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Chemoenzymatic Assembly of Isotopically Labeled Folates

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Supporting Information

ABSTRACT: Pterin-containing natural products have diverse functions in life, but an efficient and easy scheme for their in vitro synthesis is not available. Here we report a chemoenzymatic 14-step, one-pot synthesis that can be used to generate $^{13}$C- and $^{15}$N-labeled dihydrofolates (H$_2$F) from glucose, guanine, and p-aminobenzoic acid (p-ABA). This synthesis stands out from previous approaches to produce H$_2$F in that the average yield of each step is $>$91% and it requires only a single purification step. The use of a one-pot reaction allowed us to overcome potential problems with individual steps during the synthesis. The availability of labeled dihydrofolates allowed the measurement of heavy-atom isotope effects for the reaction catalyzed by the drug target dihydrofolate reductase and established that protonation at N5 of H$_2$F and hydride transfer to C6 occur in a stepwise mechanism. This chemoenzymatic pterin synthesis can be applied to the efficient production of other folates and a range of other natural compounds with applications in nutritional, medical, and cell-biological research.

INTRODUCTION

Pterin is a common motif found in natural products. Folate, the essential vitamin that fuels the one-carbon cycle for the biosynthesis of nucleotide and amino acid building blocks, was one of the first natural products found to contain pterin. The metabolic importance of pterins is illustrated by their integration into enzyme cofactors such as molybdopterin and tetrahydrobiopterin. Pterin natural products are also used as pigments in the butterflies Catopsilia argante and Appias nero, whereas bioterpins-$\alpha$-glucoside serves as a natural sunscreen for photosynthetic cyanobacteria.

$^{6,7,8}$-Tetrahydrofolic acid (H$_4$F), which in addition to the pterin ring system contains $p$-aminobenzoic acid (p-ABA) and $l$-glutamic acid (Glu), is required for the biosynthesis of metabolites that are key for cell survival and replication. A one-carbon unit in different oxidation states can be added at N5 and/or N10 of H$_4$F and used to produce metabolites such as thymidylate, purines, glycine, serine, and $S$-adenosylmethionine (SAM) (Figure 1). Because of the central importance of folate biochemistry for cell replication and survival, dihydrofolate reductase (DHFR), thymidylate synthase (TS), and serine hydroxymethyltransferase (SHMT) have long been exploited as important drug targets in the treatment of bacterial infections, malaria, and cancer, and the DHFR-targeting drugs trimethoprim, proguanil, pyrimethamine, and methotrexate are listed as essential medicines by the World Health Organization (WHO). Nevertheless, as with many clinically used drugs, resistance to antifolates has begun to emerge, and investigation of the enzymes of the one-carbon cycle is an important part of inhibitor design strategies.

Detailed mechanistic insight into enzyme-catalyzed reactions is often obtained by isotopic labeling and measurement of kinetic isotope effects (KIEs) or spectroscopic analysis. Information derived from regio- and stereospecific substrate labeling has been used to design inhibitors with dissociation constants in the micro- to picomolar range. However, the use of these techniques to investigate folate-dependent enzymes is hindered by the absence of a general and efficient method to specifically label atoms of the pterin ring system, particularly at N5, C6, C7, and C9, which are directly linked to the chemistry of the catalyzed reactions. Folate and its derivatives can be synthetized by connecting the pterin, p-ABA, and glutamate groups in sequential order, and several synthetic strategies to incorporate an isotopic label into pterin in a regiospecific manner have been reported. Pterins have been synthesized by condensing guanidine or dihydroxyacetone with the respective heterocyclic starting materials, and N5-, C2-, and C6-labeled folates have been made previously. However, because symmetric...
reagents are used in these syntheses, regioselective isotope labeling of C7 and C9 cannot easily be achieved.28,30 In all cases, the yields of labeled folate or derivatives are low (<5% overall yield), and the procedures depend on multiple purification steps. Chemoenzymatic strategies have also been described,31−33 whereby H4F was condensed with 11C-formaldehyde or 14C-formic acid to yield the corresponding isotopically labeled [11C]5,10-methylene-H4F, [14C]5-formyl-H4F, and [14C]10-formyl-H4F. However, a general and efficient method to label the pterin ring in folates has never been developed.

In nature, the pterin ring in folate is formed from guanosine triphosphate (GTP) in one biochemical step catalyzed by GTP cyclohydrolase (GTP-CH),34,35 an enzyme found in all kingdoms of life ranging from archaeabacteria, insects, plants to humans. In all GTP-CH-catalyzed reactions, GTP is converted to a pterin via a set of tandem reactions that have no equivalent in organic chemistry. GTP cyclohydrolase I (GTP-CH-I) catalyzes the formation of 7,8-dihydroneopterin triphosphate (DHNTP) from GTP by mediating four distinct chemical reactions (Figure S1): hydrolysis of the purine ring yielding an N-formyl intermediate, N-deformylation, a stereospecific Amadori rearrangement of the ribose moiety, and ring closure to form the pterin.36−38 Because no symmetric reagent is used in this reaction, GTP-CH-I can be used to synthesize the pterin ring system of folate with heavy isotopes incorporated regio- and stereoselectively.39 It is therefore surprising that GTP-CH-I has not been used in any in vitro enzymatic pathway to synthesize folates. Perhaps the low catalytic turnover (kcat = 0.05 s−1)40 and the rather low stability of the product 7,8-dihydroneopterin toward oxygen and light have limited the use of GTP-CH-I in synthesis.

Here we report a 14-step one-pot chemoenzymatic synthesis of 7,8-dihydrofolic acid (H2F) that exploits the well-established procedures to isotopically label GTP39,42,43 by using GTP-CH-I to site-specifically isotope-label pterins. The low enzymatic activity and product instability of GTP-CH-I were addressed by enzymatic coupling. By means of our methodology, H2F enriched with stable isotopes at N5 and C6 could be synthesized efficiently in pure form in >30% yield from isotopically enriched D-glucose and guanine. Given the high degree of purity and isotopic enrichment (>97%; see the Supporting Information), heavy-atom KIEs could be measured to investigate the mechanism of the Escherichia coli DHFR (EcDHFR)-catalyzed reduction of H2F to H4F.

**RESULTS AND DISCUSSION**

**In Vitro Synthesis of Folate.** The biosynthetic pathway to folate in *E. coli* uses the building blocks D-glucose, guanine, and
p-aminobenzoyl-L-glutamate (pABA-Glu). In the biosynthetic scheme of H₂F (Figure 2), C₂, C₃, and C₄ of glucose correspond to C₇, C₆, and C₉ of H₂F and N₁, C₂, N₃, C₄, C₅, C₆, N₇, and N₉ of guanine correspond to N₃, C₂, N₁, C₄b, C₄a, C₄, N₅, and N₈ in H₂F. GTP is the key intermediate in this synthetic pathway, connecting the purine salvage pathway to de novo folate biosynthesis. Accordingly, a minimum of 14 enzymes need to be assembled in vitro to produce H₂F.

The GTP biosynthetic pathway is composed of enzymes from the pentose phosphate and purine salvage pathways (Figures 2 and S2). D-Glucose serves as the starting material, which is transformed into phosphoribose pyrophosphate (PRPP) in five steps that are catalyzed by hexokinase (HK), glucose 6-phosphate dehydrogenase (G6PDH), 6-phosphogluconate dehydrogenase (6PGDH), phosphoribosylpyrophosphate synthetase (PRS), and ribose-phosphate pyrophosphokinase (Ribose-phosphate pyrophosphokinase (PRS)). PRP is then combined with guanine to form GMP under xanthine guanine phosphoribosyl transferase (XGPRT) catalysis. The resulting GMP is converted to the corresponding nucleotide triphosphate in reactions catalyzed by guanylate kinase (GK) and pyruvate kinase (PK). Since HK and GK use ATP as the phosphate source, PK can also function as the recycling enzyme. On the other hand, PRS uses ATP as the pyrophosphate source, so myokinase (MK) was included to regenerate ATP from AMP. A significant amount of NADP⁺ is also needed for GTP biosynthesis. Hence, the recently developed glutathione reductase (GR)/glutaredoxin 2 (GRX2) recycling system was used to regenerate the oxidized cofactor. The GR/GRX2 system uses disulfides like 2-hydroxyethyl...
disulfide (HED or oxidized β-mercaptoethanol) or cystine as regenerating reagents and produces thiols as useful byproducts that protect the enzymes and intermediates from oxidative damage.

The conversion of GTP to DHNTP by GTP-CH-I marks the entry point of the folate de novo pathway. It has been reported that potassium and magnesium ions are positive allosteric effectors that can increase the rate of the GTP-CH-I reaction up to 5-fold. The addition of these cations, however, was insufficient, as the reaction was found to be incomplete, giving a poor yield of DHNTP (Figure 3a). In folate de novo biosynthesis, dephosphorylation of DHNTP to 7,8-dihydro-neopterin monophosphate (DHNMP) by DHNTP pyrophosphohydrolase (DHNTPase) is the biochemical step followed by the GTP-CH-I reaction (Figure 2). Knockout of the DHNTPase gene significantly impairs folate metabolism in E. coli, which suggests that DHNTP phosphohydrolysis is a key regulatory step in folate metabolism. In other words, the activity of GTP-CH-I is most likely inhibited by its own product, DHNTP, which therefore needs to be immediately converted to DHNMP in order to sustain the activity of GTP-CH-I. In the presence of DHNTPase, GTP-CH-I showed a marked rate enhancement (Figure S3), with nearly complete conversion of GTP and a high yield of DHNMP (Figure 3b).

Additional enzymes are needed to convert DHNMP into folate. To the best of our knowledge, the natural enzyme responsible for the conversion of DHNMP to 7,8-dihydroneopterin (DHN) is unknown, and alkaline phosphatase (ALP) was used instead as a surrogate. DHN is subjected to a retro-aldol reaction catalyzed by dihydroneopterin aldolase (DHNA) to yield 6-hydroxymethyl-7,8-dihydropterin (HMDP), which then reacts with ATP in the presence of 6-hydroxymethyl 7,8-dihydropterin pyrophosphokinase (HPPK) (Figure 4).

In E. coli, the resulting intermediate, 6-hydroxymethyl-7,8-dihydropterin pyrophosphate (HMDPpp), is first condensed with pABA and then with glutamate, catalyzed by dihydropterin-oate synthase (DHPS) and dihydrofolute synthase (DHFS), respectively, to finally generate H2F. However, DHPS accepts preassembled pABA-Glu as a substrate, so DHFS is not required in the in vitro reaction. The entire H2F synthetic pathway requires only one purification step of the product, but ALP needs to be removed by ultrafiltration prior to the addition of DHNA, HPPK, and DHFS because the phosphatase can also catalyze the phosphorolysis of ATP and HMDPpp. Two additional modifications were made to further improve the overall yield. A N2-filled glovebox system was used because all reduced pterin-containing compounds, DHNTP, DHNMP, DHN, HMDP, HMDPpp, and the final product H2F, are oxygen-sensitive. Also, cystine was found to be the preferred reagent over HED for the NADP+ regeneration system operated by GR and GRX2. Perhaps β-mercaptoethanol made from the reduction of HED interferes with other enzymatic reactions, such as the chelation of Zn2+ in GTP-CH-I. The total turnover numbers for the regeneration of ATP from ADP by pyruvate kinase and from AMP by pyruvate kinase/myokinase are both ~100, while the total turnover number for our GR/GRX2-based NADP+ recycling system can reach 5 × 105. In general, a typical biosynthetic cascade produced 6.6 mg of H2F from 9 mg of glucose in an overall yield of 30%, i.e., the average yield of each chemical transformation is in excess of 91%.

**Synthesis of Selectively Labeled Folates.** Five isotopically labeled H2Fs were synthesized using the newly developed in vitro pathway (Figure 5a). Liquid chromatography—high-resolution mass spectrometry (LC-HRMS) analysis of [6,13C]H2F, produced from [3-13C]d-glucose, showed an increase of ~1 amu; 13C NMR spectroscopy revealed a singlet at 152 ppm.
Additionally, long-range coupling between 6\(^{13}\)C and protons on C7 and C9 of \([6-^{13}\)C\]|H\(_2\)F were observed in the \(^1\)H,\(^{13}\)C HMBC spectrum (Figure 5b).

To incorporate a \(^{15}\)N label into the pterin moiety at N5, \([7-^{15}\)N\]|guanine was used. The resulting product showed \(~1\) amu increase in LC-HRMS analysis and an \(^{15}\)N signal at 285 ppm coupling to C7 and C9 protons in the \(^1\)H,\(^{15}\)N HMBC spectrum (Figure 5c).

When \([3-^{13}\)C\]|D-glucose and \([7-^{15}\)N\]|guanine were combined to produce \([5-^{15}\)N][6-^{13}\)C\]|H\(_2\)F, a mass increase of \(~2\) amu was measured. The \(^{13}\)C NMR spectrum showed a doublet at 152 ppm with a coupling constant \(^1\)J\(_{CN}\) of 7.5 Hz; long-range coupling between the protons on C7 and C9 was observed in the \(^1\)H,\(^{13}\)C HMBC and \(^1\)H,\(^{15}\)N HMBC spectra (see the Supporting Information), indicating that both N5 and C6 of H\(_2\)F were isotopically enriched.

Similarly, \([6,7,9-^{13}\)C\(_3\]|H\(_2\)F and \([5-^{15}\)N][6,7,9-^{13}\)C\(_3\]|H\(_2\)F were synthesized from \(^{13}\)C<-D-glucose and \([7-^{15}\)N\]|guanine, and their identities were confirmed by HRMS and NMR spectroscopy (see the Supporting Information).

Heavy-Atom Kinetic Isotope Effects on the Reaction Catalyzed by EcDHFR. The preparation of \(^{13}\)C- and \(^{15}\)N-labeled...
dihydrofolates allowed the measurement of heavy-atom isotope effects for the reactions catalyzed by dihydrofolate reductase (DHFR), a key enzyme in one-carbon metabolism and a validated target for the treatment of bacterial infections, malaria, and cancer.\(^{56}\) DHFR catalyzes the reduction of H\(_2\)F to H\(_4\)F via transfer of the pro-R hydride from C4 of NADPH to the Re face on C6 accompanied by protonation of N5 of H\(_2\)F (Figure 6).\(^{57,58}\)

![Figure 6](image)

**Figure 6.** Reduction of 7,8-dihydrofolate (H\(_2\)F) to 5,6,7,8-tetrahydrofolate (H\(_4\)F) catalyzed by dihydrofolate reductase (DHFR).

Several aspects of the reaction mechanism warrant additional investigation. In particular, the transition state structure and the order of chemical transformation events have not been fully determined.\(^{59,60}\) The active site of DHFR provides a favorable environment for protonation of N5 by elevating the pK\(_a\) from 2.6 to 6.5 and using an active-site water as the proton source.\(^{61,62}\) Solvent and hydrogen KIE measurements combined with site-directed mutagenesis have suggested a stepwise mechanism in which protonation precedes hydride transfer.\(^{63,64}\) However, D\(_2\)O increases the viscosity of the reaction buffer relative to H\(_2\)O,\(^{65,66}\) and site-directed modification can alter the catalytic behavior of an enzyme.\(^{67}\) Thus, additional mechanistic investigations are needed to establish the order of events. Since isotopic substitution does not alter the chemistry of the reaction but only the kinetics,\(^{59,60}\) [6-13C]H\(_2\)F and [5-15N]H\(_2\)F were used to measure the 15N and 13C heavy-atom kinetic isotope effects. Pre-steady-state kinetic measurements at 15 °C by fluorescence resonance energy transfer from the active-site tryptophan in DHFR to the reduced cofactor yield first-order hydride transfer rate constants with an accuracy of up to 0.7% (Figures S25–S27 and Table S4).

While a 13C KIE of 1.015 ± 0.006 was observed for the reduction of [6,13C]H\(_2\)F, the corresponding 15N KIE for [5,15N]H\(_2\)F was essentially unity (0.999 ± 0.006) under the same conditions. To confirm this finding, [5-15N][6,13C]H\(_2\)F was used to probe both positions at the same time, and the measured value for the corresponding multiple heavy-atom KIE was 1.014 ± 0.008, which is statistically identical to that obtained when the substrate was labeled with 13C only.

The observed 15N KIE on hydride transfer indicates that protonation of N5 is not isotopically sensitive, likely because it is not rate-limiting under pre-steady-state conditions (as the reaction is essentially irreversible, the observed KIE will tend to unity rather than to the equilibrium isotope effect).\(^{22}\) On the other hand, the measured 13C KIE indicates that the hydride transfer step is rate-determining. This strongly suggests a stepwise mechanism. If the protonation and hydride transfer steps were concerted, 14N- and 13C-labeled H\(_2\)Fs should both yield measurable KIEs;\(^{19,21,22}\) this interdependence may also lead to an additive effect in the multiple heavy-atom isotope effect measurement with the double-labeled substrate.\(^{19,21,22}\) In other words, our results suggest that the pre-steady-state kinetic measurement at pH 7.0 reveals only the step of hydride transfer because protonation of N5 is in rapid equilibrium and the ensemble of reaction-ready conformations is mostly populated with protonated H\(_2\)F. Importantly, these results confirm the validity of previous solvent KIE and site-directed mutagenesis studies, which also concluded that the sequence of chemical events (protonation and hydride transfer) is distinct and strictly ordered.\(^{54,60}\) Overall, the results provided here strongly support a mechanism where protonation and hydride transfer are independent of each other and occur in a stepwise fashion.

### CONCLUSIONS

Dihydrofolate was produced enzymatically in an easy one-pot, high-yielding reaction sequence from glucose, guanine, and pABA-Glu that required only a single purification step. Potential problems with individual steps during the synthesis could be overcome through the use of a one-pot reaction. This methodology can be used to generate dihydrofolates labeled in specific positions with stable isotopes with average overall yields of >30%, facilitating many applications in cell biology and mechanistic enzymology.\(^{27–29,61,69,70}\) For the first time, heavy-atom KIEs for the DHFR-catalyzed reduction of H\(_2\)F could be measured to provide strong support for a stepwise reduction of the substrate in which protonation at N5 and hydride transfer from C4 of the NADPH to C6 of protonated dihydrofolate proceed independently. This chemoenzymatic pterin synthesis can be integrated into other enzymatic procedures to generate folate derivatives\(^{31,32}\) and other high-value natural products that are not easily accessible by conventional synthesis.\(^{71}\) It can be applied to nutritional, medical, and cell-biological research to address questions of in vivo bioavailability and to explore the kinetics of folate metabolism in intact cells and organisms.\(^{70,72–76}\)

### ASSOCIATED CONTENT

#### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.7b06358.

Full experimental procedures and supplementary figures and tables (PDF)

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