2-Acylamido Analogues of N-Acetylglucosamine Prime Formation of Chitin Oligosaccharides by Yeast Chitin Synthase 2*

Received for publication, January 29, 2014, and in revised form, March 8, 2014. Published, JBC Papers in Press, March 11, 2014, DOI 10.1074/jbc.M114.550749

Jacob Gyore 1, Archana R. Parameswar 1, Carleigh F. F. Hebbard 2, Younghoon Oh, Erfei Bi 3, Alexei V. Demchenko 4, Neil P. Price 1, and Peter Orlean 1,†

From the 1Department of Microbiology, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, the 2Departments of Chemistry and Biochemistry, University of Missouri, St. Louis, Missouri 63121, the 3Department of Cell and Developmental Biology, University of Pennsylvania Perelman School of Medicine, Philadelphia, Pennsylvania 19104, and 4Renewable Product Technology, National Center for Agricultural Utilization Research, Agricultural Research Service, United States Department of Agriculture, Peoria, Illinois 61604

Background: Chitin synthases are stimulated by N-acetylglucosamine (GlcNAc).

Results: GlcNAc and 2-acylamido analogues of GlcNAc stimulate formation of chitin oligosaccharides by yeast chitin synthase, and GlcNAc is transferred to the 2-acylamido analogues.

Conclusion: Chitin synthases use GlcNAc analogues as primers and transfer one GlcNAc at a time.

Significance: Results are new insights into polysaccharide synthase mechanism and suggest ways of synthesizing novel modified polysaccharides.

Chitin, a homopolymer of β1,4-linked N-acetylglucosamine (GlcNAc) residues, is a key component of the cell walls of fungi and the exoskeletons of arthropods. Chitin synthases transfer GlcNAc from UDP-GlcNAc to preexisting chitin chains in reactions that are typically stimulated by free GlcNAc. The effect of GlcNAc was probed by using a yeast strain expressing a single chitin synthase, Chs2, by examining formation of chitin oligosaccharides (COs) and insoluble chitin, and by replacing GlcNAc with 2-acylamido analogues of GlcNAc (1). Synthesis of COs was strongly dependent on inclusion of GlcNAc in chitin synthase incubations, and N,N′-diacetylchitobiose (GlcNAc2) was the major reaction product. Formation of both COs and insoluble chitin was also stimulated by GlcNAc2 and by N-propanoyl- (GlcNPr), N-butanoyl-, and N-glycolylglucosamine. MALDI analyses of the COs made in the presence of 2-acylamido analogues of GlcNAc showed they that contained a single GlcNAc analogue and one or more additional GlcNAc residues. These results indicate that Chs2 can use certain 2-acylamido analogues of GlcNAc, and likely free GlcNAc and GlcNAc2 as well, as GlcNAc acceptors in a UDP-GlcNAc-dependent glycosyltransfer reaction. Further, formation of modified disaccharides indicates that CSs can transfer single GlcNAc residues.

Chitin, a homopolymer of β1,4-linked N-acetylglucosamine (GlcNAc) residues, is a key component of the cell walls of fungi and the exoskeletons of arthropods. The polymer is synthesized by processive inverting enzymes of glycosyltransferase family 2, whose members include cellulose synthases and class I hyaluronic acid synthases (1–5). The chitin synthase (CS)2 reaction is typically described as transfer of GlcNAc from UDP-GlcNAc to preexisting chitin chains. Fungi usually have multiple CSs, which can be active in different cellular locations and at different times during cell growth and division (6–8).

CSs are commonly assayed by incubating membrane fractions or partially purified enzyme preparations with UDP-GlcNAc and then collecting insoluble product for quantification (9–12). In vitro activity of CSs in membranes is often stimulated up to a few -fold by the inclusion of free GlcNAc in incubations (10, 12–16), and GlcNAc has been suggested to serve as a co-substrate (14) or an allosteric activator (16) in the CS reaction. Consistent with GlcNAc serving as a co-substrate or primer, the bacterial CS homologue NodC can transfer GlcNAc from UDP-GlcNAc to the nonreducing end of free GlcNAc, as well as transfer GlcNAc to the nonreducing end of p-nitrophenyl β-GlcNAc (17). A primer function for free GlcNAc, however, has not been demonstrated for a eukaryotic CS. Preexisting chitin chains presumably serve as acceptors for further GlcNAc addition, but short chitin oligosaccharides (COs) do not, because NodC did not use short COs as GlcNAc acceptor from UDP-GlcNAc (17), nor did a purified yeast CS (Chs1) elongate chitotetraose into chitin in the presence of UDP-GlcNAc (9). However, it has been proposed that longer COs can serve as primers (18).

In this study, we explore the role of GlcNAc in detail by using an Saccharomyces cerevisiae strain that expresses a single CS, by examining low molecular weight reaction products and by studying the effects of the GlcNAc analogues N-propanoyl-(GlcNPr), N-butanoyl- (GlcNBu), and N-glycolyl- (GlcNGc) analogues.
substituted glucosamine. We show that formation of COs is strongly dependent on the inclusion of free GlcNAc or certain 2-acylamido analogues of GlcNAc in assays and that Chs2 can transfer a single GlcNAc from UDP-GlcNAc to 2-acylamido analogues of GlcNAc and extend the resulting disaccharide with further GlcNAc residues.

EXPERIMENTAL PROCEDURES

Yeast Strains and Culture Media—S. cerevisiae strains YO1111 (chs1Δ chs3Δ), YO1528 (chs1Δ chs3Δ pRS314), and YO1535 (chs1Δ chs3Δ pY0201 (CHS2 overexpresser)) were described previously (19). The CHS1 gene in YO1535 was deleted and replaced with the yeast LEU2 gene (20). The sequence of the forward oligonucleotide primer used to amplify a DNA fragment consisting of LEU2 and nucleotides immediately upstream and downstream of the CHS1 coding sequence was 5’-ACATTGAATTCATAATTAATATATAATATT- TAATATAGAATTCGTTTCCGTTGATGAC-3’, and the sequence of the reverse primer was 5’-ACATTGAAATTCTAATTTAAATATAATTAATTAATGTTTCCGTTGATGAC-3’. Elimation of Cts1 activity was verified by testing culture supernatants of candidate cts1::LEU2 mutants for release of 4-methylumbelliferone from 4-methylumbelliferyl-β-D-N,N’,N’-triacetylchitotrioside (Sigma) (21). For induction of CHS2 expression, strains were pregrown for 24 h at 30 °C in synthetic complete medium lacking tryptophan containing 2% (w/v) glucose. Cells were then collected by centrifugation for assay of formation of 10% trichloroacetic acid-insoluble material. Incubation mixtures for assay of formation of COs contained 125 or 250 nCi of UDP-[14C]GlcNAc, corresponding to final UDP-GlcNAc concentrations of 0.046 mM or 0.092 mM, respectively. In some assays of CO synthesis, unlabeled UDP-GlcNAc (from Sigma) was added to give higher final UDP-GlcNAc concentrations. Reaction mixtures were then fractionated according to an adaptation of the procedure of Bligh and Dyer (22). To stop reactions, 375 µl of chloroform/methanol 1:2 (v/v) was added to incubation tubes (22). After standing for 30 min at room temperature, 125 µl of chloroform and 50 µl of water were added to the tubes, which were then mixed by vortexing and centrifuged in a Microfuge for 15 min. The upper aqueous phase was transferred to a minicolumn containing approximately 0.5 ml of packed Dowex 1-X8 resin (200 – 400 mesh) and the column run-through collected. The column was washed twice with 250 µl of water and once with 250 µl of 50% aqueous ethanol, and the combined run-throughs were dried under a stream of air. In some experiments, the insoluble material remaining after chloroform/methanol/water extraction was precipitated in 10% TCA after removal of the organic phase. COs were separated by thin layer chromatography (TLC) on Silica Gel 60 plates that had been prerun in chloroform/methanol/water (65:25:4 v/v/v). Chromatograms were developed twice in butan-1-ol/ethanol/water (5:3:2 v/v/v), and radiolabeled material was detected by phosphorimaging. Nonradioactive standards of GlcNAc, N,N’,N’-diacetylchitobiose, and N,N’,N’-triacyctethylchitotrioside were detected by spraying with aniline-diphenylamine-phosphoric acid reagent (23).

For bulk preparation of unlabeled COs, incubation mixtures (50-µl final volume) contained 1.4 mM unlabeled UDP-GlcNAc and 0.25 mM cobalt acetate. The Dowex 1-X8 run-throughs from seven parallel incubations were pooled, evaporated to dryness, and submitted to charcoal–celite chromatography as follows. Minicolumns were prepared by loading a 5-ml disposable pipette tip with a slurry of equal amounts of activated charcoal and celite 545 in 5% aqueous ethanol to give a column bed of 5 cm. CO samples were dissolved in 1 ml of water and loaded onto the column, which was then washed with 10 ml of 5% aqueous ethanol, and the eluate collected. The column was then eluted with 25 ml of 30% aqueous ethanol, and five 5-ml fractions were collected. Analysis of the fractions by MALDI established that free GlcNAc and salt emerged predominantly in the 5% ethanol wash and in 30% ethanol fraction 1, whereas the COs were eluted predominantly in 30% ethanol, in fractions 2 and 3 (24).

Preparation of 2-Acylamido Analogues of GlcNAc—Routine procedures and sources of reagents were as follows. Column chromatography was performed on Silica Gel 60 (70–230 mesh), reactions were monitored by TLC on Kieselgel 60 F254, and compounds were detected by examination under UV light and by charring with 10% sulfuric acid in methanol. Solvents were removed under reduced pressure at <40 °C. α-Glucosamine·HCl, propanoic anhydride, butyric anhydride, acetoxyacetyl chloride, anhydrous pyridine, anhydrous methanol, and inorganic com-
pounds were purchased from Sigma-Aldrich and used as is. 1H and 13C NMR spectra were recorded in D2O at 300 MHz or 75 MHz (Bruker Avance), respectively.

GlcNPr and GlcNBu were prepared from d-glucosamine·HCl as described previously, and the analytical data for these compounds were practically the same as reported previously (25). For the preparation of GlcNGc, d-glucosamine·HCl (5.0 g, 23.2 mmol) was dissolved in cold water (25 ml), and NaHCO3 (5.8 g, 69.5 mmol) was added. The mixture was stirred vigorously in an ice bath, and acetoxyacetyl chloride (3.0 ml, 27.8 mmol) was added dropwise. The resulting mixture was stirred for additional 2 h in the ice bath, then neutralized by dropwise addition of 1 M HCl. The precipitate was filtered off, washed with ice-cold water (10 ml), and dried. The crude product (~10 g) was dissolved in pyridine (50 ml) and acetic anhydride (25 ml) was added. The reaction mixture was stirred for 16 h at room temperature, then quenched by addition of methanol (~20 ml), and the volatiles were removed under reduced pressure. The residue was dissolved in CH2Cl2 (200 ml), saturated aqueous NaHCO3 (200 ml), water (200 ml), 1 M HCl (2 × 200 ml), and finally, with water (2 × 200 ml). The organic phase was separated, dried with MgSO4, and concentrated in vacuo. The residue was purified by column chromatography on silica gel (methanol-dichloromethane gradient elution). The pure acetylated product (α-anomer) was dissolved in methanol (5 ml), and 1 M sodium methoxide in methanol (2.5 ml) was added, giving a pH of 9, and the reaction mixture was stirred for 48 h at room temperature. The resulting mixture was neutralized with Dowex (H+), the resin was filtered off and rinsed with methanol. The combined filtrate was concentrated in vacuo and dried. The residue was purified by column chromatography on silica gel (methanol-dichloromethane gradient elution) to afford GlcNGc (0.8 g) in 15% yield overall. Selected analytical data for GlcNGc are: 13C NMR (α-anomer): δ 53.6, 60.5, 60.8, 69.9, 70.7, 71.6, 90.8, 175.1 ppm; 13C NMR (β-anomer): δ 56.3, 60.7, 61.0, 69.8, 73.6, 75.9, 94.6, 175.6 ppm. The remaining analytical data were essentially the same as reported previously (26, 27).

RESULTS

To explore the effect of free GlcNAc on the activity of a single CS, we used an S. cerevisiae chs1Δ chs3Δ strain, which lacks two of the three CS activities of yeast but is viable because it retains its chromosomal copy of the gene for the remaining CS, Chs2. The activity of chromosomally encoded Chs2 in membranes from the chs1Δ chs3Δ strain grown in minimal medium is very low, and in vitro Chs2 activity only becomes detectable when CHS2 is overexpressed from a high copy, galactose-inducible plasmid (15, 19). Although Chs2 activity can be elevated by pretreating membranes with trypsin (19), membranes from the present CHS2-overexpressing strain have high Chs2 activity without prior trypsin treatment (19), and the experiments here were done without trypsin treatment of membranes. To determine the nature of Chs2 reaction products at higher resolution, we focused on COs, which are made by S. cerevisiae CSs at low UDP-GlcNAc concentrations (9, 12, 28).

GlcNAc Strongly Stimulates Formation of GlcNAc2 and COs—Chs2-overexpressing membranes from chs1Δ chs3Δ cells were incubated with fixed amounts of UDP-[14C]GlcNAc and increasing amounts of unlabeled UDP-GlcNAc, and reaction mixtures were then fractionated into aqueous-soluble, organic-soluble, and chloroform/methanol/water-insoluble material according to an adaptation of the procedure of Bligh and Dyer (22). The aqueous-soluble material obtained after chloroform/methanol/water extraction and phase partitioning was passed through Dowex 1-X8, material in the run-through separated by TLC on silica gel plates that were developed twice in butan-1-ol/ethanol/water (5:3:2 v/v/v), after which radiolabeled material was detected by phosphorimaging, as detailed under "Experimental Procedures." Positions of nonradioactive standards are indicated. B, quantification of COs and chitin. Total amounts of COs in the material that was applied to the chromatogram in A and total amounts of 10% TCA-insoluble (TCA-insol) chitin remaining after chloroform/methanol/water extraction of the incubation mixtures from A were determined and plotted against UDP-GlcNAc concentration.

FIGURE 1. Stimulation of CO and insoluble chitin synthesis by GlcNAc. A, CO synthesis. Chs2-overexpressing membranes were incubated with 125 nCi of UDP-[14C]GlcNAc and increasing amounts of unlabeled UDP-GlcNAc in the presence or absence of 32 mM GlcNAc. Aqueous-soluble reaction products were isolated, passed through Dowex 1-X8 resin, and separated by TLC on silica gel plates that were developed twice in butan-1-ol/ethanol/water (5:3:2 v/v/v), after which radiolabeled material was detected by phosphorimaging, as detailed under "Experimental Procedures." Positions of nonradioactive standards are indicated. B, quantification of COs and chitin. Total amounts of COs in the material that was applied to the chromatogram in A and total amounts of 10% TCA-insoluble (TCA-insol) chitin remaining after chloroform/methanol/water extraction of the incubation mixtures from A were determined and plotted against UDP-GlcNAc concentration.
Primers of Oligosaccharide Synthesis by Chitin Synthase

FIGURE 2. Mass spectrometric analysis of COs made in the presence of GlcNAc. Membranes from YO1535 cts1Δ cells overexpressing CHS2 were incubated with 1.4 mM unlabeled UDP-GlcNAc, and pooled CO fractions generated in seven replicate incubations were chromatographed on activated charcoal-celite, concentrated, and submitted to MALDI-TOF mass spectrometry. Indicated masses are those of sodium adduct \([M + Na]^+\) ions.

The fact that incubations performed with 1.4 mM unlabeled UDP-GlcNAc yielded larger amounts of COs gave us an opportunity to isolate amounts of unlabeled COs sufficient for analysis by MALDI. The CO fraction from incubations of membranes from the CHS2-overexpressing strain carried out with 32 mM GlcNAc contained peaks whose masses correspond to those of the sodium adduct \([M + Na]^+\) ions of GlcNAc_2, GlcNAc_3, and GlcNAc_4 (Fig. 2), whereas the corresponding fraction from incubations with control strain YO1528 harboring only the chromosomal copy of CHS2 did not contain detectable peaks corresponding to these masses. This finding confirmed that the CO fraction from incubations containing 32 mM GlcNAc contained GlcNAc oligosaccharides whose formation is dependent on overexpression of CHS2. The CO fraction from incubations carried out without free GlcNAc contained insufficient material for analysis.

We also tested GlcNAc_2, GlcNAc_3, Glc, GlcN, GalNAc, and ManNAc for their effect on CO synthesis. GlcNAc_2 stimulated formation of material with the same chromatographic mobility as GlcNAc_2, as well as more polar COs with the same mobility as those made in the presence of GlcNAc (Fig. 3A, lanes 2 and 3; Fig. 3B, lanes 1 and 2). Inclusion of GlcNAc_2 in incubations led to formation of material with chromatographic mobilities similar to those of GlcNAc_4 and larger COs (Fig. 3B, lane 3) although recovery of COs was poor, possibly because of low solubility of GlcNAc_4 in the incubation mixture. In the presence of Glc, a small amount of material with a mobility between those of GlcNAc_2 and GlcNAc_3 was formed (Fig. 3A, lane 4), whereas GlcN (Fig. 3A, lane 5), GalNAc, and ManNAc were without effect. Stimulation of insoluble chitin synthesis by Glc but not by GlcN has been noted (13, 16). One possible explanation for the new material formed in the presence of Glc is that it is a disaccharide of GlcNAc and Glc. We also noted that when glycerol was present in high concentrations, it was a potential acceptor substrate for Chs2. The finding that GlcNAc_2 interacts with GlcNAc and larger COs, but not \([^{14}C]GlcNAc_2\) synthesis, raised the possibility that GlcNAc_2 could be either an activator of CO formation or as a priming substrate, but these possibilities were not distinguished if the masses of the reaction products were determined. However, if a GlcNAc analogue could substitute for GlcNAc, then only if that analogue were a GlcNAc acceptor would the mass of the product be determined. The availability of GlcNAc analogues, as well as GlcNAc_2, stimulated chitin formation in the standard assay for 10% TCA-insoluble chitin with the indicated concentrations of GlcNAc_2, GlcNPr, GlcNBu, and GlcNGc.

FIGURE 4. Stimulation of chitin synthesis by 2-acylamido-GlcNAc analogues. Chs2-overexpressing membranes were assayed for formation of 10% TCA-insoluble chitin in the presence of the indicated concentrations of GlcNAc_2, GlcNPr, GlcNBu, and GlcNGc.

makes negligible amounts of insoluble chitin (15, 19), contained no detectable radiolabeled COs, irrespective of whether free GlcNAc was included in the incubations or not. Further, the COs are unlikely to be generated postsynthetically by the action of yeast chitinase (a possibility raised by Kang et al. (9)) because deletion of the yeast endochitinase gene CTS1 in our overexpression host was without effect on CO formation.

FIGURE 3. Effects of GlcNAc_2, GlcNAc_3, glucose, and GlcN on CO formation. A, Chs2-overexpressing membranes that had been resuspended in buffer lacking glycerol were assayed for CO formation in the presence of 32 mM GlcNAc, GlcNAc_2, Glc, and GlcN as described for Fig. 1A. B, stimulation of CO formation by GlcNAc_1–3. Incubations were performed in the presence of 32 mM GlcNAc, GlcNAc_2, and GlcNAc_3 as described for A.
GlcNAc itself did. Further, GlcNPr, GlcNBu, and GlcNGc all stimulated formation of \(^{14}C\)-labeled species that resembled the ladder of COs made in the presence of GlcNAc, but whose chromatographic mobilities were systematically shifted in a manner consistent with the possibility that the analogues had been incorporated into COs (Fig. 5). MALDI analysis of the Dowex run-throughs containing material made in the presence of GlcNPr, GlcNBu, and GlcNGc confirmed this, revealing the presence of material with masses expected for sodium adduct \([M + Na]^+\) ions of disaccharides of each GlcNAc analogue and a single GlcNAc, and of material with masses expected for sodium adduct \([M + Na]^+\) ions of trisaccharides containing each GlcNAc analogue and GlcNAc\(_2\) (Figs. 6 and 7). Because the GlcNAc analogues had been incorporated into modified COs, they must have served as acceptors for GlcNAc transfer by Chs2. The finding that modified disaccharides were made (and indeed were a major product) indicates that Chs2 transferred a single GlcNAc from UDP-GlcNAc.

**DISCUSSION**

By focusing on the soluble products of the reaction carried out by yeast Chs2, we have obtained new insights into the synthetic capabilities of CSs. Our major findings are that (i) in vitro formation of COs by Chs2 is strongly dependent on free GlcNAc and the 2-acylamido GlcNAc analogues tested; (ii)
Primers of Oligosaccharide Synthesis by Chitin Synthase

Chs2 transfers GlcNAc from UDP-GlcNAc to the GlcNAc analogues GlcNPr, GlcNBu, and GlcNGc; and (iii) Chs2 can transfer single GlcNAc residues yielding a disaccharide as major product. Our results are the first direct evidence that a eukaryotic chitin synthase can use a low molecular weight primer. The formation of COs by yeast CSs has been documented (9, 12, 23), but in these studies, free GlcNAc was always included in the incubations, masking the extent to which the monomer stimulates CO formation. Because GlcNPr, GlcNBu, and GlcNGc all serve as GlcNAc acceptors, we propose that free GlcNAc, GlcNAc_{2}, and GlcNAc_{3} do as well.

Our findings suggest that at least part of the stimulatory effect of free GlcNAc on chitin synthesis may be because of its acting as an acceptor for GlcNAc transfer, but we cannot rule out the possibility that GlcNAc has an additional role as allosteric activator of CO and insoluble chitin synthesis. However, because GlcNAc_{2}, GlcNPr, GlcNBu, and GlcNGc did not stimulate formation of unmodified GlcNAc_{2}, or GlcNAc_{3}, a role as generic activator of CO synthesis would have to be restricted to GlcNAc itself.

Horsch et al. (16) used Mucor rouxii CS preparations and GlcNAc analogues to probe the structural requirements for activation and concluded that an aminoglucopyranose skeleton with an acylated amino group and a single-bonded oxo function at C-1 were necessary for the compound to act as an effector. These authors did not report whether the stimulatory GlcNAc analogues were incorporated into CS product. Our results with the 2-acylamido analogues of GlcNAc indicate that yeast Chs2 can use these analogues as acceptors and therefore that the enzyme tolerates bulkier substituents at C-2 of acceptor GlcNAc residues. Large groups at the C-6 position may also be tolerated because addition of 6-O-dansyl-GlcNAc to regenerating Candida albicans spheroplasts led to incorporation of this GlcNAc analogue into alkali-insoluble material (29), although it is not certain that a CS was directly involved.

It is not clear how GlcNAc-stimulated CO formation, the primer function of GlcNAc and its analogues, and GlcNAc-dependent stimulation of insoluble chitin synthesis are all related to the mechanism of chitin formation by Chs2 in vitro. We consider possible explanations in the context of processive and distributive mechanisms for polysaccharide polymerization.

The current model for the polymerization mechanism of glycosyltransferase family 2 polysaccharide synthases, which is based on the structure of Rhodobacter cellulose synthase BcsA, is for chain extension one sugar residue at a time with concomitant extrusion of the growing glycan chain through a channel created by the transmembrane domains of the enzyme (30). In the context of this processive model, the COs formed by Chs2 in the presence of GlcNAc may be generated as a result of premature chain termination (9), but alternatively, they may result from aberrant initiation in vitro. Thus, GlcNAc and its analogues may intrude into the catalytic site, compete with an enzyme-bound, nascent chitin chain, and prime CO formation, whereupon some COs dissociate from the enzyme, but others remain bound and are elongated, explaining the stimulatory effect of GlcNAc and its analogues on synthesis of both COs and insoluble chitin. This speculative explanation accommodates preliminary observations that the COs formed in pulse-chase experiments appeared stable (9) and leads to the prediction that average length of the in vitro Chs2 products formed in the presence of GlcNAc will be shorter than the product made in the absence of GlcNAc.

It is formally possible that Chs2 uses a distributive polymerization mechanism, in which the synthase disengages from its elongated product after every round of catalysis, then reassociates with a new acceptor and donor substrates for transfer of another monomer (31). In this case, free GlcNAc would also be expected to enhance CO formation.

The finding that GlcNAc stimulates CO and chitin synthesis in vitro is consistent with GlcNAc being the normal primer of de novo chitin synthesis, but we cannot exclude the possibility that in vitro, GlcNAc and its 2-acylamido analogues mimic an endogenous primer that is distinct from GlcNAc. If the latter is the case, this primer moiety should be present on the COs made in the absence of free GlcNAc, but because the amounts of COs made in these incubations are too small for analysis, it is not yet possible to determine whether these COs bear a terminal moiety different from GlcNAc. If free GlcNAc is indeed the in vivo primer, it would have to be generated by dephosphorylation of GlcNAc phosphates formed during UDP-GlcNAc synthesis or following hydrolysis of UDP-GlcNAc because the free sugar is not an intermediate in UDP-GlcNAc synthesis (32, 33).

Our findings were made with S. cerevisiae Chs2 and with membranes that had not been pretreated with protease, but we propose they apply to other CSs as well. However, CSs may differ in their relative abilities to use GlcNAc and its 2-acyl-
amido analogues as acceptors, as well as in the extent to which these compounds stimulate CO formation in vitro. Partial proteolysis may also impact the response of CSs to GlcNAc and its 2-acamilo analogues, as well as the size range of CS products.

Our results have implications for the mechanism of other β-linked polysaccharide synthases of glycosyltransferase family 2. The finding that Chs2 can transfer a single GlcNAc from UDP-GlcNAc is direct support for the conclusion drawn from the structure-based model for the bacterial cellulose synthase BcsA that spatial restrictions in the substrate binding site would allow cellulose extension by one, rather than two glucoses at a time (30). Kamst et al. (17) also concluded that the bacterial chitin synthase homologue NodC sequentially transferred monosaccharides during CO synthesis. The finding that the 2-acamiloamido position can tolerate modifications raises the possibility of introducing reactive groups at this position to tether acceptor residues. Further, CSs may prove able to use the UDP-derivatives of 2-acamiloamido GlcNAc analogues as substrates and generate chitin derivatives whose 2-acamilo side chains bear groups that confer novel properties.

Acknowledgments—We thank Steve Kim for assistance and J. Sweedler for discussions.

REFERENCES

1. Somervile, C. (2006) Cellulose synthesis in higher plants. Annu. Rev. Cell Dev. Biol. 22, 53–78
2. Weigel, P. H., and DeAngelis, P. L. (2007) Hyaluronan synthases: a decade plus of novel glycosyltransferases. J. Biol. Chem. 282, 36777–36781
3. Cantarel, B. L., Coutinho, P. M., Rancurel, C., Bernard, T., Lombard, V., and Henrissat, B. (2009) The Carbohydrate-Active EnZymes database (CAZY): an expert resource for glycogenomics. Nucleic Acids Res. 37, D233–238
4. Merzendorfer, H. (2011) The cellular basis of chitin synthesis in fungi and insects: common principles and differences. Eur. J. Cell Biol. 90, 759–769
5. Orlean, P. (2012) Architecture and biosynthesis of the Saccharomyces cerevisiae cell wall. Genetics 192, 775–818
6. Shaw, J. A., Mol, P. C., Bowers, B., Silverman, S. J., Valdivieso, M. H., Durán, A., and Cabib, E. (1991) The function of chitin synthases 2 and 3 in the Saccharomyces cerevisiae cell cycle. J. Cell Biol. 114, 111–123
7. Roncero, C. (2002) The genetic complexity of chitin synthesis in fungi. Curr. Genet. 41, 367–378
8. Ruiz-Herrera, J., González-Prieto, J. M., and Ruiz-Medrano, R. (2002) Evolution and phylogenetic relationships of chitin synthases from yeasts and fungi. FEMS Yeast Res. 1, 247–256
9. Kang, M. S., Elango, N., Mattia, E., Au-Young, J., Robbins, P. W., and Cabib, E. (1984) Isolation of chitin synthetase from Saccharomyces cerevisiae: purification of an enzyme by entrapment in the reaction product. J. Biol. Chem. 259, 14966–14972
10. Shurtle, A., and Cabib, E. (1986) Chitin synthetase 2, a presumptive participant in septum formation in Saccharomyces cerevisiae. J. Biol. Chem. 261, 15147–15152
11. Cabib, E., Kang, M. S., and Au-Young, J. (1987) Chitin synthase from Saccharomyces cerevisiae. Methods Enzymol. 138, 643–649
12. Orlean, P. (1987) Two chitin synthases in Saccharomyces cerevisiae. J. Biol. Chem. 262, 5732–5739
13. Keller, F. A., and Cabib, E. (1971) Chitin and yeast budding: properties of chitin synthetase from Saccharomyces carlsbergensis. J. Biol. Chem. 246, 160–166
14. Fühnrich, M., and Ahlers, J. (1981) Improved assay and mechanism of the reaction catalyzed by the chitin synthase from Saccharomyces cerevisiae. Eur. J. Biochem. 121, 113–118
15. Nagahashi, S., Sudoh, M., Ono, N., Sawada, R., Yamaguchi, E., Uchida, Y., Mio, T., Takagi, M., Arisawa, M., and Yamada-Okabe, H. (1995) Characterization of chitin synthase 2 of Saccharomyces cerevisiae: implication of two highly conserved domains as possible catalytic sites. J. Biol. Chem. 270, 13961–13967
16. Horsch, M., Mayer, C., and Rast, D. (1996) Stereochemical requirements of chitin synthase for ligand binding at the allosteric site for N-acetylglucosamine. Eur. J. Biochem. 237, 476–482
17. Kamst, E., Bakkers, J., Quaedvlieg, N. E., Pilling, J., Kijne, J. W., Lugtenberg, B. J., and Spink, H. P. (1999) Chitin oligosaccharide synthase by Rhizobia and zebrafish embryos starts by glycosyl transfer to O4 of the reducing terminal residue. Biochemistry 38, 4045–4052
18. Becker, H. F., Pilfleteau, A., and Thellend, A. (2011) Saccharomyces cerevisiae chitin biosynthesis activation by N-acetylglutathones depends on size and structure of chito-oligosaccharides. BMC Res. Notes 4, 454
19. Oh, Y., Chang, K. J., Orlean, P., Włoka, C., Deshaies, R., and Bi, E. (2012) Mitotic exit kinase Dbt2 directly phosphorylates chitin synthase Chs2 to regulate cytokinesis in budding yeast. Mol. Biol. Cell 23, 2445–2456
20. Baudin, A., Ozier-Kalogeropoulos, O., Denouel, A., Lacleu, F., and Culin, C. (1993) A simple and efficient method for direct gene deletion in Saccharomyces cerevisiae. Nucleic Acids Res. 21, 3329–3330
21. Kuranda, M. J., and Robbins, P. W. (1991) Chitinase is required for cell separation during growth of Saccharomyces cerevisiae. J. Biol. Chem. 266, 19758–19767
22. Bligh, E. G., and Dyer, W. J. (1959) A rapid method for total lipid extraction and purification. Can. J. Biochem. Physiol. 37, 911–917
23. Tanaka, T., Fujisawa, S., Nishikiri, S., Fukui, T., Takagi, M., and Imanaka, T. (1999) A unique chitinase with dual active sites and triple substrate binding sites from the hyperthermophilic archaeon Pyrococcus kodakaraensis KOD1. Appl. Environ. Microbiol. 65, 5338–5344
24. Redmond, J. W., and Packer, N. H. (1999) The use of solid-phase extraction with graphited carbon for the fractionation and purification of sugars. Carbohydr. Res. 319, 74–79
25. Kristova, V., Martinkova, L., Husakova, L., Kuzma, M., Rauvolfova, J., Kavan, D., Pompa, P., Bezouska, K., and Kren, V. (2005) A chemoenzymatic route to mannosamine derivatives bearing different N-acyl groups. J. Biotechnol. 115, 157–166
26. Jourdian, G. W., and Rosen, S. (1962) The sialic acids. II. Preparation of N-glycolylhyoxaminos, N-glycolylhyoxaminose-6-phosphates, glycolyl coenzyme A, and glycolyl glutathione. J. Biol. Chem. 237, 2442–2446
27. Lubineau, A., Augé, C., Gauntheron-Le Narvor, C., and Ginet, J. C. (1994) Combined chemical and enzymatic synthesis of the sialylated nonreducing terminal sequence of GM1glycolylated ganglioside, a potential human tumor marker. Bioorg. Med. Chem. 2, 669–674
28. Yabe, T., Yamada-Okabe, T., Nakajima, T., Sudoh, M., Arisawa, M., and Yamada-Okabe, H. (1998) Mutational analysis of chitin synthase 2 of Saccharomyces cerevisiae: identification of additional amino acid residues involved in its catalytic activity. Eur. J. Biochem. 258, 941–947
29. Carrano, L., Tavecchia, P., Sponza, F., and Speacock, F. (1997) Dansyl-N-acetyl glucosamine as a precursor of fluorescent chitin: a method to detect fungal cell wall inhibitors. J. Antimicrob. Chemother. 50, 177–179
30. Morgan, J. L., Strumillo, J., and Zimmer, J. (2013) Structure of a bacterial cellulose synthase complex: crystallographic snapshot of cellulose synthesis and membrane translocation. Nature 493, 181–186
31. Levengood, M. R., Splain, R. A., and Kissing, L. L. (2011) Monitoring processivity and length control of a carbohydrate polymerase. J. Am. Chem. Soc. 133, 12758–12766
32. Cabib, E. (1987) The synthesis and degradation of chitin. Adv. Enzymol. Relat. Areas Mol. Biol. 59, 59–101
33. Milewski, S., Gabriel, I., and Olchowy, J. (2006) Enzymes of UDP-GlcNAc biosynthesis in yeast. Yeast 23, 1–14