ORGANIC PROCESS RESEARCH & DEVELOPMENT
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pubs.acs.org/OPRD

Development of a Chemoenzymatic Process for Dehydroepiandrosterone Acetate Synthesis

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Supporting Information

ABSTRACT: Dehydroepiandrosterone (DHEA, **2**) is an important endogenous steroid hormone in mammals used in the treatment of a variety of dysfunctions in female and male health,[1] as well as an intermediate in the synthesis of steroidal drugs, such as abiraterone acetate which is used for the treatment of prostate cancer.[2−4] In this manuscript we describe a novel, concise, and cost-efficient route toward DHEA (**2**) and DHEA acetate (**3**) from 4-androstene-3,17-dione (4-AD, **1**). Crucial to success was the identification of a ketoreductase from *Sphingomonas wittichii* for the highly regio- and stereoselective reduction of the C3-carbonyl group of 5-androstene-3,17-dione (**5**) to the required 3β-alcohol (**2**, >99% de). The enzyme displayed excellent robustness and solvent stability under high substrate concentrations (up to 150 g/L).

1. INTRODUCTION

3β-Hydroxyandrost-5-en-17-one (**2**), also known as dehydroepiandrosterone (DHEA) or prasterone, is an important endogenous steroid hormone[1] and a precursor in the synthesis of other steroidal drugs such as abiraterone acetate (Zytiga), a drug developed for the treatment of castration-resistant prostate cancer.[2−4] Current routes toward DHEA (**2**) and DHEA acetate (**3**) are typically based on the selective degradation of yam-derived diosgenin to 16-dehydropregnenolone acetate (**29**),[5,6] followed by oxime formation and rearrangement (Scheme 1).[5−8]

Dependence on raw materials with variable availability often drives the development of alternative processes for steroid drug manufacture.[5] Here, we aimed to develop a novel and scalable route to DHEA acetate (**3**) from 4-androstene-3,17-dione (4-AD, **1**), which is derived from phytosterols obtained from soybeans (e.g., stigmasterol, **31**; Scheme 1).[5,9−11]

Nature offers a vast array of enzymes that can be used to access the structural and functional diversity of steroids[10,11] and they often display high substrate specificity, as well as remarkable regio- and stereoselectivity. During the initial phase of route scouting for possible ways to make dehydroepiandrosterone acetate (**3**) from 4-AD (**1**), we considered several possible chemoenzymatic approaches, including routes A and B depicted in Scheme 2.

Although hydrolases can be used for the regioselective esterification of polyhydroxylated steroid derivatives,[12,13] our initial trials with 5-androstene-3,17-diol (5-AD-diol, **6**, Scheme 2, Route A) indicated that with Novozyme 435 (*Candida antarctica* Lipase B) the reaction progressed slowly and required high enzyme loading (60h, 100% w/w enzyme, complete conversion to **28**). Inspired by natural metabolic pathways for androgens, we turned our attention to oxidoreductases (Route B, Scheme 2).[14−20] In mammals 4-AD (**4**) is synthesized from DHEA (**2**) by the action of two enzymes: 3β-hydroxysteroid dehydrogenase (3β-HSD) catalyzing its oxidation to 5-androstene-3,17-dione (5-AD, **5**)[14,21−26] and ketosteroid isomerase (KSI), which catalyzes the thermodynamically favored isomerization of the double bond to the conjugated α,β-unsaturated ketone **1** (K_{eq} = 2400).[20,27−30] Thus, we hoped to take advantage of the reversibility of biooxidation and use an enzyme for the stereo- and regioselective reduction of the C3-carbonyl group—a reverse sequence to the natural mammalian metabolic pathway. Ultimately, this proved successful, and the results are described hereafter.

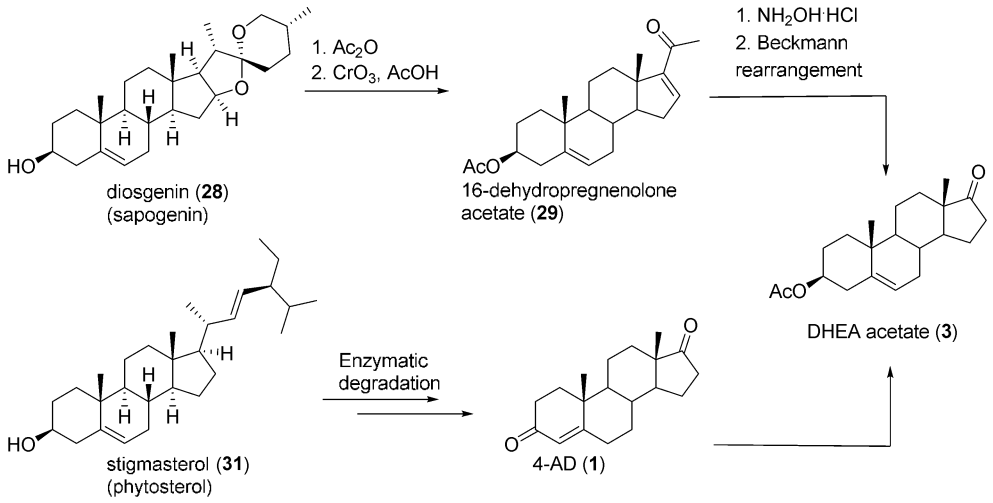
2. RESULTS AND DISCUSSION

In order to successfully convert 4-AD (**1**) into DHEA acetate (**3**), we envisaged a three-step process. First, we planned to convert 4-AD to 5-AD (**5**) through a selective $\Delta^4-\Delta^5$ isomerization.[31−33] Second, we needed to identify a highly stereoselective ketoreductase with appropriate industrial properties to selectively reduce 5-AD (**5**) to DHEA (**2**), which was the key to success of this project. As ketoreductases and hydroxysteroid dehydrogenases may display vastly different degrees of regioselectivity (3 vs 17 positions) and stereoselectivity (α vs β),[14,21−26] finding the enzyme with exclusive 3β-stereoselectivity was crucial. Finally, we planned to convert

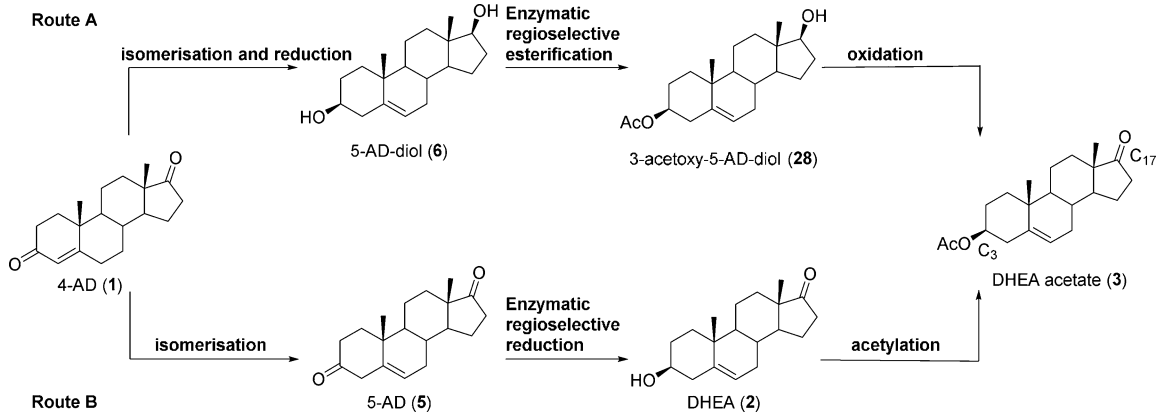
Received: June 16, 2016
Published: July 5, 2016

DOI: 10.1021/acs.oprd.6b00215
Org. Process Res. Dev. 2016, 20, 1520−1528

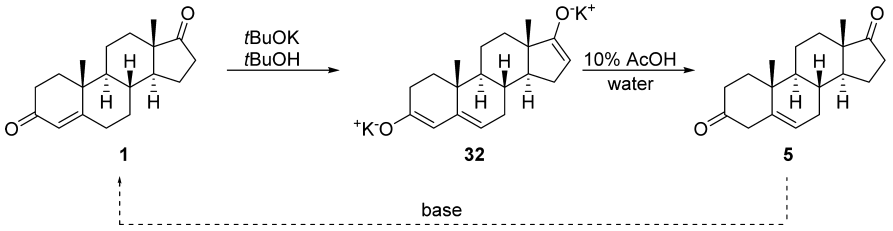
Scheme 1. Diosegenin (28) and Stigmasterol (31) as Precursors for DHEA Acetate (3) Synthesis



Scheme 2. Proposed Synthetic Strategies To Convert 4-AD (1) to DHEA Acetate (3)



Scheme 3. Isomerization of 4-AD (1) to 5-AD (5)



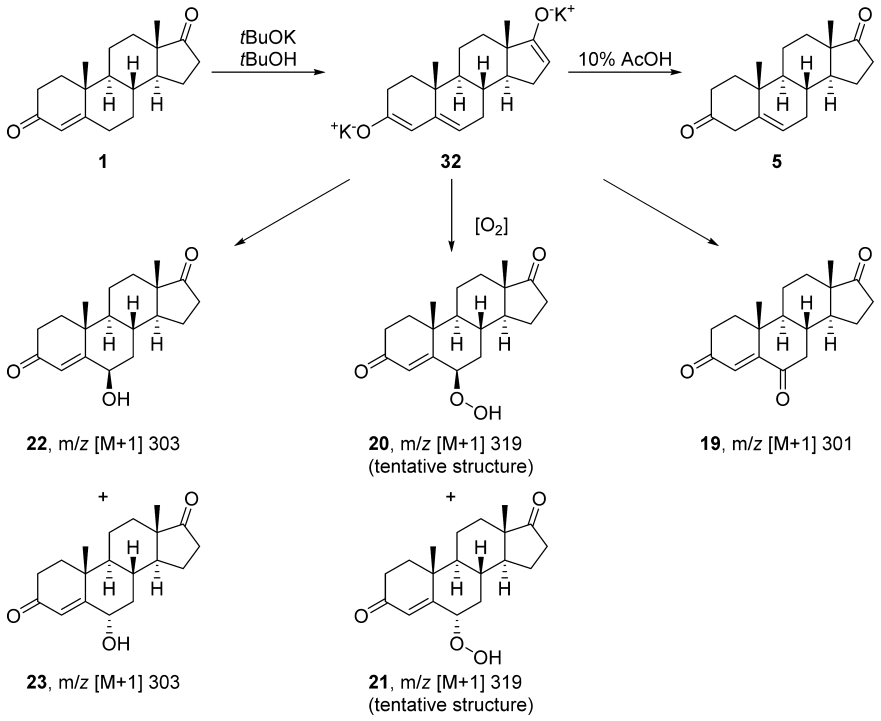
DHEA (2) into DHEA acetate (3) and to develop an efficient acetylation and crystallization to provide the material with the required purity (≥99.5% by HPLC area).

2.1. Isomerization. Several approaches to prepare 5-AD (5) are described in the literature;[19,34,35] however, these were considered suboptimal for our process requirements, as they required multistep syntheses. Our attention was drawn by short communications on deconjugation of α,β-unsaturated ketones,[31−33] including an example of a low-yielding potassium hydroxide-catalyzed isomerization of 4-AD (1).[32] After an initial screen, we were able to identify a promising initial set of reaction conditions that afforded 5-AD (5) in >80% yield (Scheme 3). Treatment of 4-AD (1) with 10 equiv of potassium *tert*-butoxide in *tert*-butanol for 90 min, followed by the kinetic quench of the extended enolate (32) into 10% (v/v) aqueous acetic acid, allowed precipitation of the product 5, which was then isolated by filtration.

Encouraged by these results, we proceeded to develop the process further. Initially, we observed great variability in the reaction outcome, with the relative amount of the desired 5-AD (5) varying from 50 to 95% (by HPLC area %). From consideration of the isomerization mechanism (Scheme 3), the root cause of this problem became evident. The initial formation of the dianion 32 occurs readily (<30 min) using 2.0−2.5 equiv of potassium *tert*-butoxide. (Note: while we have drawn this as the dianion, this is purely based on mechanism proposed in the literature[31] and the observation that we required >2 eq of base, and we did not obtain any additional confirmation of the structure). The subsequent kinetic protonation results in the desired 5-AD (5) isomer, which is sensitive to even mildly basic conditions and readily isomerizes

DOI: 10.1021/acs.oprd.6b00215
Org. Process Res. Dev. 2016, 20, 1520−1528

Scheme 4. Impurities Generated during Isomerization of 4-AD (1) to 5-AD (5)



back to 4-AD (**1**). Fortunately, the exposure of the 5-AD (**5**) to basic conditions could be minimized by quenching the enolate into an excess of acetic acid, rather than by adding the acid to the reaction mass. The addition rate, efficient mixing and temperature (<30 °C) have to be carefully controlled to achieve high yields and to prevent localized high pH "hotspots" during the quench. Failure to control these physical parameters leads to significant isomerization and apparent poor conversion. Moreover, 5-AD (**5**) quenched this way precipitated from the solution and could be readily isolated by filtration, which is a significant process advantage.

While the controlled quench addressed one of the issues with the reaction, we observed formation of several other impurities, as evidenced by additional peaks in the HPLC chromatogram and NMR spectra. The levels of these impurities varied from batch to batch, and their content changed upon storage of the 5-AD (**5**). Moreover, the formation of the same impurities was then also observed during the bioreduction step (vide infra, see Scheme 4).

The main impurities were isolated chromatographically and characterized by NMR and MS (see Supporting Information for details). The spectroscopic data obtained for one of the main side products were in agreement with the structure of androst-4-ene-3,6,17-trione (**19**, *m*/*z* 301 $[M + 1]^+$). This oxygenated impurity was reported previously by Pollack et al. and its formation ascribed to autoxidation of the steroid backbone by molecular oxygen present in the reaction.[19] We identified two further impurities, 6*β*- and 6*α*-hydroxyandrost-4-ene-3,17-dione (**22** and **23**, respectively, *m*/*z* 303 $[M + 1]^+$).[36] In addition we were able to isolate small quantities of two further compounds, which proved unstable, and we observed their conversion to trione **19** over the course of the NMR experiments. Based on the similarity of their ^{1}H NMR spectra to the isomeric 6-hydroxyandrost-4-ene-3,17-diones (**22** and **23**) and mass spectrometry data (both had *m*/*z* of 319), these compounds were tentatively assigned as 6*β*- and 6*α*-perhydroxyandrost-4-ene-3,17-diones (**20** and **21**), respectively. Their presence would be in agreement with the involvement of oxygen in the side-product formation; however, no further elucidation of the mechanism of autoxidation and possible interconversion between the compounds **19**–**23** was performed. Nevertheless, this highlighted the need to carry out the isomerization under oxygen-free conditions. Thus, the introduction of a rigorous nitrogen sparging protocol during the reactions reduced the levels of these impurities sufficiently; on a 300 g scale we were able to prepare crude 5-AD (**5**) of acceptable purity: typically 89–93% by HPLC area, containing 3–5% of 4-AD (**1**) and 3–4% oxygenated impurities **19**–**23**.

In summary, our efforts resulted in an efficient 4-AD (**1**) isomerization procedure, giving 5-AD (**5**) in approximately 80% yield and acceptable purity. We reduced the base requirement from 10 to 2 equiv of potassium *tert*-butoxide, providing significant cost reduction for this step. The material generated under the optimized conditions was used directly in the subsequent biocatalytic step, as it was not suitable for prolonged storage.

2.2. Development of the Enzymatic Step. *2.2.1. Ketoreductase Screening.* The key step of our proposed route relied on identifying a highly regio- and stereoselective ketoreductase enzyme to convert 5-AD (**5**) to the desired 3*β*-hydroxyandrost-5-ene-17-one (DHEA, **2**) exclusively. The bioreduction of diketone **5** could theoretically result in up to 16 possible products: four possible diastereoisomers of monohydroxysteroids (C3-OH or C17-OH) and further four possible diols (**6**). An additional eight isomeric products could be expected, if the double bond moves back to C4. The complexity of the chromatographic analysis of such a mixture and lack of commercially available reference materials added to the challenging nature of the enzymatic screen. Therefore, to simplify and accelerate the identification of regioselective enzymes, we took advantage of the reversibility of the ketoreductase-catalyzed reactions. Specifically, we screened

DOI: 10.1021/acs.oprd.6b00215
Org. Process Res. Dev. 2016, 20, 1520–1528

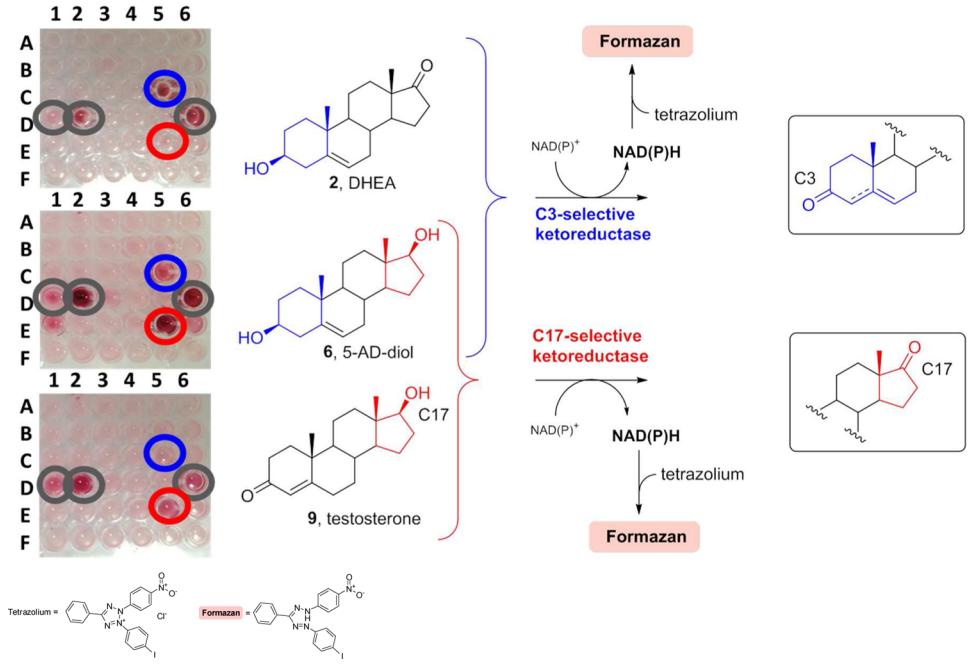


Figure 1. Principle of screening for regioselective ketoreductases in the oxidative direction using a NAD(P)H-linked colorimetric assay.

the enzyme libraries toward the oxidation of hydroxysteroids as depicted in Figure 1. The screen was performed using a routine colorimetric formazan-linked assay, which detects reduced NAD(P)H cofactor, formed during the biooxidation.[37] In parallel, we tested ketoreductases for the oxidation of commercially available DHEA (**2**), testosterone (**9**), and androst-5-ene-3β,17β-diol (5-AD-diol, **6**), observing red coloration in the wells with biocatalyst active toward individual compounds after 60 min at 30 °C (the low substrate solubility in aqueous media did not allow monitoring of the reactions spectrophotometrically and the plates were inspected visually).

The pictures show snapshots of typical screening plates tested with three different hydroxysteroids: top panel—DHEA (**2**); middle panel—5-AD-diol (**6**); bottom panel—testosterone (**9**). NAD(P)H cofactor formed in the oxidation in the presence of tetrazolium (2-(4-iodophenyl)-3-(4-nitrophenyl)-5-phenyl-2*H*-tetrazolium chloride—INT) and diaphorase causes red coloration of the wells with an active enzyme. Colors were as follows: highlighted in blue circles—an enzyme with exclusive activity toward C3β-hydroxyl group; in red circles—an enzyme with exclusive activity toward C17β-hydroxyl group; in gray circles—enzymes active toward both C17- and C3-hydroxyl groups (nonselective).

Using this screening strategy we quickly discriminated between the enzymes displaying 3β- versus 17β-regioselectivity (see Figure 1, top vs bottom panel). Androst-5-ene-3β,17β-diol (**6**, Figure 1, middle panel) was added to the screening program as a control to confirm the regioselectivity toward C3 and C17 hydroxyl groups.

The colorimetric screening strategy simplified and accelerated the screening for regioselective enzymes, without the need to put effort into complex and lengthy chromatographic analysis. We efficiently tested a collection of almost 400 proprietary and commercial ketoreductases to identify a short-chain dehydrogenase/reductase from *Sphingomonas wittichii*[38] as **the sole enzyme** with the desired 3β-stereoselectivity. Subsequent studies on the enzymatic reduction of 5-AD (**5**) demonstrated that the *Sphingomonas wittichii* ketoreductase catalyzed formation of DHEA with high diastereoselectivity (**2**, >99% de)—spiking experiments showed no detectable formation of 3α-epimer **13** by HPLC. Moreover, the enzyme showed almost no activity toward the isomer 4-AD (**1**).

2.2.2. Reaction Optimization. We optimized process parameters, such as substrate and ketoreductase loading, cosolvent, phase ratio, pH, and temperature in a series of experiments (details are shown in Table 1). We aimed to maximize the substrate concentration and to minimize the

Table 1. Optimization Studies of 5-AD (5) Bioreduction

parameter	evaluated range	set value
cofactor	$NAD^+/NADP^+$	NAD^+
pH	6.0–8.0	6.3
enzyme loading and form enzyme addition	0.25–10% (w/w or v/w) one batch vs multiple additions	first generation ketoreductase: 3% w/w (powder, 1 batch)[a]
		second generation ketoreductase: 5% v/w (liquid, 4 batches)[a]
		third generation ketoreductase: 0.25% w/w (powder, 1 batch)[b]
temperature	20–50 °C	33 °C
cosolvent[c]	2-MeTHF, EtOAc, MTBE, DIIPE, BuOAc, toluene, *n*-BuOH, THF, DMSO, DMF	2-MeTHF, EtOAc
cosolvent volume	0–66% v/v	50–60% v/v
buffer	TRIS, phosphate	phosphate
substrate conc.	3–150 g/L	100 g/L
$MgCl_2$[d]	0–5 mM	0 mM
base	2.0 M NaOH, 1.7 M Na_2CO_3, 1.5 M K_2CO_3	1.5 M K_2CO_3

[a]Used for the >200 g scale campaign. [b]Loading for the optimized enzyme powder. [c]Optimized water immiscible cosolvents were initially tested at 30% v/v, while water miscible ones were at 6% v/v. [d]Magnesium chloride was added to see if it would improve the protein stability/activity under the reaction conditions; however, no difference was observed.

DOI: 10.1021/acs.oprd.6b00215
Org. Process Res. Dev. 2016, 20, 1520–1528

enzyme loading in order to improve the volumetric efficiency and the cost of the process. In parallel, we also improved the gene and the protein expression of the ketoreductase to minimize the fermentation requirement (vide infra).

All of the bioreductions were conducted in a Multimax system, using 50 mL reactors with overhead stirring, temperature control, and pH control. We used glucose and glucose dehydrogenase to recycle the NAD(P)H cofactors, adjusting the pH with a base (2.0 M NaOH or 1.7 M Na_2CO_3). The best conversions were obtained at 25−35 °C and pH 6.0−7.0. Very early into the process development, we concluded that biotransformations proceeded more efficiently under biphasic reaction conditions, using 2-MeTHF or EtOAc—this increased the substrate solubility in the reaction media and allowed much higher conversions and substrate loadings than the addition of water miscible cosolvents. Consequently we were able to run >200 g scale batches at concentrations up to 150 g/L, achieving full conversion. EtOAc was selected as the best solvent overall, since it was significantly cheaper, although it required 10−20% higher enzyme loadings. Moreover, EtOAc offered a process safety advantage, as 2-MeTHF may form explosive peroxides. We replaced 2 M NaOH with 1.7 M Na_2CO_3 to avoid localized high pH "hotspots" leading to side-product formation. Ultimately, we preferred 1.4 M K_2CO_3 solution as a base, as it possesses higher solubility in water in comparison to Na_2CO_3 (112 g/100 mL versus 21.5 g/100 mL at 20 °C), which improved process reproducibility and eliminated the risk of line blockage in the pH control apparatus seen occasionally with saturated sodium carbonate solutions.

Under the optimized conditions >200 g scale enzymatic reductions proceeded efficiently using our second generation biocatalyst (liquid cell-free extract of the gene and expression optimized ketoreductase). Such biotransformations reached full conversions in 24−28 h, giving crude DHEA (**2**) in 88−90% purity by HPLC. Further improvements of biocatalyst form (powder, third generation enzyme) further reduced the time required to reach >95% conversion to 6−8 h at 0.25−0.30% w/w enzyme loading.

During these bioreductions, we observed the formation of similar impurities to the isomerization step. Unsurprisingly, their content increased significantly at elevated temperatures (>40 °C). Under such conditions, at pH 7.5 and in the presence of air, 5-AD (**5**) decomposed almost completely over 3 days. The most prominent impurities were 4-AD (**1**) and trione (**19**) as well as hydroxy- and perhydroxysteroids **20**−**23**. Nevertheless, maintaining the pH at 6−7 and temperature <35 °C ensured an efficient biotransformation and minimized the reverse isomerization. The content of 4-AD (**1**) present in starting 5-AD (**5**) material did not increase by more than 2−3%. Sparging of the bioreduction solutions with nitrogen was necessary to keep the level of the oxygenated impurities below 8% from the initial 4−6% present in the input crude 5-AD (**5**).

In addition, we observed the formation of some impurities specific to the bioreduction itself. We detected low levels of 5-AD-diol (**6**, < 0.5% by HPLC area), possibly arising from reduction at C17 catalyzed by the *Sphingomonas wittichii* ketoreductase and/or other endogenous, nonselective *E. coli* derived ketoreductase enzymes present in either the ketoreductase or glucose dehydrogenase preparations. This impurity could be minimized by monitoring conversion and stopping the reaction as soon as it reached completion.

2.2.3. Molecular Biology and Fermentation. The first generation ketoreductase preparation used in the screen and the initial process development had relatively low activity, 17−35 U/g of enzyme powder, as it contained a large amount of insolubly expressed protein. Consequently, high enzyme loadings (3−5% w/w, 2U per g of substrate) were required to achieve full conversion of 5-AD (**5**). Therefore, we decided to improve the protein expression, fermentation and downstream processing of the enzyme. This resulted in 10−15 fold improved enzyme productivity, lowering enzyme loadings, which also resulted in better process parameters (elimination of the emulsions we observed with the first generation enzyme preparations). It is worth noting that such improvements in biocatalyst production can be very effective in improving the efficiency of a biotransformation and are rapidly implemented.[39]

First, we optimized the gene encoding the ketoreductase for heterologous expression in a phage-resistant *E. coli* BL21(DE3) strain containing pET26b vector. This afforded an isopropyl β-D-1-thiogalactopyranoside (IPTG) inducible *E. coli* strain, in which 90% of the ketoreductase was solubly expressed. Second, we developed high optical density fermentation (20 L, glucose feed, 176 OD, see Supporting Information for details), which after clarification and ultrafiltration (10 kDa membrane) resulted in second-generation enzyme produced as liquid cell free extract of 39 U/mL activity.

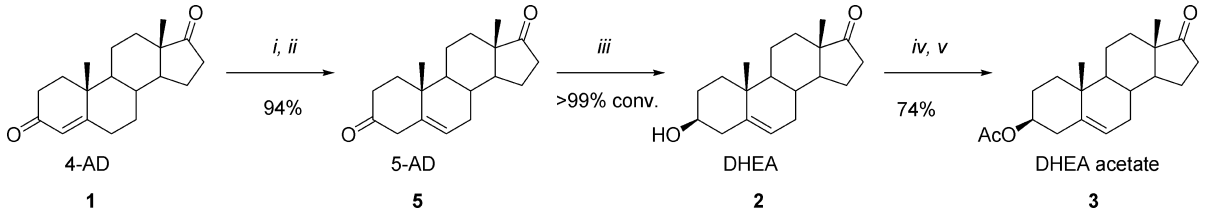
Unfortunately, upon storage for 1 month at 2−8 °C, we observed that the enzyme preparation lost 75% of its activity and the later batches of the bioreduction required higher than expected enzyme loading. We discovered that lyophilization improved its storage and stability over time. Consequently, later batches of the enzyme were lyophilized to give third generation ketoreductase powder with 400−500 U/g activity. This represented an overall 10−15 fold improvement in comparison to the first generation biocatalyst (17−35 U/g), and it allowed a decrease in the enzyme loading from 3 to 5% to 0.25−0.30% w/w to achieve 95−99% conversion in 6h. Not only did the reduction in biocatalyst loading lower the cost of the biocatalyst, but it improved the ease of the workup, as quick phase separation was observed after the biotransformation.

2.2.4. Purification of DHEA. Initially we intended to develop an efficient crystallization of crude DHEA (**2**) after the biotransformation step (79−91% purity by HPLC). A literature evaluation indicated that five polymorphs of DHEA (**2**) are known (forms I−V), as well as three monohydrate polymorphs and numerous solvates with solvents like alcohols and ethers.[40,41] Crystallization studies of the crude DHEA (**2**) isolated from the biotransformation gave a product of >98% purity using a variety of solvents, but the recoveries were low (10−55%, results not shown). Therefore, we decided to telescope the crude DHEA to the subsequent acetylation step and focus on developing an efficient crystallization of DHEA acetate (**3**) instead.

2.3. Acetylation and Final Crystallization. The acetylation of DHEA (**2**) to its acetate (**3**) proved to be a facile reaction and proceeded quantitatively under a variety of reaction conditions tested. Successful reaction conditions included: (i) dichloromethane/acetic anhydride/pyridine/DMAP; (ii) dichloromethane/acetic anhydride/boron trifluoride diethyl etherate; (iii) acetic acid/acetic anhydride/sodium acetate; (iv) toluene/acetic anhydride/triethylamine/DMAP (details not shown). In the early stages of development DHEA acetate (**3**) was prepared using acetic anhydride, triethylamine with catalytic DMAP in toluene.[38] These conditions gave a fast, robust reaction with low-cost raw materials, and acetate (**3**) was

DOI: 10.1021/acs.oprd.6b00215
Org. Process Res. Dev. 2016, 20, 1520−1528

Scheme 5. Optimized Conditions for the >200 g Scale Process to Convert 4-AD (1) to DHEA Acetate (3)[a]



[a](i) *t*-BuOK (2.1 equiv), *t*-BuOH (6 vol), 30−35 °C, N_2, 20 min; (ii) 2.5% AcOH in water (20 vol), 20−30 °C, N_2, 60 min, 94% yield, 93% pure; (iii) 100 g/L, EtOAc−phosphate buffer (40 mM, pH 6.5) 60:40 v/v, NAD^+ (0.075% w/w), glucose (1.1 equiv), glucose dehydrogenase (0.044% w/w), ketoreductase from *Sphingomonas wittichii* (liquid preparation, 2 U per g of 5-AD), temp. 33 °C, 29 h, N_2, >99% conversion, 91% purity; (iv) 2.0 equiv of Ac_2O, AcOH (3 vol), NaOAc (1.25 equiv), 60 °C, N_2, 16 h, quench with MeOH−water (1.5 vol); (v) crystallization from hot MeOH (4 vol), 74%, purity >99.5% (by HPLC). 64% overall yield.

obtained in >98% purity (by HPLC) as 2 crops in 85−87% yield.

During further process development and optimization work, we aimed to reduce the number of unit operations and to develop a facile acetylation procedure that could be telescoped into the final crystallization process. After some further optimization we achieved full conversion of DHEA (**2**) using acetic anhydride in the presence of sodium acetate in acetic acid over 16 h (Scheme 5). Quenching the reaction into a mixture of water and methanol (9:1, 1.5 vol) precipitated crude DHEA acetate (**3**) in 88% yield and 98% purity. This material was subsequently recrystallized from methanol (4 vol), affording final product **3** in 74% yield and >99.5% purity (by HPLC), meeting the product specifications. These modifications considerably simplified the process and provided both cost and operational benefits.

3. SUMMARY

We developed a novel, high yielding chemoenzymatic route to DHEA acetate (**3**) from 4-AD (**1**). The key enabling reaction of this process was a highly regio- and stereoselective bioreduction of 5-AD (**5**) to DHEA (**2**). A fast colorimetric assay was crucial in the identification of a short-chain dehydrogenase from *Sphingomonas wittichii*, which possessed the desired selectivity. The enzyme displayed good robustness and performance under the biphasic reaction conditions,[38] which enabled the biotransformations to be conducted at high substrate concentrations (up to 150 g/L). Optimization of the gene expression as well as the fermentation conditions of an *E. coli* host strain resulted in 10−15 fold improvement of the enzyme productivity and gave us access to a cost-effective biocatalyst. Development of both the 4-AD to 5-AD isomerization and the final acetylation and purification provided a robust process, suitable for further scale-up. Identification of the impurities generated in the process enabled the development of control strategies and was crucial to obtain high purity final product.

4. EXPERIMENTAL SECTION

4.1. Materials and Methods. 4-AD (**1**) was supplied by Dr. Reddy's de Mexico, Cuernavaca-Cuautla, 62578 Civac Jiutepec Morelos, Mexico. Testosterone (**9**) was obtained from Sigma. Epitestosterone (**10**) was obtained from LGC Standards, Queens Road, Teddington, Middlesex, TW11 0LY, UK. 3*β*,17*β*-5-AD-diol (**6**) was provided by Dr. Reddy's Laboratories Ltd., Custom Pharmaceutical Services, TDC-1 Bollaram Road, Miyapur, Hyderabad 500049, Telangana, India. 3*α*-DHEA acetate (**14**) was obtained from Bujno Synthesis, Dorodna 16, Warsaw, Poland. 3*α*-DHEA (**13**) and 3*α*-DHEA acetate (**14**) were also synthesized from 3*β*-DHEA (**2**) using a Mitsunobu reaction sequence according to a previously reported method[42] (see Supporting Information for details). All enzymes used in the screen were proprietary to Dr. Reddy's Laboratories or obtained from commercial suppliers (Almac, Codexis, Daicel, Evocatal, Johnson Matthey, Prozomix and Syncore). Glucose dehydrogenase GDH CDX-901 (66 U/mg) was supplied by Codexis. Nicotinamide cofactors NAD^+ and $NADP^+$ were obtained from Europa Bioproducts. Routine NMR spectra were recorded on a Bruker DRX 400 MHz spectrometer and chemical shifts for ^1H spectra were referenced relative to internal tetramethylsilane or residual solvent peaks. If additional resolution and sensitivity was required, compounds were analyzed on a 700 and 500 MHz NMR instrument with a cryoprobe, School of Chemistry, University of Cambridge, Lensfield Road, Cambridge CB2 1EW, UK.

4.2. Biology and Fermentation. For detailed information on the methods, please see the Supporting Information.

4.2.1. Analytical Methods. The isomerization and biotransformations were monitored by HPLC: Method A using ELSD and UV (λ = 200 nm) detectors and Luna C18 column 150 × 4.6 mm, column temp. 50 °C, flow 1 mL/min, MP 50:50 A:B, A: water, B: MeOH−MeCN 30:70, inj. vol: 10 μL. The progress of the biotransformation reactions was also monitored by the base consumption as well as by ^1H NMR spectroscopy. LC-MS data were collected using ESI(+) ion detector and HPLC method A, where 0.1% v/v was added to water.

The purity of the DHEA acetate (**3**) was determined by HPLC: Method B using UV detector (λ = 205 nm) and Kinetex C8 column 2.6 μm 100 Å 150 × 4.6 mm, flow 1 mL/min, column temp. 40 °C, using mobile phase gradient (A = 80:20 water−MeCN, B = MeCN, see Table 2), inj. vol: 10 μL.

Table 2. Mobile Phase Gradient for HPLC Analysis of DHEA Acetate (3) Using the Kinetex C8 Column (Method B)

time (min)	0	5	20	25	35	50	55	60
mobile phase A	65	65	35	10	5	5	65	65
mobile phase B	35	35	65	90	95	95	35	35

4.2.2. Enzyme Activity Assay. The activity of the ketoreductase from *Sphingomonas wittichii* was determined in 5 g use tests or spectrophotometrically using 4-heptanol as a substrate, by following its oxidation at 340 nm, monitoring the conversion of the $NAD(P)^+$ cofactor to NAD(P)H. One unit of activity is defined as sufficient enzyme to catalyze the oxidation

DOI: 10.1021/acs.oprd.6b00215
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of 1 μmol/min of 4-heptanol under the assay conditions (see the Supporting Information for details).

4.2.3. Colorimetric Enzyme Screening Using INT/Diaphorase. In a spectrophotometric 96-well plate ketoreductase (0.1−0.6 mg/mL), diaphorase (0.1−0.6 mg/mL), NAD^+ (0.4 mg/mL), and $NADP^+$ (0.4 mg/mL) were rehydrated with a solution of INT in deionized water (1 mg/mL, 190 μL). A sample of 10 μL of a DMSO solution of the respective hydroxysteroid (20 mg/mL stock solution of **2**, **6**, or **9**) was added to commence the reaction. The plates were sealed and incubated in a Heidolph shaker at 30 °C, 750 rpm, and they were visually inspected after 1, 5, and 24 h.

4.2.4. Biotransformation Reactions (Optimization Studies): General Procedure. In a Multimax reactor vessel 5-AD (**5**, 0.3−3.0 g) was predissolved in water immiscible cosolvent (5−25 mL, MTBE, 2-MeTHF, EtOAc). Buffer cocktail (10−25 mL) containing ketoreductase (1−3% w/w), glucose (1.1−2.0 equiv), NAD^+ (7−10 mg), and $NADP^+$ (7−10 mg) and glucose dehydrogenase (CDX-901, 3−10 mg, 66 U/mg) in phosphate buffer (50 mM, 10−25 mL) was added, and the reaction mixtures were stirred for 21 h at 20−50 °C. The reaction pH (5.5−8.5) was maintained by autotitration with 2 M NaOH or 1.7 M sodium carbonate solution. The products were analyzed by HPLC and NMR spectroscopy.

4.2.5. Chemistry. The initial reaction conditions were performed as described previously.[38] The optimized process was performed as described below.

4.2.5.1. Preparation of 5-Androsten-3,17-dione (5). *tert*-Butanol (2.00 L) was sparged with nitrogen for 90 min at 30−35 °C. Potassium *tert*-butoxide (235 g, 2.09 mol) was added, and the mixture was stirred with nitrogen sparging for a further 90 min at 30−35 °C. 4-AD (**1**, 300 g, 1.00 mol) was added, and the reaction was stirred for a further 1 h with nitrogen sparging. Separately, acetic acid (150 mL) was added to a 20 L vessel containing water (6.00 L) that had been sparged with nitrogen for 24 h, and the mixture was stirred at 20 °C under nitrogen. The reaction mixture was then slowly added to the acetic acid solution via cannula over 10−15 min. Once the addition was complete, the mixture was cooled to 12 °C and stirred for 1 h. The precipitate obtained was filtered, washed with water (3 × 2.00 L), and dried under vacuum at 40 °C. The product is obtained as a free-flowing white powder (283 g, 94% yield), purity by HPLC: 93%, 4-AD (**1**), 3%; oxygenated impurities (**19**−**23**), 4%. ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.38 (d, 1H), 3.28−3.33 (m, 1H), 2.86 (dd, 1H), 2.45−2.50 (2H), 1.05−2.60 (m, 15H), 1.22 (s, 3H), 0.92 (s, 3H).

4.2.5.2. Preparation of Dehydroepiandrosterone (2). 5-AD (**5**, 8.0 g, 27.9 mmol, 94% pure by HPLC, 2% 4-AD, 4% impurities **19**−**23**) was dissolved in EtOAc (40 mL) at 33 °C under nitrogen atmosphere and stirred vigorously. To this was added a solution of phosphate buffer (50 mM, 40 mL, pH 6.3) containing glucose (6.0 g, 33.3 mmol, 1.2 equiv), NAD^+ (15 mg), glucose dehydrogenase (CDX-901, 8 mg, 528 U), and ketoreductase powder (3rd generation, 20 mg, 0.25% w/w, 9 U) was added. The reaction temperature was maintained at 32.5 °C (jacket temp 33 °C), while the pH 6.3−6.5 was kept constant by addition of 1.5 M K_2CO_3 solution in water. The reaction conversion was monitored by base consumption as well as by HPLC and ^{1}H NMR spectroscopy. After 6 h the reaction reached ∼95% conversion. It was stirred for a total of 21 h to give >99% conversion. The mixture was warmed up to 70 °C to fully dissolve partially precipitated DHEA, and the phases were separated. The separated organic layer was dried over magnesium sulfate and evaporated to give crude DHEA as solid residue (7.2 g, 24.2 mmol, 90% yield). Purity by HPLC: 93% [5-AD (**5**, 0.5%), 4-AD (**1**, 1.9%), 5-AD-diol (**6**, 0.5%)]. ^{1}H NMR ($CDCl_3$, 400 mHz) δ 5.38 (d, 1 H), 3.50−3.58 (m, 1 H), 2.47 (dd, 1 H), 2.22−2.39 (m, 2H), 2.04−2.12 (m, 2H), 1.92−1.98 (m, 1 H), 1.83−1 0.89 (m, 3H), 1 0.44−1 0.71 (m, 6H), 1.22−1.29 (m, 2H), 0.97−1.14 (m, 2H), 1.04 (s, 3H), 0.89 (s, 3H).

4.2.5.3. Preparation of DHEA Acetate (3) from 5-AD (5) on 200 g Scale (Telescoped Process). 5-AD (**5**, 235 g, 0.82 mol) was loaded into a 5 L reactor and sparged with nitrogen for 30 min upon gentle stirring. EtOAc (1.15 L) was added, and the mixture was stirred at 33 °C under nitrogen until the substrate was fully dissolved. In a separate flask KH_2PO_4 (7.85 g) and glucose (162 g, 0.90 mol) were dissolved in 1.65 L of deionized water at 20 °C, and the pH was adjusted to 6.3 using solid KOH (1.40 g, ≥85% assay). The solution was sparged with nitrogen for 2−5 h. NAD^+ (0.20 g), glucose dehydrogenase (CDX-901, 165 mg, 10.9 kU), and ketoreductase cell free extract (second generation, 4.0 mL, 40 U) were added and stirred until fully dissolved. The buffer solution of enzymes was added to the vigorously stirred solution of 5-AD in EtOAc at 32.5 °C. The reaction was stirred at 32.5 °C, and pH 6.3−6.5 was maintained by autotitration with 1.7 M Na_2CO_3 solution in water. The reaction conversion was monitored by base consumption as well as by ^{1}H NMR spectroscopy. After 4 h, the reaction reached 43% conversion, and additional portions of ketoreductase (3 mL, 30 U), NAD^+ (300 mg) and GDH (160 mg, 10.9 kU) were added; after 8 h more ketoreductase (4 mL, 40 U), NAD^+ (300 mg), and GDH (160 mg, 10.9 kU) were added. The mixture was stirred for 22 h and reached full conversion. The reaction mixture was warmed up to 55 °C to fully dissolve the partially precipitated DHEA, and the phases were separated. The aqueous layer was extracted with EtOAc (1 L) at 55 °C. The combined organic layers were washed with brine (0.4 L) and water (0.4 L) and passed through a magnesium sulfate plug, washed with additional EtOAc (0.4 L). The solvent was partially evaporated under vacuum (100 mbar/50 °C water baths) to give 643 g of DHEA (**2**) in EtOAc, which solidified. Sample analysis indicated 36% potency by HPLC, equivalent to 0.80 mol, yield 97% (91% purity by HPLC, 4-AD, 7%; oxygenated impurities, 2%). This material was suspended in acetic acid (400 mL), and the residual EtOAc was removed under reduced pressure. Additional 320 mL of acetic acid were added (720 mL total, 3 vols), acetic anhydride (150 mL, 1.60 mol), and sodium acetate (80.0 g, 0.98 mol). The reaction was stirred at 60 °C for 16 h under a nitrogen atmosphere. Upon completion (by ^{1}H NMR), the reaction was cooled to 25 °C; a mixture of water (1125 mL) and methanol (125 mL) was added to the reaction mixture over 10 min, and it was stirred for 1 h. The precipitate was filtered and washed with further 3:1 water/methanol solution (1000 mL). The wet cake (320 g) was dissolved in hot methanol (1000 mL), and this solution was allowed to cool to 20 °C, then cooled further in an ice bath. The solid was collected and washed with additional methanol−water mixture (1:2, 300 mL). The solid was placed in a drying oven at 40 °C overnight to give DHEA acetate (**3**) as a white solid (171.4 g, 74% yield for 2 steps, and purity 99.5% by HPLC). ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.41 (d, 1H), 4.57−3.65 (m, 1H), 2.46 (dd, 1H), 2.28−2.36 (m, 2H), 2.04 (s, 3H), 1.80−2.20 (m, 6H), 0.95−1.75 (m, 10), 1.05 (s, 3H), 0.89 (s, 3H).

DOI: 10.1021/acs.oprd.6b00215
Org. Process Res. Dev. 2016, 20, 1520−1528

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.oprd.6b00215.

Synthesis and characterization of the main process impurities; structural assignment data for the oxygenated compounds **19**−**23**; experimental for molecular biology and fermentation; enzyme activity assay and sample chromatograms (PDF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We acknowledge Pieter de Koning for invaluable discussions and his help in preparation of this manuscript.

■ ABBREVIATIONS

DHEA, dehydroepiandrosterone; 5-AD, androst-5-ene-3,17-dione; 4-AD, androst-4-ene-3,17-dione; HSD, hydroxysteroid dehydrogenase; KSI, ketosteroid isomerase; NAD^+, nicotinamide adenine dinucleotide (oxidized form); NADH, nicotinamide adenine dinucleotide (reduced form); $NADP^+$, nicotinamide adenine dinucleotide phosphate (oxidized form); NADPH, nicotinamide adenine dinucleotide phosphate (reduced form); GDH, glucose dehydrogenase; IPTG, isopropyl β-D-1-thiogalactopyranoside

■ REFERENCES

(1) Mo, Q.; Lu, S. F.; Simon, N. G. *J. Steroid Biochem. Mol. Biol.* **2006**, *99*, 50−58.

(2) Potter, G. A.; Barrie, S. E.; Jarman, M.; Rowlands, M. G. *J. Med. Chem.* **1995**, *38*, 2463−2471.

(3) Barrie, S. E.; Jarman, M.; Potter, G. A. 17-Substituted steroids useful in cancer treatment. WO1993020097 A1, 1993.

(4) Ding, H. X.; Liu, K. K.-C.; Sakya, S. M.; O'Donnell, C. J.; Flick, A. C.; Li, J. *Bioorg. Med. Chem.* **2011**, *19*, 1136−1154.

(5) Al Jasem, Y. Al; Khan, M.; Taha, A.; Thiemann, T. *Mediterr. J. Chem.* **2014**, *3*, 796−830.

(6) Marker, R. E.; Krueger, J. *J. Am. Chem. Soc.* **1940**, *62*, 3349−3350.

(7) Rosenkranz, G. *Steroids* **1992**, *57*, 409−418.

(8) Xi, Z.; Zhang, G.; Wang, Y. Method for preparation of dehydroepiandrosterone (DHEA). CN 102603839 A1, 2012.

(9) Wang, X.-L.; Kim, H.-J.; Kang, S.-I.; Kim, S.-I.; Hur, H.-G. *Arch. Microbiol.* **2007**, *187*, 155−160.

(10) Donova, M. V.; Egorova, O. V. *Appl. Microbiol. Biotechnol.* **2012**, *94*, 1423−1447.

(11) Bhatti, H. N.; Khera, R. A. *Steroids* **2012**, *77*, 1267−1290.

(12) Cruz Silva, M. M.; Riva, S.; Sá E Melo, M. L. *Tetrahedron* **2005**, *61*, 3065−3073.

(13) Cruz Silva, M. M.; Riva, S.; Sá E Melo, M. L. *Tetrahedron: Asymmetry* **2004**, *15*, 1173−1179.

(14) Thomas, J. L.; Strickler, R. C.; Myers, R. P.; Covey, D. F. *Biochemistry* **1992**, *31*, 5522−5527.

(15) Thomas, J. L.; Mason, J. I.; Brandt, S.; Spencer, B. R.; Norris, W. *J. Biol. Chem.* **2002**, *277*, 42795−42801.

(16) Rajapaksha, M.; Thomas, J. L.; Streeter, M.; Prasad, M.; Whittal, R. M.; Bell, J. D.; Bose, H. S. *Biochemistry* **2011**, *50*, 11015−11024.

(17) Bertolino, A.; Benson, A. M.; Talalay, P. *Biochem. Biophys. Res. Commun.* **1979**, *88*, 1158−1166.

(18) Benson, A. M.; Talalay, P. *Biochem. Biophys. Res. Commun.* **1976**, *69*, 1073−1079.

(19) Wilde, T. C.; Blotny, G.; Pollack, R. M. *J. Am. Chem. Soc.* **2008**, *130*, 6577−6585.

(20) Pollack, R. M. *Bioorg. Chem.* **2004**, *32*, 341−353.

(21) Oppermann, U. C.; Filling, C.; Berndt, K. D.; Persson, B.; Benach, J.; Ladenstein, R.; Jörnvall, H. *Biochemistry* **1997**, *36*, 34−40.

(22) Han, Q.; Campbell, R. L.; Gangloff, A.; Huang, Y.; Lin, S. *J. Biol. Chem.* **2000**, *275*, 1105−1111.

(23) Benach, J.; Filling, C.; Oppermann, U. C. T.; Roversi, P.; Berndt, K. D.; Jornvall, H.; Ladenstein, R. *Biochemistry* **2002**, *41*, 14659−14668.

(24) Grimm, C.; Maser, E.; Möbus, E.; Klebe, G.; Reuter, K.; Ficner, R. *J. Biol. Chem.* **2000**, *275*, 41333−41339.

(25) Kochakian, C. D. *J. Steroid Biochem.* **1982**, *17*, 541−546.

(26) Fogal, S.; Bergantino, E.; Motterle, R.; Castellin, A.; Arvotti, G. Process for the Preparation of Testosterone. US 20110207172 A1, 2011.

(27) Pollack, R. M.; Zeng, B.; Mack, J. P. G.; Eldin, S. *J. Am. Chem. Soc.* **1989**, *111*, 6419−6423.

(28) Pollack, R. M.; Thornburg, L. D.; Wu, Z. R.; Summers, M. F. *Arch. Biochem. Biophys.* **1999**, *370*, 9−15.

(29) Wu, Z. R.; Ebrahimian, S.; Zawrotny, M. E.; Thornburg, L. D.; Perez-Alvarado, G. C.; Brothers, P.; Pollack, R. M.; Summers, M. F. *Science* **1997**, *276*, 415−418.

(30) Ha, N. C.; Choi, G.; Choi, K. Y.; Oh, B. H. *Curr. Opin. Struct. Biol.* **2001**, *11*, 674−678.

(31) Ringold, H. J.; Malhotra, S. K. *Tetrahedron Lett.* **1962**, *15*, 669−672.

(32) D'Incan, E.; Viout, P. *Tetrahedron* **1984**, *40*, 3421−3424.

(33) Amar, D.; Permutti, V.; Mazur, Y. *Tetrahedron* **1969**, *25*, 1717−1726.

(34) Morton, D.; Dick, A. R.; Ghosh, D.; Davies, H. M. L. *Chem. Commun.* **2012**, *48*, 5838−5840.

(35) Davies, H.; Ghosh, D.; Morton, D. Substituted androst-4-ene diones. WO2011127232 A2, 2011.

(36) Kollerov, V. V.; Shutov, A. A.; Fokina, V. V.; Sukhodol'skaya, G. V.; Donova, M. V. *J. Mol. Catal. B: Enzym.* **2008**, *55*, 61−68.

(37) *Enzyme Assays. Hight-throughput Screening, Genetic Selection and Fingerprinting*; Reymond, J.-L., Ed.; Wiley-VCH, 2006.

(38) Fryszkowska, A.; Quirmbach, M. S.; Gorantla, S. S. C.; Alieti, S. R.; Poreddy, S. R.; Dinn, N. K. R.; Timmanna, U.; Dahanukar, V. Process for the preparation of dehydroepiandrosterone and its intermediates. WO2014188353 A2, 2014.

(39) Bornscheuer, U. T.; Huisman, G. W.; Kazlauskas, R. J.; Lutz, S.; Moore, J. C.; Robins, K. *Nature* **2012**, *485*, 185−194.

(40) Chang, L. C.; Caira, M. R.; Guillory, J. K. *J. Pharm. Sci.* **1995**, *84*, 1169−1179.

(41) Parasrampuriar, J.; Yonker, M. B.; Schwartz, K. E.; Gurwith, M. J. DHEA composition and method. US 7045513 B1, 2006.

DOI: 10.1021/acs.oprd.6b00215
Org. Process Res. Dev. 2016, 20, 1520−1528

(42) Ge, Y.; Huang, Y.; White, S. K. Methods and compounds for preparing 3alpha-oxygen substituted steroids. WO 2012083090 A2, 2012.

DOI: 10.1021/acs.oprd.6b00215
Org. Process Res. Dev. 2016, 20, 1520−1528