Engineered Biosynthesis of a Novel Amidated Polyketide, Using the Malonamyl-Specific Initiation Module from the Oxytetracycline Polyketide Synthase

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Tetracyclines are among the most important antibiotics known to mankind in the last half century (15). The broad-spectrum antimicrobial activities of tetracyclines have resulted in their widespread clinical use against infectious gram-positive and gram-negative bacteria (21). The emergence of microbial resistance to tetracyclines has severely limited their effectiveness and has prompted the search for analogs that can overcome the known modes of antibiotic resistance (14, 40, 55). The recently published, elegant total synthesis of 6-deoxytetracyclines by strain CH999 revealed that the minimal PKS and OxyD are necessary and sufficient for the biosynthesis of amidated polyketides. A novel alkaloid (WJ35, or compound 2) was synthesized as the major product when the oxy-encoded minimal PKS, the C-9 ketoreductase (OxyJ), and OxyD were coexpressed in CH999. WJ35 is an isoquinolone compound derived from an amidated decaketide backbone and cyclized with novel regioselectivity. The expression of OxyD with a heterologous minimal PKS did not afford similarly amidated polyketides, suggesting that the oxy-encoded minimal PKS possesses novel starter unit specificity.

One of the distinguishing structural features of tetracyclines compared to other aromatic polyketides is the universal presence of an amide unit at one terminus of the polyketide backbone (Fig. 1). Substrate feeding studies have suggested that the amide unit stems from an intact malonate unit (59, 60). The enzymes involved in the biosynthesis of the amide starter unit have not been identified to date. The biosynthesis of the polar amide starter unit is especially interesting from a combinatorial perspective, since all other aromatic polyketides are primed by chemically inert aliphatic and aromatic starter units (41). The polar amide unit can serve as a useful reaction handle for orthogonal semisynthetic modifications of polyketides. Elucidating the formation of the amide group will therefore enable the exploration and engineering of tetracycline biosynthesis as well as expand the repertoire of tools that can be used in combinatorial biosynthesis of other polyketides.

In this work, we report the identification of an amidotransferase, OxyD, encoded in the oxy (otc) gene cluster, that is involved in the biosynthesis of the amidated backbone. Using a heterologous host, we show that coexpression of OxyD with the minimal oxy-encoded PKS affords a novel isoquinolone compound derived from an amidated decaketide backbone.

MATERIALS AND METHODS

Bacterial strains and general techniques for DNA manipulation. Streptomyces coelicolor strain CH999 was used as a host for the transformation of shuttle vectors. Protoplast preparation and polyethylene glycol-assisted transformation were performed as described by Hopwood et al. (23). Escherichia coli XLI-Blue (Stratagene) was used for the manipulation of plasmid DNA. Streptomyces rimosus (ATCC 10970) was obtained from ATCC and was cultured for extraction of genomic DNA. Unmethylated DNA was obtained using the methylease-deficient strain GM2163 (New England Biolabs).

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Sequencing of oxy tetraacycline cluster. The complete genomic DNA library of S. rimosus was constructed using a pWEB cosmid cloning kit (Epigen). The cosmids clone pYT264, which harbors the 21.2-kb oxy gene cluster flanked by otek (18) and otrB, was identified by PCR screening. A combination of shotgun and primer-walking techniques was used to obtain the sequence information. Open reading frames (ORFs) were detected and analyzed using Frameplot software (http://www.nih.go.jp/jun/cgi-bin/frameplot.pl), and the putative roles of the reading frames (ORFs) were detected and analyzed using Frameplot software. The cluster was renamed in this study to facilitate sequence analysis. The five previously sequenced genes of the cluster are cross-referenced in Table 1.

TABLE 1. Genes in the oxytetracycline biosynthetic cluster and deduced roles based on sequence homology

<table>
<thead>
<tr>
<th>Gene</th>
<th>Start position</th>
<th>Stop position</th>
<th>Predicted size (kDa)</th>
<th>Cts homolog (reference)</th>
<th>Protein (reference)</th>
<th>Deduced role</th>
<th>% Identity</th>
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<tr>
<td>otekA (otcB)</td>
<td>134</td>
<td>625</td>
<td>18</td>
<td>TcsD (43)</td>
<td>CAD15553 (52)</td>
<td>Transcription regulation</td>
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<td>oteA (otcY1-1)</td>
<td>770</td>
<td>2047</td>
<td>45</td>
<td>TcsE (43)</td>
<td>SnoA (62)</td>
<td>Ketosynthase</td>
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<td>oteB (otcY2-1)</td>
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<td>3312</td>
<td>44</td>
<td>TcsF (43)</td>
<td>ChbA (61)</td>
<td>Chain length factor</td>
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<td>3675</td>
<td>10</td>
<td>TcsG (43)</td>
<td>Sim4 (20)</td>
<td>Acyl carrier protein</td>
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<td>5524</td>
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<td>TcsG (43)</td>
<td>AnB (8)</td>
<td>Asparagine synthetase</td>
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<td>oteE (otcY5-5)</td>
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<td>6777</td>
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<td>MtmO1 (32)</td>
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<td>8241</td>
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<td>12396</td>
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<td>ChaF (61)</td>
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<td>oteN (otcD4)</td>
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<td>oteO (otcD5)</td>
<td>15734</td>
<td>16503</td>
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<td>TcsE (43)</td>
<td>ZP00569712 (26)</td>
<td>Unknown</td>
<td>31</td>
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<td>oteP (otcD6)</td>
<td>17835</td>
<td>18613</td>
<td>35</td>
<td>TcsE (43)</td>
<td>AfnK (16)</td>
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<td>oteQ (otcD7)</td>
<td>18911</td>
<td>19732</td>
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<td>TcsE (43)</td>
<td>AspB2 (44)</td>
<td>Aminotransferase</td>
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<td>19336</td>
<td>19808</td>
<td>16</td>
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<td>ActVA ORF2 (11)</td>
<td>PNP-oxidase</td>
<td>50</td>
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<td>oteS (otcD9)</td>
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<td>20103</td>
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<td>TcsE (43)</td>
<td>MtmOH (32)</td>
<td>Oxygenase</td>
<td>46</td>
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<td>oteT (otcD10)</td>
<td>21064</td>
<td>22089</td>
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<td>TcsE (43)</td>
<td>MtmMI (32)</td>
<td>N-Methyltransferase</td>
<td>45</td>
</tr>
</tbody>
</table>

a We compared the partially annotated chlorotetracycline PKS cluster (43, 51) from Streptomyces aureofaciens with the oxy c-encoded PKS cluster.

b Gene names in parentheses are loci of the oxy (ote) PKS previously identified through mutant complementation studies. Sequence information for these genes is not available publicly, except for that shown in bold. The cluster was renamed in this study to facilitate sequence analysis. References for previously sequenced genes are listed in the text.

c No stop codon was detected. The putative protein size was based on alignment with closely related acyl-CoA ligases.

d A 60-bp deletion at the 3’ end was found in the deposited otekD1 sequence and has been corrected here.
GTACGGGAATCCCGTACCCCT-3'. The introduced restriction sites are shown in italics, and the restriction enzymes are indicated in parentheses. The optimal ribosome binding site was introduced at the 5' end of each gene and is underlined. All oxy genes were amplified from pYT264, and multicistronic cassettes were constructed using the compatible XbaI/SpeI cohesive ends for most of the genes, except for oxyA and oxyB, which were cloned as a single PacI/XbaI cassette. Different combinations of genes were introduced into pYT315 (a pRM5-derived vector) to yield the constructs shown in Table 2.

Culture conditions and purification of polyketides. Strains were grown on solid R5 plates with 25 mg/liter thiostrepton at 30°C for 7 to 10 days. For analytical high-performance liquid chromatography (HPLC) analysis, a well-pigmented plate was chopped into fine pieces and extracted with 50 ml of ethyl acetate-methanol-acetic acid (89%-9.8%-1.2%). Extracts were dried over anhydrous Na2SO4. The solvent was removed in vacuo, and the residue was dissolved in 0.5 ml of dimethyl sulfoxide (DMSO). The polyketide products were separated by reverse-phase HPLC and detected at 254 and 280 nm using an analytical C18 column (Varian Pursuit 5u; 250 mm × 4.6 mm) with a linear gradient of 5% acetonitrile (ACN) in water (0.1% trifluoroacetic acid [TFA]) to 95% ACN in water (0.1% TFA) over 30 min with a flow rate of 1 ml/min. HPLC retention times were as follows: for RM20b, 19.3 min; and for WJ35 (compound 2), 15.0 min. For large-scale production and isolation of compound 2, 60 R5 plates (2 liters) streaked with the transformed CH999 strains were incubated at 30°C for 7 to 10 days. The plates were chopped into fine pieces and extracted with 2 liters of ethyl acetate-methanol-acetic acid (89%-9.8%-1.2%). The solvent was removed in vacuo, and the residue was dissolved in 10 ml of H2O-ACN-DMSO (50%-25%-25%) and filtered for injection into a semipreparative reverse-phase column (Varian Pursuit 5u; 250 × 200 mm; 10 μm). A 10% to 50% ACN gradient was used over 45 min with a flow rate of 3 ml/min. The solvent was removed in vacuo from the collected fractions containing the expected biosynthetic product. The residue was dissolved in 2 ml of acetone to be loaded onto two preparative thin-layer chromatography (TLC) plates (20-cm × 20-cm × 0.25 mm silica gel [60F-254]). The preparative TLC plates were developed in ethyl acetate-methanol-acetic acid (94%-5%-1%) and water (0.1% TFA) gradient was used over 45 min with a flow rate of 3 ml/min. The solvent was removed in vacuo from the collected fractions containing the expected biosynthetic product. The residue was dissolved in 2 ml of acetone to be loaded onto two preparative thin-layer chromatography (TLC) plates (20-cm × 20-cm × 0.25 mm silica gel [60F-254]). The preparative TLC plates were developed in ethyl acetate-methanol-acetic acid (94%-5%-1%) and water (0.1% TFA) gradient was used over 45 min with a flow rate of 3 ml/min. The solvent was removed in vacuo from the collected fractions containing the expected biosynthetic product.

Spectroscopic analysis. High-resolution mass spectrometry (HRMS) was performed at the UCLA Pasarow Mass Spectrometry Laboratory with an IonSpec Ultima 7.0 Telsa electrospray ionization and matrix-assisted laser desorption ionization–Fourier transform mass spectrometry. The HRMS result for compound 2 was m/z = 388.1043 ([C19H18NO8] +). Nuclear magnetic resonance (NMR) spectrometers were obtained on Bruker DRX-500 spectrometers at the NMR facility of the Department of Chemistry and Biochemistry at UCLA. 1H and 13C chemical shifts were referenced to the solvent peak (acetone-d6) and were 6.205 and 29.9 ppm, respectively. Standard parameters were used for one-dimensional (1D) and 2D NMR experiments, which included 1H, 13C, heteronuclear multiple quantum correlation (HMQC) (1H-13C), 1H-15N, and heteronuclear multiple-bond correlation (HMBC) (1H-13C, 1H-15N) analyses. 13C NMR experiments were performed on a DRX-600 instrument, and formamide (8H-95 DMSO-d6) was used as an internal reference. The observed 13C NMR signal for compound 2 was 6.115. For detailed NMR data, see Table 3.

Nucleotide sequence accession number. The sequence of the oxy gene cluster was deposited in GenBank under accession number DQ143963.

RESULTS

Sequencing of oxytetracycline gene cluster. To study the origin of the amide moiety observed among all tetracyclines and to gain additional insight into the biosynthesis of tetracyclines, we sequenced the oxytetracycline (oxy and otc) gene cluster using a combination of shotgun sequencing and cosmid walking techniques. The gene cluster was previously mapped to the R5 chromosome and to gain additional insight into the biosynthesis of tetracyclines, we sequenced the oxytetracycline (oxy and otc) gene cluster using a combination of shotgun sequencing and cosmid walking techniques. The gene cluster was previously mapped to the R5 chromosome and to gain additional insight into the biosynthesis of tetracyclines, we sequenced the oxytetracycline (oxy and otc) gene cluster using a combination of shotgun sequencing and cosmid walking techniques. The gene cluster was previously mapped to the R5 chromosome and to gain additional insight into the biosynthesis of tetracyclines, we sequenced the oxytetracycline (oxy and otc) gene cluster using a combination of shotgun sequencing and cosmid walking techniques. The gene cluster was previously mapped to the R5 chromosome and to gain additional insight into the biosynthesis of tetracyclines, we sequenced the oxytetracycline (oxy and otc) gene cluster using a combination of shotgun sequencing and cosmid walking techniques. The gene cluster was previously mapped to the R5 chromosome and to gain additional insight into the biosynthesis of tetracyclines, we sequenced the oxytetracycline (oxy and otc) gene cluster using a combination of shotgun sequencing and cosmid walking techniques. The gene cluster was previously mapped to the R5 chromosome and to gain additional insight into the biosynthesis of tetracyclines, we sequenced the oxytetracycline (oxy and otc) gene cluster using a combination of shotgun sequencing and cosmid walking techniques. The gene cluster was previously mapped to the R5 chromosome and to gain additional insight into the biosynthesis of tetracyclines, we sequenced the oxytetracycline (oxy and otc) gene cluster using a combination of shotgun sequencing and cosmid walking techniques.

FIG. 2. Organization of oxy (ote) biosynthetic gene cluster. The biosynthetic enzymes are located between the two resistance genes otrA and otrB. Previously sequenced genes are boxed. For details of enzyme function assignments, see Table 1.

![FIG. 2. Organization of oxy (ote) biosynthetic gene cluster.](http://aem.asm.org/)
TABLE 2. Plasmid constructs and resulting polyketide products

<table>
<thead>
<tr>
<th>Plasmid</th>
<th>Genes</th>
<th>Major product</th>
<th>Approx. yield (mg/liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pYT319</td>
<td>oxyABC</td>
<td>SEK15</td>
<td>30</td>
</tr>
<tr>
<td>pYT318</td>
<td>oxyABCJ</td>
<td>RM20b</td>
<td>30</td>
</tr>
<tr>
<td>pWJ35</td>
<td>oxyABCDJ</td>
<td>Compound 2</td>
<td>20</td>
</tr>
<tr>
<td>pWJ35a</td>
<td>oxyABCD aclIII</td>
<td>Compound 2</td>
<td>20</td>
</tr>
<tr>
<td>pWJ40</td>
<td>acl ORFs I-II oxyCDJ</td>
<td>Mutacin</td>
<td>20</td>
</tr>
<tr>
<td>pWJ48</td>
<td>tcmKL oxyCDJ</td>
<td>RM20b</td>
<td>&lt;5</td>
</tr>
</tbody>
</table>

* Streptomyces coelicolor strain CH999 was used as the host for polyketide biosynthesis. Each plasmid is derived from pRM5.

Biosynthesis of an amidated polyketide by extended minimal oxy-encoded PKS. To examine the roles of OxyD in the biosynthesis of an amidated polyketide in vivo, a series of Streptomyces coelicolor shuttle vectors derived from pRM5 were constructed (35). The plasmids were transformed into S. coelicolor strain CH999 (35) and were analyzed for polyketide biosynthesis (Table 2).

The minimal oxy-encoded PKS (oxyABC, in pYT319) produced ample amounts of SEK15 (see Fig. 4) (53 (30 mg/liter), while the addition of OxyJ (pYT318) yielded reduced deca-ketide RM20b as the major product (30 mg/liter), consistent with the data reported by Fu et al. (19). OxyJ is therefore the regiospecific C-9 ketoreductase in the oxy-encoded PKS. Therefore, to reconstitute the steps of oxytetraycline biosynthesis, OxyJ was coexpressed in all subsequent studies.

Significantly, a new polyketide product was identified when OxyD was coexpressed with the minimal oxy-encoded PKS and OxyJ. The oxyD gene encoding the amidotransferase was cloned into pYT318 to yield pWJ35. CH999 transformed with pWJ35 produced an intense yellow pigmentation on solid R5 medium that was not observed before. HPLC analysis of the CH999/pWJ35 extract revealed that a new metabolite (WJ35, 20 mg/liter) (Fig. 3). The acetate-primed CH999/pWJ35 fermentation and was purified to homogeneity. The mass ([M + H]+) of compound 2 was detected by 388. LC-MS analysis of the CH999/pYT318 extract with positive ion extraction for m/z 388 showed that no trace of compound 2 was produced in the absence of OxyD, confirming the essential role of OxyD in the biosynthesis of compound 2. A sufficient amount of compound 2 was extracted from 2 liters of CH999/pWJ35 fermentation and was purified to homogeneity.
using reverse-phase preparative HPLC and normal-phase thin-layer chromatography. HRMS indicated a molecular formula of C_{19}H_{17}NO_{8} (m/z = 388.1027 [M + H]^+; difference of 0.0016), consistent with the molecular composition of an amidated decaketide that has been subjected to one ketoreduction at C-9 and two cyclization/dehydration events. When OxyJ was replaced by the heterologous ActIII KR (pWJ35a; Table 2), no change in yield and selectivity of compound 2 was observed.

The structure of compound 2 was elucidated using a combination of 1D and 2D NMR experiments (Table 3) and is shown in Fig. 4. Data obtained from $^{13}$C, distortionless enhancement by polarization transfer (90, 135), and HMQC experiments identified 19 carbon signals, supporting the number of carbon atoms predicted by HRMS. No methyl carbon atom is present, consistent with the lack of an acetate starter unit. The presence of the α-pyrene moiety as a result of O-1/C-5 cyclization is clearly evident from both $^1$H ($\delta_{1H} = 5.3$ and $\delta_{1H} = 6.1$) and $^{13}$C (63) data. The C-6 methylene was assigned using $^1$H-$^1$C HMBC (Table 3). The linear connectivities exist between C-6 and C-9 were readily established using correlation spectroscopy and $^1$H-$^1$C HMBC. The $^1$H multiplet at $\delta_{1H}$ 4.5 is assigned to H-9 and is nearly identical to the H-9 protons present in mutactin (66) and YT46 (57), with each containing a 9-OH as a result of C-9 ketoreduction (Fig. 4). The assignments of the C-8/C-10 methylenes were readily achieved using correlation spectroscopy, HMQC, and HMOC experiments. The key assignment of the C-7 aliphatic ketone enabled us to eliminate the common C-7/C-12 intramolecular cyclization observed among aromatic polyketides (36). The remaining carbon backbone cyclizes and dehydrates through a C-13/C-18 intramolecular aldol condensation, which is confirmed by the coupling between H-14 and H-16 ($J_{HH} = 2.1$ Hz). The nucleophilic amide group is thus favorably positioned to attack the electrophilic C-11 to yield, after dehydration, an isoquinolone heterocycle. The sharp proton singlet at $\delta_{1H}$ 12.9, which shows long-range coupling to C-16, C-17, and C-18, is assigned to OH-17. The broad singlet at $\delta_{1H}$ 10.2 is assigned to the NH proton. These assignments are consistent with the isoquinolone protons observed in the natural product fredericamycin (7). The presence of a lactam ring was unambiguously supported by the $^1$H-$^1$N HMBC experiment, in which both H-10 and H-12 showed long-range coupling to the nitrogen (Table 3). Therefore, WJ35 is a shunt product of the oxy-encoded PKS in the absence of the first-ring cyclase.

**DISCUSSION**

The tetracyclines are universally primed with a unique malonate starter unit not found in any other polyketides. Past work has cloned five oxy genes and shed light on the minimal PKS. However, the initiation mechanism that leads to the production of the unique malonate starter unit is not well understood. The lack of this information has hampered efforts to engineer the initiation of tetracycline biosynthesis.

**OxyD does not interact with heterologous minimal PKSs.** We assayed whether heterologous minimal PKSs that are normally primed by acetate can interact productively with OxyD and OxyC to yield amidate polyketides. The act-encoded KS-CLF (65) and the tcm-encoded KS-CLF (54) were each coexpressed in the presence of Act KR, OxyD, and OxyC in CH999. Heterologous KS-CLFs have been shown to function with the OxyC ACP to produce acetate-primed compounds (26). To our surprise, no amidated polyketides were recovered from these strains (Table 2). We were able to detect only acetate-primed mutactin and RM20b from CH999/pWJ40 and CH999/pWJ48, respectively. This is in sharp contrast to the broad compatibility between the R1128 initiation module and heterologous minimal PKSs (57). Hence, fundamental differences exist between oxy-encoded and other minimal PKSs that allow the former to accept both amide and acetate starter units.

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**Table 3. Proton and carbon NMR data for WJ35 (compound 2)**

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<thead>
<tr>
<th>Position</th>
<th>$^{13}$C $\delta$ (ppm)</th>
<th>$^1$H $\delta$ (ppm)</th>
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<td>1</td>
<td>165.9</td>
<td>10.2</td>
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<td>2</td>
<td>90.9</td>
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<td>3</td>
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<td>4</td>
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<td>C2, C5</td>
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<td>5</td>
<td>160.9</td>
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<td>6</td>
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<td>7</td>
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<td>8</td>
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<td>14</td>
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<td>6.40 (d, 1H, 2.1)</td>
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<tr>
<td>15</td>
<td>164.9</td>
<td>11.16 (s, 1H), OH</td>
<td>C14, C15, C17, C18</td>
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<tr>
<td>16</td>
<td>101.7</td>
<td>6.25 (d, 1H, 2.1)</td>
<td>C14, C15, C17, C18</td>
</tr>
<tr>
<td>17</td>
<td>163.2</td>
<td>12.91 (s, 1H), OH</td>
<td>C16, C17, C18</td>
</tr>
<tr>
<td>18</td>
<td>106.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>167.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH</td>
<td>10.18 (s, 1H)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Proton and carbon NMR data for WJ35 (compound 2).

a Spectra were obtained at 500 MHz for protons and 125 MHz for carbon and were recorded in acetone-d$_6$ for compound 2.

b Numbering of the carbon backbone is shown in Fig. 4.

c Observed $^1$H-$^1$C and $^1$H-$^1$N HMBC signals.
as well as an extended minimal PKS including OxyD. Significantly, the coexpression of minimal PKS with the C-9 KR and OxyD produced a unique, amidated polyketide 2 at a high yield (Table 2). Establishing the origin of the amide unit and constructing the complete backbone required for tetracycline biosynthesis are significant steps towards rational bioengineering of this family of compounds. Isolation of this novel isoquinolone 2 revealed several important biochemical properties of the oxy-encoded PKS, as follows.

(i) OxyD is the only enzyme required to biosynthesize and insert an amide starter unit into the polyketide backbone in the heterologous host. CH999/pWJ35 produced predominantly the amidated polyketide, indicating preferential incorporation of a malonamyl unit over acetyl-OxyC by the oxy-encoded minimal PKS, even in the absence of an acetyl-ACP editing enzyme. A homologous enzyme (TcsG) from the chlorotetracycline PKS (43) likely performs the same catalytic function as OxyD during chlorotetracycline biosynthesis.

(ii) The amidated compound 2 is derived from an intact decaketide (10-carbonyl) backbone, indicating that in the heterologous host CH999, the oxy-encoded minimal PKS is able to maintain correct chain length control. We did not find any truncated polyketide products in the extract of CH999/pWJ35, presumably because these truncated products are present at much lower levels in this strain and may have escaped our purification and detection protocols. We did detect a truncated polyketide in a pWJ35-derived construct coexpressing OxyK (OtcD1) (unpublished data), consistent with the conclusion by Petkovic and coworkers that the oxy-encoded PKS also synthesizes truncated polyketides (46).

(iii) The most surprising structural feature of compound 2 is perhaps the lack of C-7/C-12 cyclization. The decaketide backbone must undergo two unique cyclization steps (C-13/C-18 and N-19/C-11) to yield the isoquinolone backbone. This is apparently a dominant mode of cyclization, since no alternatively cyclized amidated polyketides were detected in the fermentation extract. The cyclization regioselectivity of compound 2 was completely unanticipated, considering that C-9-reduced, acetate-primed decaketides cyclize solely between C-7 and C-12 (as observed in RM20b/c) (49). From the crystal structures of act-encoded KR (29) and act-encoded KS-CLF (25), it has been tempting to propose that the C-7/C-12 connectivity is formed within the active site of KS, prior to C-9 reduction by the KR. It is evident from the novel structural features of compound 2 that C-9 keto-reduction must take place independently of C-7/C-12 cyclization. OxyJ must therefore recognize an uncyclized polyketide backbone to yield compound 2.

(iv) Furthermore, formation of the isoquinolone must take place immediately after the complete assembly and release of the polyketide product. Premature C-13/C-18 cyclization will prevent the correct C-7/C-12 cyclization catalyzed by OxyK during the tailoring steps of tetracycline biosynthesis (Fig. 1). Malonate is a very rare metabolite under normal physiological conditions and is a toxic compound due to its potent inhibition of succinate dehydrogenase in the tricarboxylic acid cycle (30), and hence it is unlikely to serve as a substrate for

FIG. 4. Biosynthesis of compound 2 by the extended oxy-encoded minimal PKS.
OxyD. Therefore, we hypothesize that biologically plausible malonyl substrates for OxyD are malonyl-CoA and malonyl-OxyC. Malonyl-OxyC may be preferred over malonyl-CoA for the following reasons. (i) Malonyl-CoA is involved in other essential cellular processes, including fatty acid biosynthesis. Amidation of a significant amount of the intracellular malonyl-CoA pool may therefore be detrimental to host strain viability (we did not observe any difference in the growth characteristics of CH999/pWJ35). Malonyl-OxyC, on the other hand, is dedicated to the oxy-encoded PKS and is not involved in the primary metabolism of the host. The robust growth of CH999/pWJ35 supports the above argument that the malonyl-CoA pool is not depleted. (ii) It is known that a cognate ACP-bound acyl substrate has a micromolar $K_m$ towards the KS-CLF, while the same acyl-CoA has $K_m$ values exceeding 100 $\mu$M (56). The lower $K_m$ of acyl-ACP is a result of extensive protein-protein interactions between the acyl-ACP and the KS-CLF. Therefore, under in vivo conditions, a significantly lower concentration of malonamyl-ACP than of malonamyl-CoA may be required to prime the KS-CLF. We are currently investigating the substrate specificities of OxyD in vitro.

It is unknown why heterologous pairing of minimal PKSs with OxyD failed to yield amidated polyketides. One likely possibility is that the exclusively acetate-primed KS-CLFs, including the act- and tcm-encoded PKSs, do not tolerate the presence of a polar starter unit in their active sites. Alternately, OxyD may interact with the KS-CLF heterodimer to shuttle the malonamyl starter unit to the active site of KS and may require specific residues present on the surfaces of OxyA-OxyB. We have demonstrated that the chain length specificities of KS-CLFs can be drastically altered through rational mutagenesis (58). Therefore, the specificity of oxy-encoded KS-CLF may be similarly engineered to synthesize amidated polyketides of various lengths in coordination with OxyD.

While our in vivo results show that OxyD is a key determinant in the formation of the amide unit in W335 and, most logically, oxytetracycline, our results do not completely rule out a late role of OxyD during tetracycline assembly. In this model, the oxy-encoded PKS is primed directly by a malonyl group and proceeds with chain elongation. The acid-primed polyketide can then be amidated by OxyD to yield an amidated polyketide (W335) or can undergo spontaneous decarboxylation to yield an acetate-primed compound (RM20b, which will require the oxy-encoded KS to synthesize an 11-carbonyl, C$_{11}$ backbone). However, it is difficult to hypothesize the exact timing and substrate of the OxyD-catalyzed amidation reaction in this model (e.g., partially elongated, linear, or cyclized). We are currently performing in vitro assays to unequivocally identify the possible malonyl substrates of OxyD, which will provide a definitive mechanism for the formation of the amidated unit.

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