

Production of geranylgeraniol on overexpression of a prenyl diphosphate synthase fusion gene in *Saccharomyces cerevisiae*

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Abstract An acyclic diterpene alcohol, (*E,E,E*)-geranylgeraniol (GGOH), is one of the important compounds used as perfume and pharmacological agents. A deficiency of squalene (SQ) synthase activity allows yeasts to accumulate an acyclic sesquiterpene alcohol, (*E,E*)-farnesol, in their cells. Since sterols are essential for the growth of yeasts, a deficiency of SQ synthase activity makes the addition of supplemental sterols to the culture media necessary. To develop a GGOH production method not requiring any supplemental sterols, we overexpressed *HMG1* encoding hydroxymethylglutaryl-CoA reductase and the genes of two prenyl diphosphate synthases, *ERG20* and *BTS1*, in *Saccharomyces cerevisiae*. A prototrophic diploid coexpressing *HMG1* and the *ERG20-BTS1* fusion accumulated GGOH with neither disruption of the SQ synthase gene nor the addition of any supplemental sterols. The GGOH content on the diploid cultivation in a 5-l jar fermenter reached 138.8 mg/l under optimal conditions.

Keywords Geranylgeraniol · Mevalonate pathway · Hydroxymethylglutaryl-CoA reductase · Prenyl diphosphate synthase · Yeast recombinant

Introduction

An acyclic diterpene alcohol, (*E,E,E*)-geranylgeraniol (GGOH), is known to be a fragrant constituent of essential oils. It has been used not only as one of the important ingredients in perfumes, but also as a valuable material for the chemical synthesis of pharmacological agents and hydrophobic vitamins such as vitamins A and E (Benford et al. 1999; Hyatt et al. 2002). The diphosphate derivative of GGOH, (*E,E,E*)-geranylgeranyl diphosphate (GGPP), is a significant intermediate in the early stage of carotenoid biosynthesis, particularly in plant cells. Although there are eight geometric isomers of GGPP as to the combination of the *E/Z* conformation at three carbon–carbon double bonds, only the (*E,E,E*)-isomer exhibits significant biological activity (Ogura and Koyama 1998). The chemical synthesis of GGOH has been difficult because of the introduction of three *E* double bonds into the isoprenoid structure. Although, in the last few years, the chemical synthesis for (all-*E*)-prenyl alcohols has been performed with relatively high yields (Negishi et al. 2002; Yu et al. 2005), metabolic engineering still exhibits greater potential as to an efficient production of (all-*E*)-prenyl alcohols because living cells accomplish a variety of simultaneous reactions with specific stereo-specificities. We previously reported that a recombinant *Saccharomyces cerevisiae* overexpressing the genes encoding the enzymes in the mevalonate pathway could produce 145.7 mg/l of (*E,E*)-farnesol (FOH), suggesting that the yeast has phosphatase activity that converts prenyl diphosphates into prenyl alcohols (Ohto et al.

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2009b). But, it was unclear whether GGPP could be similarly dephosphorylated and secreted into the extracellular fraction to be easily extracted with organic solvent without cell disruption.

In all organisms, GGPP is synthesized through an enzymatic condensation reaction of allylic diphosphates such as dimethylallyl diphosphate, (*E*)-geranyl diphosphate, and (*E,E*)-farnesyl diphosphate (FPP) with isopentenyl diphosphate(s). Since two FPPs are also head-to-head condensed to produce squalene (SQ), which is an intermediate during sterol biosynthesis, GGPP biosynthesis would compete with SQ biosynthesis for FPP (Fig. 1). SQ accumulates intracellularly due to overexpression of a 3-hydroxy-3-methylglutaryl-CoA reductase gene (*HMG1*), this enzyme being one of the rate-limiting enzymes in the mevalonate pathway (Donald et al. 1997). Chambon et al. reported that a sterol-auxotrophic yeast deficient in the SQ synthase gene could produce 0.74–1.3 mg/l of FOH in a culture (Chambon et al. 1990; Chambon et al. 1991). The addition of an inhibitor of SQ synthase allowed yeasts to produce FPP and FOH, but not a sufficient amount of GGOH (Bergstrom et al. 1993; Muramatsu et al. 2008b). Recently, with both SQ synthase and phytoene synthase inhibitors, a carotenoid-producing yeast *Rhodotorula rubra* IFO 0870 could produce 53.7 mg/l of GGOH (Muramatsu et al. 2008b). The overexpression of an isopentenyl

diphosphate delta-isomerase gene and a mutated FPP synthase one in *Escherichia coli* led to the accumulation of 0.13 mg/l GGOH in the cells (Ohto et al. 2009a). In the present study, a recombinant yeast overexpressing the genes encoding enzymes involved in the mevalonate pathway led to the production of GGOH without the addition of any supplemental sterols. In particular, the coexpression of *HMG1* and a prenyl diphosphate synthase fusion gene was effective for the production of GGOH by *S. cerevisiae*.

Materials and methods

Strains

S. cerevisiae strains A451 (ATCC 200589) was purchased from the ATCC (American Type Culture Collection, Manassas, VA). AURGG101, which comprises A451 bearing AUR1-C, was previously described (Ohto et al. 2009b). YPH499 (ATCC 76625) and YPH500 (ATCC 76626) were purchased from Stratagene (La Jolla, CA).

Construction of YEp expression vectors

YEp (multicopy-type) expression vectors were constructed from pRS vectors (Stratagene) and pYES2 (Invitrogen,

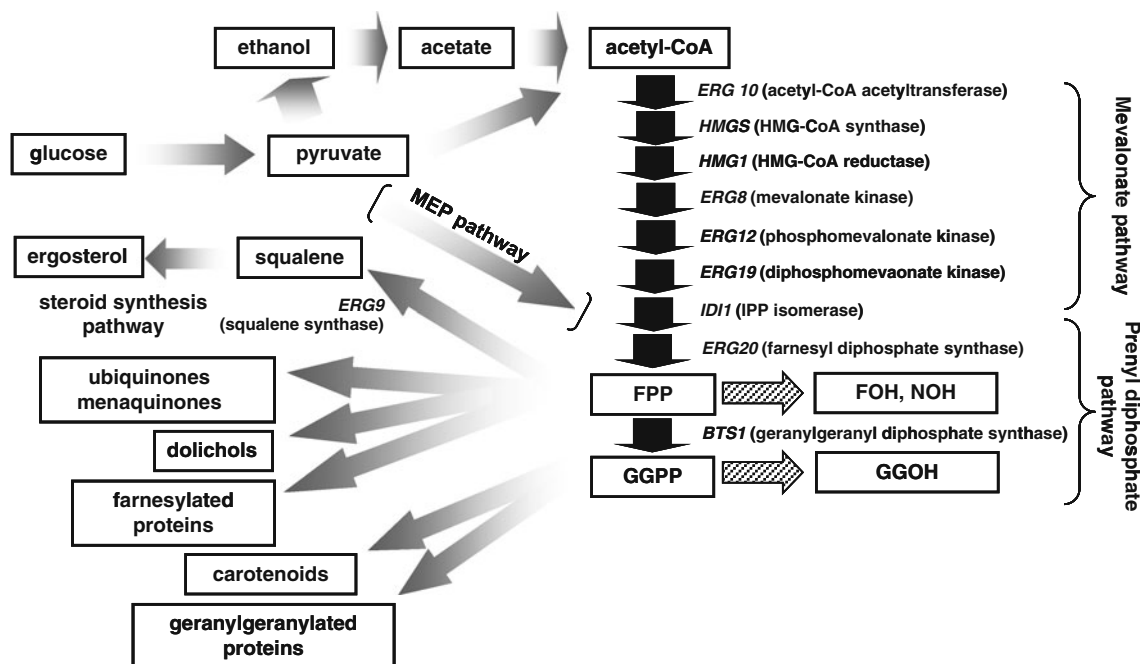


Fig. 1 Isoprenoids biosynthesis pathway. Black arrows indicate the sequence of enzyme reactions. The corresponding genes were cloned from *S. cerevisiae* and overexpressed in this study. The MEP (methylerythritol phosphate) pathway and the mevalonate pathway are known for isopentenyl diphosphate (C5 isoprenoid) synthesis. The MEP pathway is a prokaryotic pathway in bacteria and some

unicellular eukaryotes. The mevalonate pathway is the only route to C5 isoprenoid in animals, plants (except plastids), archaea, and fungi including *S. cerevisiae*. FPP, (*E,E*)-farnesyl diphosphate; FOH, (*E,E*)-farnesol; NOH, (*E*)-nerolidol; GGPP, (*E,E,E*)-geranylgeranyl diphosphate; GGOH, (*E,E,E*)-geranylgeraniol

Carlsbad, CA), as previously reported (Ohto et al. 2009b). The nucleotide sequences of these vectors are available under DDBJ accession No. AB304849–AB304876.

Preparation of episome DNA constructs for overexpression

Using the primer DNA pairs shown in Fig. 2, the farnesyl diphosphate synthase gene (*ERG20*) and the geranylgeranyl diphosphate synthase gene (*BTS1*) were amplified by PCR from pT7-*ERG20* and pYES-GGPS (Ohto et al. 2009b), respectively, ligated at the *Eco*O109I sites to prepare *ERG20* and *BTS1* fusion genes, and then inserted into pRS435GAP (DDBJ accession No. AB304858) and pRS445GAP (AB304870). The names and nucleotide sequences of the primers are as follows: SacII-BTS1, 5'TCC CCG CGG ATG GAG GCC AAG ATA GAT3'; BTSI-XhoI, 5'CAA CTC GAG TCA CAA TTC GGA TAA GTG3'; BTSI-109I, 5'GCA GGG ACC CCA ATT CGG ATA AGT GGT C3'; 109I-BTS1, 5'GTA GGG TCC CTG GAG GCC AAG ATA GAT G3'; *ERG20*-109I, 5'GCA GGG ACC CTT TGC TTC TCT TGT AAA CT3'; 109I-*ERG20*, 5'GTA GGG TCC TCA GAA AAA GAA ATT AGG AG3'; -21, 5'TGT AAA ACG ACG GCC AGT3'; and T7, 5'TAA TAC GAC TCA CTA TAG GG3'. The names of the resultant episome DNAs harboring the fusion genes are shown in Fig. 2. The episome DNAs for overexpression of other wild-type genes were described previously (Ohto et al. 2009b).

Culture conditions for episome DNA-harboring yeasts

The transformants with episome DNAs were selected on agar plates of SD medium (BIO101, Vista, CA) lacking the specified amino acids as to the auxotrophic markers at 30 °C. They were cultivated in 2.5 ml aliquots of YM7 or YMO

medium in glass tubes by rotary shaking at 130 rpm at 30 °C. YM7 medium comprises the YM broth (Becton, Dickinson and Company, Franklin Lakes, NJ) adjusted to pH 7.0 with NaOH, and YMO comprises YM7 including 3.0% (w/v) soybean oil (Nacalai Tesque, Kyoto, Japan).

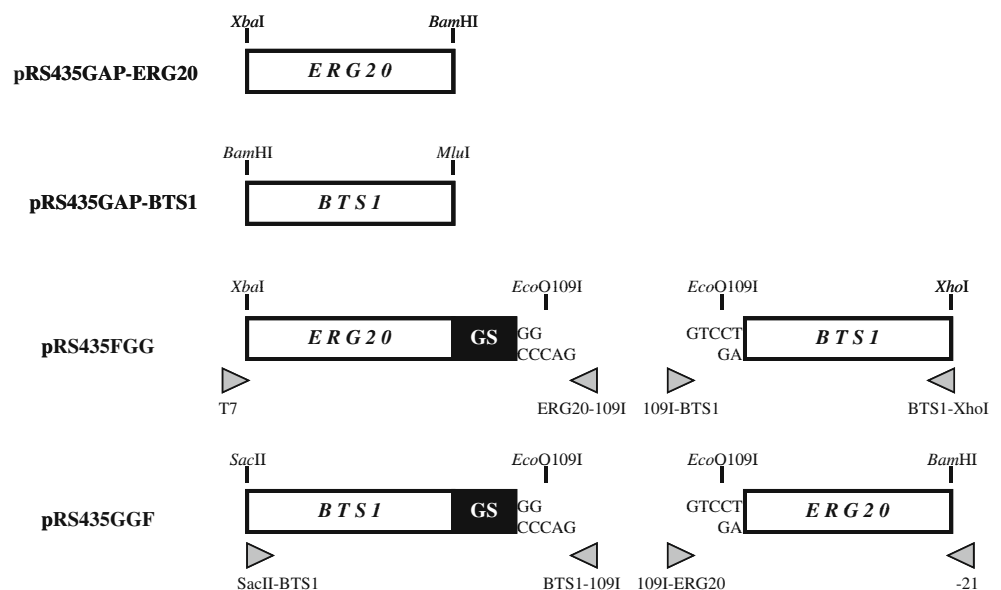
Construction of a diploid recombinant strain

DNA fragments of the *ADE2*, *HIS3*, *LYS1*, and *URA3* coding regions were prepared by PCR from YPH499 genomic DNA based on the sequence in the *S. cerevisiae* genome database. The *ADE2* and *HIS3* fragments were introduced into YPH499-originating recombinants using a medium lacking adenine and histidine, and the *LYS1* and *URA3* fragments were introduced into YPH500 using a medium lacking lysine and uracil. The resultant YPH499 recombinant bearing *ADE2* and *HIS3*, named YPH499-AH, and the YPH500 one bearing *LYS1* and *URA3*, named YPH500-KU, were mated on a minimum SD plate to produce diploid prototrophs.

Preparation of DNA, RNA and crude enzyme

The yeast transformants were cultivated in 100 ml aliquots of SD or SG medium and then cultured in 300-ml Erlenmeyer flasks at 26 °C with reciprocal shaking at 120 times/min. The cultivation was finished when OD₆₀₀ reached around 3–4 (corresponding to 23–53 h), followed by the preparation of DNA, RNA, and a crude enzyme solution. The yeast genomic DNA and total RNA were prepared according to the standard procedures. For the preparation of crude enzyme solutions, cells were harvested by centrifugation, disrupted at 4 °C with glass beads and then suspended in sterilized water. Each suspension was

Fig. 2 Typical constructs of prenyl diphosphate synthase and those fusion genes. *ERG20* and *BTS1* were fused at the *Eco*O109I site added by means of PCR with primers (gray triangles) and then inserted into the pRS435GAP expression vector. *ERG20*, farnesyl diphosphate synthase gene; *BTS1*, geranylgeranyl diphosphate synthase gene; *GS*, glycine-serine residues



centrifuged at 12,000 rpm at 4 °C for 10 min, and the resultant supernatant was used for the enzyme assay. Protein concentrations were determined with Protein Assay (Bio-Rad, Hercules, CA).

Northern blot hybridization

Probes for Northern blot hybridization were prepared with a PCR DIG Probe Synthesis Kit (Roche Diagnostics, Mannheim Germany) using the templates and primer pairs listed in Table 1. The templates for pT7ERG20, pYESGGPS, and pYHMG1 were described previously (Ohto et al. 2009b). As a control probe, the coding region of the α -tubulin gene, *TUB1*, was amplified from YPH499 genomic DNA and prepared as a DIG-labeled probe in the same way. Five milligrams of yeast total RNA per lane was subjected to electrophoresis on a formaldehyde-denaturated agarose gel, followed by transfer to a Hybond N nylon membrane (GE Healthcare Ltd, Amersham Place, UK), and cross-linked to it according to a conventional method. Northern blot hybridization was carried out with 100 ng/ml probe DNA at 50 °C for 24 h according to the standard protocol for a DIG Easy Hyb Kit (Roche Diagnostics). The signals were detected as chemiluminescence using a DIG Luminescent Detection Kit (Roche), followed by exposure of the blot to X-ray film.

Prenyl alcohol production in a jar fermenter

The yeast transformants were inoculated from slants into 200 ml aliquots of DOB-based selection medium (BIO101) in 500-ml Erlenmeyer flasks with baffle plates and cultured at 30 °C for 30 h with shaking at 120 rpm. Ten milliliters of the resultant culture was inoculated into 5 l of medium comprising 300 g of glucose, 100 g of yeast extract, 100 g of bactopectone, 550 g of soybean oil, and 5 ml of Adekanol LG109 (Adeka, Tokyo Japan). The operational conditions were as previously given (Ohto et al. 2009b). Two milliliters of the culture broth was periodically taken, and the concentrations of glucose, ethanol, and acetate were determined as previously reported (Muramatsu et al. 2008b). Cell density was measured by directly counting

cells in diluted broth on a hematoplate under a phase-constant microscope.

Extraction of prenyl alcohols and GC/MS analysis

To 2.5 ml of a main culture, 2.5 ml of methanol was added, followed by thorough mixing. Five milliliters of pentane was added to the mixture, followed by vigorous agitation. After standing for a few minutes, the pentane layer was transferred to a new glass tube for analysis by GC/MS (Ohto et al. 2009b).

Results

Prenyl alcohol production by the recombinants overexpressing the genes of the enzymes in the mevalonate and prenyl diphosphate pathways under the control of the *TDH3* promoter

In order to determine the effects of genes related with the mevalonate and prenyl diphosphate biosynthesis for GGOH production, each gene was introduced individually into *S. cerevisiae* YPH499 by means of pRS434GAP (AB304854) and pRS435GAP (AB304858), which were YE_p vectors bearing the *TDH3* promoter that is constitutively active. Although pRS434GAP was used for the expression of *HMG1* and pRS435GAP for other genes, these vectors have almost the same sequences except for the selection marker (*TRP1* and *LEU2*, respectively). Pronounced FOH production was observed on the overexpression of *HMG1* among the nine genes responsible for prenyl alcohol production, whereas GGOH increased in amount on overexpression of *BTS1*, *HMG1* and *ERG20*, in that order (Fig. 3). The YE_p vector elevated the productivity of GGOH 5-fold compared with the YI_p vector (data not shown).

Overexpression of a *ERG20* and *BTS1* fusion gene

The PCR fragments of *ERG20*, *BTS1*, the *BTS1-ERG20* fusion gene, and the *ERG20-BTS1* fusion gene were

Table 1 Hybridization probes for Northern blot hybridization

Probe no.	Target gene	Template	Primer 1 ^a	Primer 2 ^b
I	<i>ERG20</i>	pT7ERG20	SCFPS1	SCFPS2
II	<i>BTS1</i>	pYESGGPS	BTS1(1–21)	BTS1(1008–982)
III	<i>HMG1</i>	pYHMG1	HMG1(1267–1293)	HMG1(2766–2740)

^a BTS1(1–21), 5'ATG GAG GCC AAG ATA GAT GAG3'; HMG1(1267–1293), 5'AAC TTT GGT GCA AAT TGG GTC AAT GAT3'; SCFPS1, 5'ATG GCT TCA GAA AAA GAA ATT AG3'

^b BTS1(1008–982), 5'TCA CAA TTC GGA TAA GTG GTC3'; HMG1(2766–2740), 5'TCC TAA TGC CAA GAA AAC AGC TGT CAC3'; SCFPS2, 5'CTA TTT GCT TCT CTT GTA AAC TT3'

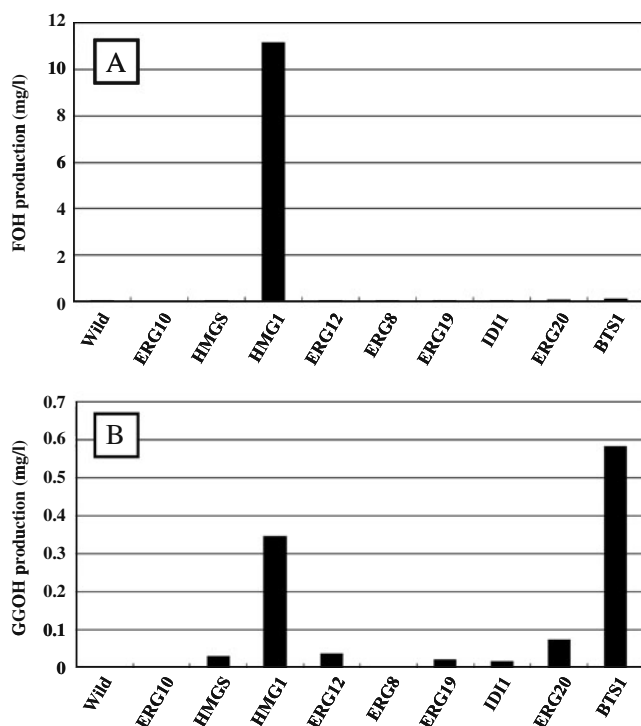


Fig. 3 FOH and GGOH production by recombinants overexpressing genes in the mevalonate and prenyl diphosphate pathways. The FOH (a) and GGOH (b) production by the recombinants of the YPH499 strain overexpressing *HMG1* and other genes with pRS435GAP. The enzyme genes (*ERG10*, *HMG5*, *HMG1*, *ERG12*, *ERG8*, *ID11*, *ERG20*, and *BTS1*) correspond to those in Fig. 1. *Wild* indicates the YPH499 wild type as a control strain. The recombinants were cultivated in glass tubes containing 2.5 ml of YM7 medium with shaking (130 rpm) at 30 °C for 7 days

inserted into the multiple cloning sites of the YEp vector of pRS435, which is located between the *TDH3* promoter and the *CYC1* terminator, to prepare pRS435GAP-*ERG20*, pRS435GAP-*BTS1*, pRS435GGF, and pRS435FGG, respectively, followed by transformation into *S. cerevisiae* YPH499. As shown in Fig. 2, the two amino acid linker sequence of Gly-Ser between the two prenyl diphosphate synthases was designed for the fusion of their enzymes. The fusion genes are supposed to lead the formation of a fused protein comprised of the *BTS1* and the *ERG20*. Although the host strain and the recombinant pRS435GAP-*ERG20*/YPH499 produced little GGOH in the culture broth, the overexpression of *BTS1* was an effective means of enhancing GGOH production. This effect was remarkably observed on fusion with the *ERG20* gene synergistically, being particularly higher, eight-fold, on fusion with *ERG20* at 6 bp downstream from *BTS1* (pRS435GGF) compared with *BTS1* alone (pRS435GAP-*BTS1* in Fig. 4).

We further introduced this effective episome of pRS435GGF for GGOH production into SQ-overproducing strain pRS435GAP-*HMG1*/YPH499 (Ohto et al. 2009b). The expression of the *BTS1-ERG20* fusion gene and *HMG1* was

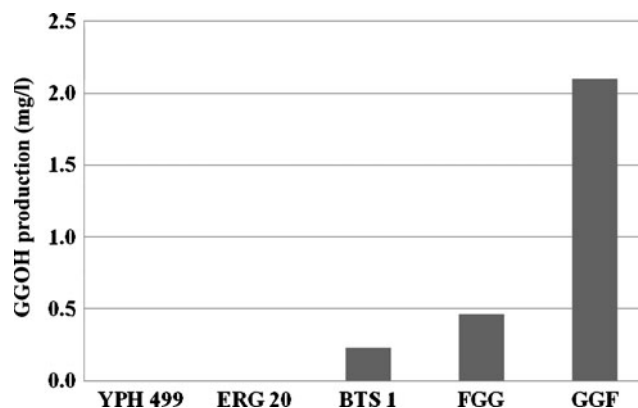


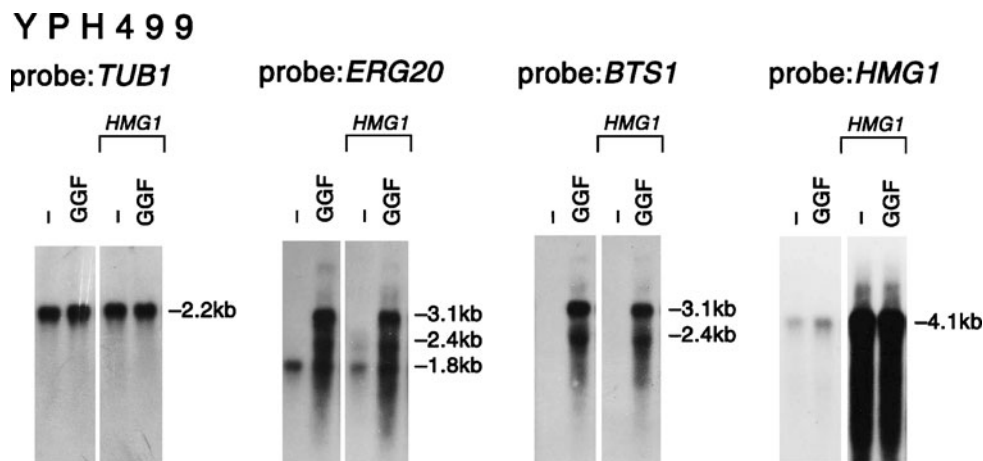
Fig. 4 GGOH production by recombinants. The recombinants were cultivated in glass tubes containing 2.5 ml of YM7 medium with shaking (130 rpm) at 30 °C for 7 days. *YPH499*, host strain; *ERG20*, pRS435GAP-*ERG20*/YPH499; *BTS1*, pRS435GAP-*BTS1*/YPH499; *FGG*, pRS435FGG/YPH400; *GGF*, pRS435GGF/YPH499

confirmed by Northern blot hybridization, where the probe hybridizing to the α -tubulin gene, *TUB1*, was used as a control (Fig. 5). Using the probes of *ERG20* and *BTS1*, strong signals of 3.1 kb were detected for pRS435GGF/YPH499 and pRS435GGF/pRS434GAP-*HMG1*/YPH499 harboring the *BTS1-ERG20* fusion gene. *HMG1* was also confirmed to be overexpressed in the recombinants having pRS434GAP-*HMG1*. With YPH499 as the host strain, considerably strong *ERG20* expression was observed, but a *BTS1* transcript was not detected. The recombinant overexpressing three effective components (*BTS1*, *ERG20*, and *HMG1*) was used as a promising producer for GGOH production in a jar fermenter.

Jar fermenter production

Prototrophic cells generally exhibit tolerance to environmental stresses such as osmotic pressure, alcohol and other chemical compounds. pRS435GGF/pRS434GAP-*HMG1*/YPH499 was transformed with supplementary genes (*ADE2* and *HIS3*) and then mated with YPH500-KU bearing *LYS1* and *URA3* to generate a prototroph diploid of pRS435GGF/pYESHMG044/YPH501-AHKU, designated as the GGOH strain. The important factors (cell growth rate in the logarithmic phase and cell density in the stationary phase) for the commercial production of GGOH improved with the disappearance of each nutrient requirement marker (data not shown). As the GGOH strain showed the best GGOH production (8.3 mg/l) in a test tube containing YMO medium, it was cultivated in a 5-l jar fermenter with sufficient aeration and glucose as a carbon source for GGOH production (Fig. 6). After prolonged fermentation for 133.5 h, the GGOH and SQ production reached 138.8 mg/l and 60.0 mg/l, respectively. Other prenol alcohol production was negligible during the whole

Fig. 5 Northern blot hybridization. In each panel, the four lanes contain YPH499 wild type (–), pRS435GGF/YPH499 (*GGF*), pRS434GAP-*HMG1*/YPH499 (*HMG1*, –), and pRS435GGF/pRS434GAP-*HMG1*/YPH499 (*HMG1*, *GGF*). The sizes of fragments were determined with RNA ladder marker (Nippon Gene, Tokyo, Japan). The recombinants were cultivated in glass tubes containing 2.5 ml of YM7 medium with shaking (130 rpm) at 30 °C for 3 days



fermentation. The FOH production reached a maximal level of 2.09 mg/l at 61.5 h, and gradually decreased thereafter.

Discussion

Having three carbon atoms yielding 16 geometrical isomers, time-consuming purification steps are inevitable for the chemical synthesis of GGOH. In contrast, for short-chain prenyl diphosphates having not more than 20 carbon atoms, organisms are able to synthesize all-*E* isomers through type I prenyl transferases (Ogura and Koyama 1998). Hence, we anticipated that a fermentation process comprising the synthesis of all-*E* prenyl diphosphate isomers would be highly advantageous for chemical synthesis, especially for that of geranylgeranyl diphosphate, which has four carbon–carbon double bonds. Although the metabolic pathway for GGPP has been revealed in various organisms (Fig. 1), it has so far been difficult to establish overproduction technology based on biochemical pathways

(Barkovich and Liao 2001; Ohto et al. 2009a). The low activity of GGPP synthase in *S. cerevisiae* is a crucial problem for GGOH production because GGPP is supposed to be utilized only as an isoprenoid moiety of geranylgeranylated proteins, and FPP, one of the substrates for GGPP synthase, is converted into various compounds, mainly into SQ (Fig. 1).

Co-overexpression of *BTS1* in the YIp vector and *HMG1* in the YEep vector for GGOH overproduction was ineffective compared to the overexpression of *HMG1* in the YEep vector in *S. cerevisiae* A451 for FOH overproduction, as previously reported (Ohto et al. 2009b). Then, we introduced all mevalonate pathway and the prenyl diphosphate pathway-related genes into YEep expression vectors that are maintained as multicopy vectors. Overexpression of *BTS1* and *HMG1* resulted in a more effective production of GGOH, and the YEep vector proved to be superior to the YIp vector for GGOH production (Fig. 3). It was interesting that the overexpression of *ERG20* would be the third significant factor for GGOH production, regardless of the high level expression in wild-type cells. The enzyme encoded by *BTS1* catalyzes the condensation of FPP and isopentenyl diphosphate into GGPP, but is incapable of utilizing C5-allylic diphosphate substrates (Jiang et al. 1995). A supply of FPP depending upon the expression of *ERG20* must be inevitable for GGOH overproduction.

It was reported that type I prenyl diphosphate synthases retain sufficient activity as fusion proteins with maltose binding protein and glutathione S-transferase (Ohto et al. 1998). Based on this information, we designed fusions of *ERG20* and *BTS1* and found that the overexpression of the *BTS1*-*ERG20* fusion gene was the most effective among the single or fused genes of prenyl diphosphate synthases we had tested (Fig. 4). Before this study, some natural fused genes had been known for diterpenoid biosynthesis. In the first stage of carotenoid biosynthesis, it was reported that a single gene coded for a protein with both activities of

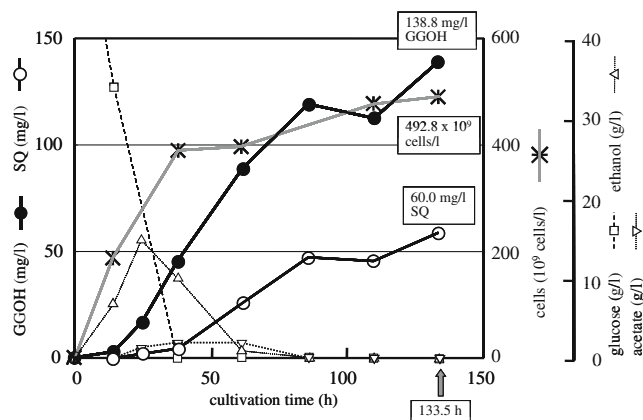


Fig. 6 Five liter jar fermenter cultivation of the GGOH strain. The culture conditions are given under Materials and Methods

prephytoene diphosphate synthase and phytoene synthase (Velayos et al. 2000). The formation of a gibberellic acid skeleton in fungi is achieved through a bifunctional diterpene cyclase comprising two domains, ent-copalyl diphosphate synthase responsible for cyclization of GGPP and ent-kaurene synthase (Kawaide 2006). Moreover, there has been an attempt to produce capsidiol using an artificial fusion gene of FPP synthase and sesquiterpene cyclase. The amount of epi-aristolochene produced by the fused enzyme was considerably higher than that by a mixture of the two wild type enzymes (Brodelius et al. 2002). The present data also show that the fused enzyme, which is involved in more than two successive enzymatic reactions in a metabolic pathway, enhances the production of hydrophobic compounds in an aqueous environment. The adjacency of two active sites would be convenient for preventing the first product from diffusing into the aqueous solution as small particles before the next enzymatic reaction, and the fused protein might be more stable in the recombinant strain.

Because of the ability of soybean oil to improve prenyl alcohol productivity (Muramatsu et al. 2008a), we cultivated the diploid prototroph bearing *HMG1* and the *BTS1-ERG20* fusion gene in the optimized medium. A diploid prototroph are commercially attractive for a high growth rate shortening the cultivation period, alcohol tolerant, and broad selectivity as to medium, leading to a low cost. The maximal production of GGOH here (138.8 mg/l) is a significant value compared with other terpenoids produced by recombinants, such as limonene (5 mg/l), taxadiene (1.3 mg/l), and lycopene (22 mg/l) (Carter et al. 2003; Huang et al. 2001; Kim and Keasling 2001).

This is the first report on the overproduction of GGOH by a microorganism. It had so far been difficult to overproduce hydrophobic terpenoids including GGOH with metabolically engineered microorganisms. However, the prospects are bright because the fusion gene of *BTS1-ERG20* showed such impressive ability. Further investigation of the on expression of other genes involved in the mevalonate and prenyl diphosphate pathways is necessary, and the difference between multicopy genome integration and episome retention has to be elucidated for the improvement of GGOH production.

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