²⁺ ions had virtual no effect on these activities, especially not on transferase activity, whereas Ca²⁺ and Mn²⁺ ions slightly activated both activities of GtfB-ΔN and GtfW-ΔN.
Table 1. Effects of various compounds on GtfB-ΔN and GtfW-ΔN activity. Incubations were performed at 40 °C in a 25 mM NaAc buffer (pH 5.0) with amylose V (0.25%, w/v) as substrate. The hydrolysis activity without additional compound was set at 100% (0.6 U/mg for GtfB-ΔN and 1.3 U/mg for GtfW-ΔN). ND = not detectable. The experiments were done in duplicate.

<table>
<thead>
<tr>
<th>Compounds (1 mM)</th>
<th>GtfB-ΔN Hydrolysis activity (%)</th>
<th>Transferase activity (%)</th>
<th>GtfW-ΔN Hydrolysis activity (%)</th>
<th>Transferase activity (%)</th>
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<tbody>
<tr>
<td>None</td>
<td>100 ± 4</td>
<td>405 ± 35</td>
<td>100 ± 8</td>
<td>180 ± 16</td>
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<td>EDTA</td>
<td>75 ± 5</td>
<td>388 ± 51</td>
<td>90 ± 7</td>
<td>143 ± 14</td>
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<tr>
<td>NaCl</td>
<td>118 ± 12</td>
<td>404 ± 22</td>
<td>108 ± 11</td>
<td>171 ± 13</td>
</tr>
<tr>
<td>CaCl₂</td>
<td>111 ± 19</td>
<td>422 ± 65</td>
<td>121 ± 23</td>
<td>206 ± 33</td>
</tr>
<tr>
<td>MnCl₂</td>
<td>125 ± 15</td>
<td>425 ± 71</td>
<td>137 ± 16</td>
<td>223 ± 23</td>
</tr>
<tr>
<td>MgCl₂</td>
<td>94 ± 12</td>
<td>378 ± 5</td>
<td>108 ± 12</td>
<td>198 ± 18</td>
</tr>
<tr>
<td>KCl</td>
<td>86 ± 10</td>
<td>435 ± 6</td>
<td>109 ± 11</td>
<td>183 ± 10</td>
</tr>
<tr>
<td>CuCl₂</td>
<td>51 ± 5</td>
<td>ND</td>
<td>35 ± 7</td>
<td>ND</td>
</tr>
<tr>
<td>FeCl₂</td>
<td>50 ± 6</td>
<td>175 ± 42</td>
<td>64 ± 4</td>
<td>74 ± 15</td>
</tr>
<tr>
<td>FeCl₃</td>
<td>35 ± 5</td>
<td>85 ± 25</td>
<td>46 ± 6</td>
<td>32 ± 10</td>
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</table>

Kinetic analysis and acceptor specificity of GtfB-ΔN

With amylose V as a substrate, GtfB-ΔN displayed Michaelis-Menten type kinetics for hydrolysis, transferase, and total enzyme activity. The kinetic parameters of GtfB-ΔN were calculated from plots of 1/[V] versus 1/[S]. The turnover rate (k<sub>cat</sub>) of the transferase reaction is about 4 times higher than that of the hydrolysis reaction (Table 2). The k<sub>cat</sub>/K<sub>m</sub> value for the transferase reaction is 3 fold higher than for the hydrolysis reaction, indicating that the transferase activity is predominant, resulting mostly in synthesis of modified amylose (IMMP) and in low glucose release.

Table 2. Kinetic parameters of the L. reuteri 121 GtfB-ΔN enzyme with the amylose V substrate. A fixed amount of GtfB-ΔN enzyme (60 nM) was used with varying concentrations of amylose V (0.025-0.4%, w/v) at pH 5.0 and 40 °C.

<table>
<thead>
<tr>
<th>Activity</th>
<th>K&lt;sub&gt;m&lt;/sub&gt; (g·L&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>k&lt;sub&gt;cat&lt;/sub&gt; (s&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>k&lt;sub&gt;cat&lt;/sub&gt;/K&lt;sub&gt;m&lt;/sub&gt; (g&lt;sup&gt;-1&lt;/sup&gt;·s&lt;sup&gt;-1&lt;/sup&gt;·L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrolytic activity</td>
<td>0.50 (±0.04)</td>
<td>9.06±0.18</td>
<td>18.5 (±1.8)</td>
</tr>
<tr>
<td>Transferase activity</td>
<td>0.69 (±0.07)</td>
<td>36.22±1.14</td>
<td>53.0 (±7.2)</td>
</tr>
<tr>
<td>Total Activity</td>
<td>0.64 (±0.02)</td>
<td>45.04±1.14</td>
<td>70.6 (±4.0)</td>
</tr>
</tbody>
</table>

A molecular mass of 99 kDa (GtfB-ΔN) was used in the calculation of the k<sub>cat</sub>. 
To study the acceptor substrate specificity of GtfB-ΔN, the total activities with amylose V in the presence/absence of different acceptor substrates were determined (Table 3). The transglycosylation factor (TF), defined as the ratio of the amylose degradation ratio in the presence/absence of small acceptor substrates was measured. TF reflects the suitability of a certain acceptor substrate for its enzyme (39-41). Addition of these small acceptor substrates increased the reaction rates of GtfB-ΔN with amylose V in all cases. The TFs for α1→4 linked maltose and glucose as acceptor substrates were higher than 1 and similar. The TFs for the α1→6 linked acceptor substrates isomalt(tri)ose clearly were much higher, indicating that isomalt(tri)ose are strong acceptor substrates for the GtfB-ΔN enzyme (Table 3).

Table 3. Amylose V (0.25%, w/v) degradation activity (total activity, measured using iodine staining assay) and transglycosylation factors of the L. reuteri 121 GtfB-ΔN enzyme in the presence of different acceptor substrates (10 mM). Experiments are carried out in duplicate and average data was described.

<table>
<thead>
<tr>
<th>Without acceptors</th>
<th>Amylose degradation (U/mg)</th>
<th>Transglycosylation factor&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose</td>
<td>6.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Maltose</td>
<td>7.3</td>
<td>2.6</td>
</tr>
<tr>
<td>Maltotriose</td>
<td>7.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Isomaltose</td>
<td>13.5</td>
<td>4.7</td>
</tr>
<tr>
<td>Isomaltotriose</td>
<td>19.0</td>
<td>6.7</td>
</tr>
</tbody>
</table>

<sup>a</sup> The transglycosylation factor is defined as the ratio of amylose degradation rates in the presence/absence of an acceptor substrate.

**GtfB is functional at higher substrate concentrations**

To explore the effects of substrate concentration on the functionality of GtfB, the enzyme was incubated at various Paselli MD6 maltodextrins (partial hydrolysis product of potato starch with a dextrose equivalent between 5 and 7 and 2.9% α1→6 glycosidic linkages) concentrations keeping the substrate to enzyme ratio at 1000:1 on a mass basis. The results show that GtfB is fully functional at high substrate concentrations. GtfB introduced α1→6 glycosidic linkages at all substrate concentrations, though most efficiently at concentrations between 5 and 30% Paselli MD6 with a maximum of 42.2% α1→6 glycosidic linkages at 30%
concentration (Fig. 7). Moreover, at high substrate concentrations the enzyme has basically no hydrolytic activity, as above 15% (w/v) substrate there is no increase in reducing power compared to the maltodextrins substrate (3.9% reducing power) used.

Fig. 7. The Paselli MD6 substrate (0.93%-55.8%, w/v) was incubated with *Lactobacillus reuteri* 121 GtfB-ΔN enzyme (1-60 µg/ml). The reducing power of the samples and the percentages of α1→6 glycosidic linkages in the products were determined by 1H NMR. Reactions were performed for 72 h, incubated at 37°C and pH 5.0.

**Discussion**

The amino acid sequences of 4,6-α-GTases are highly similar to those of glucansucrases, and they constitute a subfamily of GH70. Most of the glucansucrases characterized from *Lactobacilli* have relatively large N-terminal variable regions, possibly involved in cell wall binding, but a clear functional role has not been established (28). Previous research showed that truncation of the N-terminal variable region of some glucansucrases had no effect on the size and linkage-type distribution of the products formed, but resulted in a much higher expression level in *E. coli* (24-26, 42). The purified truncated Gtf180-ΔN and GtfA-ΔN proteins also yielded crystals suitable for X-ray diffraction (29-31). The subsequent elucidation of high resolution 3D structures of truncated
glucansucrase proteins revealed that their peptide chains follow a “U”-path with multiple domains (e.g. glucansucrase Gtf180) (29, 31, 43). Multiple sequence alignment of 4,6-α-GTases with glucansucrases showed that they also have a large N-terminal variable domain (data not shown). In GtfB, this N-terminal domain is formed by residues 1-733. Notably, GtfB differs from glucansucrases in lacking the C-terminal polypeptide segment of domain V. Applying a similar strategy as with the glucansucrase, the N-terminal truncation of GtfB (GtfB-ΔN) resulted in a significant enhanced expression level in *E. coli* compared to the full length wild type GtfB without affecting the activity of the enzyme and products formed.

To biochemically characterize this novel group of 4,6-α-GTase enzymes, several assays have been used, such as HPAEC and quantitative TLC measurement of the saccharides formed from maltoheptaose, or the glucose released from maltose as substrate (16, 18). Both assays have limitations; e.g. they do not allow determination of the specific hydrolysis and transferase activities of these 4,6-α-GTases, nor a kinetic analysis. Dextran dextrinases (DDases) from *Gluconobacter oxydans* also catalyze the cleavage of an α(1→4) linked glucosyl unit from the non-reducing end of a donor substrate and its subsequent transfer to an acceptor substrate forming an α(1→6) linkage (44). The amino acid sequences of these DDase enzymes have not been annotated yet, and further comparison with 4,6-α-GTases are not possible yet. The dinitrosalicylic acid assay based on changes in reducing power, and a viscosity build-up assay based on the changes of rheological properties from maltodextrin to dextran have been used for estimating the activity of DDases (45). However, the poor sensitivity of dinitrosalicylic acid and interference by unreacted maltodextrins, and the complex non-Newtonian and time-dependent flow behavior of the maltodextrin/dextran mixture in the reaction mixture severely limits the use of this method. Later, a more reliable assay based on discrete transglycosylation reactions was successfully applied, using maltose as a standard substrate (44). The generated panose was demonstrated to be a valid indicator for transglycosylation activity. A similar assay using *p*-nitrophenyl-α-D-glucopyranoside (NPG) instead of maltose also provided a reliable estimate of DDase transglycosylation activity. However, these assays are also not applicable
for 4,6-α-GTases because of their low or undetectable activity with maltose or NPG. Thus, proper assays for 4,6-α-GTase activities remained to be established.

Starch-converting enzyme activities can be determined with various methods by following amylose degradation/modification (34, 46). Also 4-α-glucanotransferase enzymes that catalyze both intermolecular (disproportionation) and intramolecular (cyclization) reactions can be studied in this way (39, 47). As shown in our study, amylose also is an efficient substrate for the 4,6-α-GTase catalyzed transferase and hydrolysis reactions. The data shows that the iodine-amylose staining assay is a suitable method to estimate the total activity of 4,6-α-GTases, whereas the GOPOD assay serves to determine hydrolysis ($H$) activity. The data from both assays can be combined calculate transferase ($T$) activity. Ratios $T/H = 4.3:1$ for GtfB-ΔN and 1.7:1 for GtfW-ΔN were obtained under the optimal conditions for both enzymes, indicating that GtfB is less hydrolytic than the GtfW enzyme. Under suboptimal temperature conditions the $T/H$ ratio for GtfB even reached 6.0:1. The data clearly shows that GtfB is a proper transglycosylase, with relatively minor hydrolysis activity. $T/H$ ratios have been reported for other transglycosylase enzymes. For glucansucrase Gtf180-ΔN from *L. reuteri* 180 and glucansucrase GtfA-ΔN from *L. reuteri* 121, these ratios are 2.4:1 and 0.6:1 (30, 48); For cyclodextrin glucanotransferase of *Thermoanaerobacterium thermosulfurigenes* this ratio even is 8.1:1 (49).

Determination of the total activity of GtfB with amylose V in the presence/absence of acceptor substrates clearly showed that isomaltodextrins are preferred over maltodextrins as acceptor substrates. Such information strongly contributes to our understanding of the transglycosylation reaction catalyzed by 4,6-α-GTase enzymes, especially in combination with detailed 3D structural information allowing to identify and characterize acceptor binding sites. To this end we are currently aiming to crystallize constructs of GtfB and its homologues (in preparation).

To conclude, N-terminal truncation of the *L. reuteri* GtfB enzyme (GtfB-ΔN) remarkably enhanced the soluble expression level while retaining full activity. Using amylose V as substrate, the GOPOD assay and the amylose-iodine staining method allowed the characterization of the new 4,6-α-GTase enzymes GtfB and GtfW, including their optimal reaction conditions, hydrolysis and transferase
activities. The data shows that GtfB is less hydrolytic than GtfW, which is in agreement with the NMR results. Using these assays, various properties of GtfB, the best characterized 4,6-α-GTase enzyme, were determined including its kinetic parameters and acceptor substrate specificity. The GtfB enzyme remained active at high substrate concentrations resulting in high product conversions, a promising feature for industrial applications. Moreover at high substrate concentrations the hydrolytic activity of GtfB is virtually absent. The developed assays thus provide a firm basis for the future characterization of other, natural and engineered, 4,6-α-GTase enzymes.

Acknowledgements

The study was financially supported by the Chinese Scholarship Council (to YB), the University of Groningen and by the TKI Agri&Food program as coordinated by the Carbohydrate Competence Center (CCC-ABC; www.cccresearch.nl).

References


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Fig. S1. The glucose and reducing sugar released in 150 min from reactions catalyzed by 60 nM of the *L. reuteri* 121 GtfB-ΔN enzyme with 0.25% (w/v) amylose V as substrate at 40 °C and pH 5.0.