Phytochemistry, Vol 23, No 10, pp 2131–2154, 1984
Printed in Great Britain

0031–9422/84 $3 00 + 0 00

REVIEW ARTICLE NUMBER 4

STEROID TRANSFORMATIONS BY MICROORGANISMS

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(*Received* 3 *January* 1984)

Key Word Index—Steroids, microbial transformation, enzyme immobilization

Abstract—Microbial transformations of various steroids are reviewed Newer developments in this field are discussed A compilation of different steroid substrates used for transformations by various microorganisms during the period 1979–1982, along with the metabolites formed, is included

INTRODUCTION

Application of microbiology in the preparation of foods and beverages has been in use from the dawn of civilization However, the use of microorganisms for steroid conversions is of comparatively recent origin Although processes involving reduction of the 17-keto group [1] and oxidation of the Δ^5-3β-hydroxyl structure to Δ^4-3-oxo [2] were patented in 1937, the importance of microbial transformation was first realized in 1952 when Murray and Peterson patented the process of 11α-hydroxylation of progesterone by a *Rhizopus* species The chemical methods of preparation of progesterone from widely available plant steroids, e g diosgenin and stigmasterol, were well standardized However, conversion of progesterone to corticosteroids necessitated introduction of an oxygen function at the C-11 position The chemical processes used for the purpose were not economical and the single-step, high yielding, microbial process for the preparation of 11α-hydroxyprogesterone was immediately employed for industrial exploitation Since then microbial reactions for the transformation of steroids have proliferated and several microbial hydroxylations and dehydrogenations have become industrially important for the production of steroid hormones and their analogues Very recently microbial production of androstanes by degradation of side chains of cholesterol or sitosterol has also become industrially important The voluminous literature which developed has been covered by three comprehensive monographs [3–5] Several other monographs [6–8] and reviews [9–22] cover literature up to 1978 The present review attempts to present the position reached during the period 1979–1982

Much of the recent interest centres on the development of processes suitable for industrial exploitation Degradation of the side chains of cholesterol and sitosterol has received considerable attention, obviously due to its industrial potential Other reactions such as hydroxylation, dehydrogenation etc have also been studied Reports on the mechanism of hydroxylation have appeared and an excellent review on this topic has recently been published [23] Development of newer analytical techniques has facilitated separation and purification of microbial metabolites The newer technique of High Performance Liquid Chromatography (HPLC) has been employed for the separation of metabolites which are difficult to separate by column chromatography or preparative TLC For example, 5,6α-epoxy-5α-stigmastan-3β-ol (**1**) and 5,6β-epoxy-5β-stigmastan-3β-ol (**2**) were separated by HPLC on a μ Porasil microparticulate silica gel column [24] For rapid identification of the metabolites various spectroscopic methods, particularly ^{1}H NMR, ^{13}C NMR and mass spectrometry, are being used increasingly

HYDROXYLATION

The first commercialized microbial process in the steroid field was the process of 11α-hydroxylation of progesterone Microbial hydroxylation reactions are unique in their diversity and importance in that they offer access to otherwise inaccessible sites in the steroid molecule As such the reactions are of considerable commercial interest, particularly 11- and 16α-hydroxylations leading to adrenal cortex hormones and their analogues During the period under review a variety of steroid substrates have been examined for hydroxylation studies The substrates and the metabolites are shown in Table 1

SIDE CHAIN DEGRADATION

As previously mentioned microbial degradation of the C-17 saturated side chain of widely available sterols such as cholesterol, sitosterol, campesterol etc for the preparation of androstanes has received much attention A review of the biochemical production of androsta-1,4-diene-3,17-dione (ADD) and androst-4-ene-3,17-dione (AD) from cholesterol has appeared [25] Newer techniques have been introduced for optimization of the process for obtaining better yields of the androstane derivatives Production of androst-4-ene-3,17-dione from a choles-

Table 1 Microbial hydroxylations of various steroid substrates

Substrates	Microorganism	Products	References
1α-Hydroxylation			
3β-Hydroxyandrost-5-en-17-one	*Penicillium oxalicum* or *Aspergillus* sp	1α,3β-Dihydroxyandrost-5-en-17-one	56
17α-Ethynyl-17-hydroxy-18-methyl-4,15-estradien-3-one	*Aspergillus clavatus*	1α,17-Dihydroxy-17α-ethynyl-18-methyl-4,15-estradien-3-one	57
3β-Hydroxyandrost-5-en-17-one	*Penicillium* sp	1α,3β-Dihydroxyandrost-5-en-17-one	58
1β-Hydroxylation			
12,12-Difluoro-5α-androstan-3-one	*Rhizopus nigricans*	1β,16β-Dihydroxy-12,12-difluoro-5α-androstan-3-one	59
5α-Androstan-17-one	*Calonectria decora*	1β,6α-Dihydroxy-5α-androstan-17-one	59
5α-Androstan-17-one	*Aspergillus ochraceus*	1β,6α-Dihydroxy-5α-androstan-17-one	59
3,3-Difluoro-5α-androstan-17-one	*Calonectria decora*	1β,6α-Dihydroxy-3,3-difluoro-5α-androstan-17-one	59
12,12-Difluoro-5α-androstan-17-one	*Calonectria decora*	(a) 1β,6α-Dihydroxy-12,12-difluoro-5α-androstan-17-one (b) 1β,6α,17-Trihydroxy-12,12-difluoro-5α-androstan	59
N-Acetyl-17a-aza-D-homo-androst-5-en-3β-yl acetate	*Cunninghamella elegans*	(a) *N*-Acetyl-17a-aza-D-homoandrost-5-ene-1β,3β-diol (b) *N*-Acetyl-5,6β-epoxy-17a-aza-D-homo-5β-androstane-1β,3β-diol (c) *N*-Acetyl-17a-aza-D-homoandrost-5-ene-1β,3β,7β-triol	60
5α-Androstan-17-one	*Cunninghamella elegans*	1β,7α-Dihydroxy-5α-androstan-17-one	61
3β-Acetoxy-5α-androstan-17-one	*Cunninghamella elegans*	1β,7α-Dihydroxy-3β-acetoxy-5α-androstan-17-one	61
3α-Hydroxy-5α-androstan-17-one	*Cunninghamella elegans*	1β,3α-Dihydroxy-5α-androstan-17-one	61
6β-Methoxy-3α,5-cyclo-5α-androstan-17-one	*Rhizopus nigricans*	1β-Hydroxy-6β-methoxy-3α,5-cyclo-5α-androstan-17-one	62
3α-Hydroxylation			
5α-Androstan-17-one	*Rhizopus nigricans*	3α,11α-Dihydroxy-5α-androstan-17-one	59
7,7-Difluoro-5α-androstan-17-one	*Rhizopus nigricans*	3α,11α-Dihydroxy-7,7-difluoro-5α-androstan-17-one	59
3β-Hydroxylation			
5α-Androstan-17-one	*Calonectria decora*	(a) 3β,12β,15α-Trihydroxy-5α-androstan-17-one (b) 3β,11α,16β-Trihydroxy-5α-androstan-17-one	59
5α-Androstan-16-one	*Rhizopus nigricans*	3β,7α-Dihydroxy-5α-androstan-16-one	59
3α-Fluoro-5α-androstan-16-one	*Rhizopus nigricans*	3β,7α-Dihydroxy-3α-fluoro-5α-androstan-16-one	59
5α-Androstan-17-one	*Rhizopus nigricans*	3β,7β-Dihydroxy-5α-androstan-17-one	59
4α-Hydroxylation			
12,12-Difluoro-5α-androstan-3-one	*Rhizopus nigricans*	4α,16β-Dihydroxy-12,12-difluoro-5α-androstan-3-one	59
7,7-Difluoro-5α-androstan-17-one	*Rhizopus nigricans*	4α,11α-Dihydroxy-7,7-difluoro-5α-androstan-17-one	59
Pregn-4-ene-3,20-dione	*Gymnoascus reesii*	3-Carboxy-3,4-seco-4α-hydroxy-5α-pregnan-20-one	63
5-Hydroxylation			
Sitosterol	*Pseudomonas* sp	5α-Stigmastan-3β,5,6β-triol	24
Androst-4-ene-3,17-dione	*Cunninghamella elegans*	5-Hydroxy-5β-androstan-3,6,17-trione	64
5,6α-Epoxy-3β-hydroxy-5α-androstan-17-one	*Rhizopus arrhizus* ATCC 11145	(a) 3β,5,6β-Trihydroxy-5α-androstan-17-one (b) 3β,5-Dihydroxy-5α-androstan-17-one	65
5,6β-Epoxy-3β-hydroxy-5β-androstan-17-one	*Rhizopus arrhizus*	(a) 3β,5,6β-Trihydroxy-5α-androstan-17-one (b) 3β,5-Dihydroxy-5α-androstan-17-one	65

6α-Hydroxylation			
3α-Fluoro-5α-androstan-16-one	*Calonectria decora*	6α,11α-Dihydroxy-3α-fluoro-5α-androstan-16-one	59
5α-Androstan-17-one	*Calonectria decora*	(a) 1β,6α-Dihydroxy-5α-androstan-17-one (b) 6α-Hydroxy-5α-androstane-1,17-dione (c) 6α,19-Dihydroxy-5α-androstane-1,17-dione	59
5α-Androstan-17-one	*Aspergillus ochraceus*	(a) 1β,6α-Dihydroxy-5α-androstan-17-one (b) 6α,11α-Dihydroxy-5α-androstan-17-one	59
3,3-Difluoro-5α-androstan-17-one	*Calonectria decora*	(a) 6α,11α-Dihydroxy-3,3-difluoro-5α-androstan-17-one (b) 1β,6α-Dihydroxy-3,3-difluoro-5α-androstan-17-one	59
3,3-Difluoro-5α-androstan-17-one	*Rhizopus nigricans*	6α,11α-Dihydroxy-3,3-difluoro-5α-androstan-17-one	59
12,12-Difluoro-5α-androstan-17-one	*Calonectria decora*	(a) 1β,6α-Dihydroxy-12,12-difluoro-5α-androstan-17-one (b) 1β,6α,17β-Trihydroxy-12,12-difluoro-5α-androstane	59
25-Hydroxycholesterol	*Rhizoctonia muneratii*	6α,25-Dihydroxycholesterol	66
Pregn-4-ene-3,20-dione	*Caldariella acidophila*	6α-Hydroxypregn-4-ene-3,20-dione	67
B-Norandrost-4-ene-3,17-dione	*Rhizopus arrhizus* ATCC 11145	6α-Hydroxy-B-norandrost-4-ene-3,17-dione	68
17β-Hydroxy-B-norandrost-4-ene-3-one	*Rhizopus arrhizus* ATCC 11145	6α,17β-Dihydroxy-B-norandrost-4-en-3-one	68
17aβ-Hydroxy-17aα-methyl-D-homo-androstane-3,17-dione	*Curvularia clavata*	6α,17aβ-Dihydroxy-17aα-methyl-D-homoandrostane-3,17-dione	69
21-Acetoxy-5α,6α-epoxy-3β-hydroxy-6β,16α-dimethylpregnan-20-one	*Flavobacterium dehydrogenans*	6α,21-Dihydroxy-6β,16α-dimethylpregn-4-ene-3,20-dione	70, 71
Androst-5-ene-3,17-dione	*Rhizopus arrhizus* ATCC 11145	6α-Hydroxyandrost-4-ene-3,17-dione	65
Pregn-4-ene-3,20-dione	*Caldariella acidophila*	6α-Hydroxypregn-4-ene-3,20-dione	67
Androst-4-ene-3,17-dione	*Rhizopus nigricans*	6α,11β-Dihydroxyandrost-4-ene-3,17-dione	72
6β-Hydroxylation			
Sitosterol	*Pseudomonas* sp	5α-Stigmastane-3β,5,6β-triol	24
17β-Hydroxyandrost-4-ene-3-one	*Giberella fujikuroi*	6β,17β-Dihydroxyandrost-4-en-3-one	73
9β,10α-Androst-4-ene-3,17-dione	*Rhizopus arrhizus*	6β,9β-Dihydroxy-10α-androst-4-ene-3,17-dione	74
25-Hydroxycholesterol	*Rhizoctonia muneratii*	6β,25-Dihydroxycholesterol	66
Sitosterol	*Pseudomonas* sp	6β-Hydroxystigmast-4-en-3-one	75
Stigmasterol	*Pseudomonas* sp	6β-Hydroxystigmast-4,22-diene-3-one	75
Pregna-4,16-diene-3,20-dione	*Absidia orchidis*	6β,15β-Dihydroxypregna-4,16-diene-3,20-dione	76
Pregn-4-ene-3,20-dione	*Syncephalastrum racemosum*	6β-Hydroxypregn-4-ene-3,20-dione	77
3α-Acetoxy-5α-androstan-17-one	*Cunninghamella elegans*	6β,11β-Dihydroxy-3α-acetoxy-5α-androstan-17-one	61
17α-Aza-D-homo-5α-androstan-17-one	*Cunninghamella elegans*	6β-Hydroxy-17α-aza-D-homo-5α-androstan-17-one	61
17α-Aza-D-homo-3α-acetoxy-5α-androstan-17-one	*Cunninghamella elegans*	6β-Hydroxy-17α-aza-D-homo-3α-acetoxy-5α-androstan-17-one	61
Pregn-4-ene-3,20-dione	*Caldariella acidophila*	6β-Hydroxypregn-4-ene-3,20-dione	67
B-Norandrost-4-ene-3,17-dione	*Rhizopus arrhizus*	6β-Hydroxy-B-norandrost-4-ene-3,17-dione	68
17β-Hydroxy-B-norandrost-4-en-3-one	*Rhizopus arrhizus*	6β,17β-Dihydroxy-B-norandrost-4-en-3-one	68
6α-Methyl-11-deoxy-17α-hydroxy-pregn-4-ene-3,20-dione-21-acetate	*Cunninghamella blakesleeana*	6β,17β-Dihydroxy-B-norandrost-4-en-3-one	78
D-Homo-pregn-4-ene-3,20-dione	*Aspergillus ochraceus*	6β,11α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Rhizopus arrhizus* ATCC 10260	6β,11α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Cunninghamella echinulata* NRRL 1386	6β,11α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
5α-Androstan-3-one	*Aspergillus ochraceus*	6β,11α-Dihydroxy-5α-androstan-3-one	59

Table 1 (*Continued*)

Substrate	Microorganism	Products	References
16,16-Difluoro-5α-androstan-3-one	*Aspergillus ochraceus*	6β,11α-Dihydroxy-16,16-difluoro-5α-androstan-3-one	59
3α-Fluoro-5α-androstan-16-one	*Aspergillus ochraceus*	6β,11α-Dihydroxy-3α-fluoro-5α-androstan-16-one	59
Androst-5-ene-3,17-dione	*Rhizopus arrhizus*	6β-Hydroxyandrost-5-ene-3,17-dione	65
5,6α-Epoxy-3β-hydroxy-5α-androstan-17-one	*Rhizopus arrhizus* ATCC 11145	3β,5,6β-Trihydroxy-5α-androstan-17-one	65
5,6β-Epoxy-3β-hydroxy-5β-androstan-17-one	*Rhizopus arrhizus* ATCC 11145	3β,5,6β-Trihydroxy-5α-androstan-17-one	65
7α-Hydroxylation			
17α,21-Dihydroxypregn-4-ene-3,20-dione	*Mucor hiemlis*	7α,17α,21-Trihydroxypregn-4-ene-3,20-dione	80
Androst-4-ene-3,17-dione	*Rhizopus nigricans*	7α-Hydroxyandrost-4-ene-3,17-dione	72
Stigmasterol	*Pseudomonas* sp	Stigmasta-5,22-diene-3β,7α-diol	75
3β-Hydroxypregn-5-en-20-one	*Cladosporium herbarum*	3β,7α-Dihydroxypregn-5-en-20-one	81
3-Keto-13,14-seco-5α-androstan-13ξ-hydroxy-17-carboxylic acid	*Helicostylum piriforme*	(a) 7α,13ξ-Dihydroxy-3-keto-13,14-seco-5α-androstan-17-carboxylic acid (b) 3β,7α-Dihydroxy-13,14-seco-5α-androstan-13ξ-hydroxy-17-carboxylic acid	82
Testolactone	*Helicostylum piriforme*	7α-Hydroxytestolactone	82
Androst-4-ene-3,17-dione	*Botryodiploudia theobromae*	(a) 7α-Hydroxyandrost-4-ene-3,17-dione (b) 7α,17β-Dihydroxyandrost-4-ene-3-one	83
5α-Androstan-17-one	*Cunninghamella elegans*	(a) 7α-Hydroxy-5α-androstan-17-one (b) 1β,7α-Dihydroxy-5α-androstan-17-one	61
3β-Acetoxy-5α-androstan-17-one	*Cunninghamella elegans*	(a) 7α-Hydroxy-3β-acetoxy-5α-androstan-17-one (b) 1β,7α-Dihydroxy-3β-acetoxy-5α-androstan-17-one	61
3α-Hydroxy-5α-androstan-17-one	*Cunninghamella elegans*	(a) 3α,7α-Dihydroxy-5α-androstan-17-one (b) 1β,3α,7α-Trihydroxy-5α-androstan-17-one	61
17α-Aza-D-homo-5α-androstan-17-one	*Cunninghamella elegans*	7α-Hydroxy-17α-aza-D-homo-5α-androstan-17-one	61
17α-Aza-3α-acetoxy-D-homo-5α-androstan-17-one	*Cunninghamella elegans*	7α-Hydroxy-17α-aza-3α-acetoxy-D-homo-5α-androstan-17-one	61
Sitosterol	*Pseudomonas* sp	Stigmast-5-ene-3β,7α-diol	24
2α,3α-Epoxy-5α-androstan-17-one	*Helicostylum piriforme*	7α-Hydroxy-2α,3α-epoxy-5α-androstan-17-one	83
D-Homo-pregn-4-ene-3,11,20-trione	*Curvularia lunata* NRRL 2380	7α,14α-Dihydroxy-D-homo-pregn-4-ene-3,11,20-trione	79
3β-Acetoxy-17a-aza-D-homo-androst-5-en-17-one	*Cunninghamella elegans*	3β,7α-Dihydroxy-17a-aza-D-homoandrost-5-en-17-one	60
3β-Hydroxy-17a-aza-D-homo-androst-5-en-17-one	*Cunninghamella elegans*	3β,7α-Dihydroxy-17a-aza-D-homoandrost-5-en-17-one	60
17α-Aza-D-homoandrost-5-en-3β-yl acetate	*Cunninghamella elegans*	17α-Aza-D-homoandrost-5-ene-3β,7α-diol	60
N-Acetyl-17-aza-D-homoandrost-5-en-3β-yl acetate	*Cunninghamella elegans*	*N*-Acetyl-17-aza-D-homo-androst-5-ene-3β,7α-diol	60
3β-Acetoxyandrost-5-en-17-one	*Cunninghamella elegans*	3β,7α-Dihydroxyandrost-5-en-17-one	64
5α-Androstan-16-one	*Rhizopus nigricans*	3β,7α-Dihydroxy-5α-androstan-16-one	59
3α-Fluoro-5α-androstan-16-one	*Rhizopus nigricans*	(a) 3β,7α-Dihydroxy-3α-fluoro-5α-androstan-16-one (b) 7α-Hydroxy-3α-fluoro-5α-androstan-16-one	59
5,6α-Epoxy-5α-androstane-3,17-dione	*Rhizopus arrhizus* ATCC 11145	3β,7α-Dihydroxy-5,6α-epoxy-5α-androstan-17-one	65
5,6β-Epoxy-3β-hydroxy-5β-androstan-17-one	*Rhizopus arrhizus* ATCC 11145	3β,7α-Dihydroxy-5,6β-epoxy-5β-androstan-17-one	65
7β-Hydroxylation			
Pregna-4,16-diene-3,20-dione	*Absidia orchidis*	7β,15β-Dihydroxypregna-4,16-diene-3,20-dione	76
3α,7α-Dihydroxy-5β-cholanic acid	*Clostridium absonum*	3α,7β-Dihydroxy-5β-cholanic acid	84

3β-Hydroxy-15β,16β-methyleneandrost-5-en-17-one	*Botryodiploidia malorum*	3β,7β-Dihydroxy-15β,16β-methyleneandrost-5-en-17-one	85
3β-Acetoxy-17a-aza-D-homo-androst-5-en-17-one	*Cunninghamella elegans*	3β,7β-Dihydroxy-17a-aza-D-homo-androst-5-en-17-one	60
3β-Hydroxy-17a-aza-D-homo-androst-5-en-17-one	*Cunninghamella elegans*	3β,7β-Dihydroxy-17a-aza-D-homo-androst-5-en-17-one	60
N-Acetyl-17a-aza-D-homo-androst-5-en-3β-yl acetate	*Cunninghamella elegans*	(a) *N*-Acetyl-17a-aza-D-homoandrost-5-ene-3β,7β-diol (b) *N*-Acetyl-17a-aza-D-homoandrost-5-ene-1β,3β,7β-triol	60
D-Homo-pregn-4-ene-3,20-dione	*Penicillium janthinellum*	7β,11α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Pellicularia filamentosa* ATCC 13289	7β,17α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
3α-Fluoro-5α-androstan-16-one	*Aspergillus ochraceus*	7β,11α-Dihydroxy-3α-fluoro-5α-androstan-16-one	59
5α-Androstan-17-one	*Aspergillus ochraceus*	7β,11α-Dihydroxy-5α-androstan-17-one	59
12,12-Difluoro-5α-androstan-3-one	*Calonectria decora*	3β,7β,15α-Trihydroxy-12,12-difluoro-5α-androstane	59
16,16-Difluoro-5α-androstan-3-one	*Calonectria decora*	(a) 7β,12β-Dihydroxy-16,16-difluoro-5α-androstan-3-one (b) 3β,7β,12β-Trihydroxy-16,16-difluoro-5α-androstane	59
12,12-Difluoro-5α-androstan-17-one	*Calonectria decora*	7β,15α,17β-Trihydroxy-12,12-difluoro-5α-androstane	59
12,12-Difluoro-5α-androstan-17-one	*Aspergillus ochraceus*	7β-Hydroxyandrost-5-en-17-one	59
3β-Hydroxyandrost-5-en-17-one	*Cunninghamella elegans*	3β,7β-Dihydroxyandrost-5-en-17-one	64
Androst-5-en-3β-ol	*Cunninghamella elegans*	Androst-5-ene-3β,7β,12β-triol	64
Pregn-4-ene-3,20-dione	*Aspergillus fumigatus*	7β,15β-Dihydroxy-pregn-4-ene-3,20-dione	86, 87
9α-Hydroxylation			
Sitosterol	*Mycobacterium fortuitum*	(a) 9α,17β-Dihydroxyandrost-4-en-3-one (b) 3-Ketobisnorchol-4-ene-9α,22-diol (c) 9α-Hydroxy-3-ketobisnorchol-4-en-22-oic, methyl ester (d) 9α-Hydroxy-3-ketobisnorchol-4-en-22-oic acid	88
Androst-4-ene-3,17-dione	*Corynebacterium equi*	9α-Hydroxyandrost-4-ene-3,17-dione	89
Androst-4-ene-3,17-dione	*Corynespora casiicola*	9α-Hydroxyandrost-4-ene-3,17-dione	90
Cholesterol	*Mycobacterium vaccae*	9α-Hydroxyandrost-4-ene-3,17-dione	28
Sitosterol and campesterol mixture	*Mycobacterium vaccae*	9α-Hydroxyandrost-4-ene-3,17-dione	49
5α-Androstane-3,17-dione	*Corynebacterium simplex*	(a) 9α-Hydroxy-5α-androstane-3,17-dione (b) 9α-Hydroxy-5α-androst-11-ene-3,17-dione (c) 9α,17α-Dihydroxy-5α-androstan-3-one (d) 9α,17β-Dihydroxy-5α-androstan-3-one	91
3-Oxo-pregn-4,17(20)-diene-20-carboxylic acid	*Corynebacterium equi*	(a) 9α-Hydroxy-3-oxopregna-4,17(20)-diene-20-carboxylic acid (b) 9α-Hydroxy-3-oxo-pregna-4,17(20)-diene-20-carboxylic acid, methyl ester	92
Cholesterol	*Mycobacterium parafortuitum*	9α-Hydroxyandrost-4-ene-3,17-dione	93
3-Keto-13,14-seco-5α-androstan-13ξ-hydroxy-17-carboxylic acid	*Helicostylum piriforme*	9α-Hydroxy-3-keto-13,14-seco-5α-androstan-13ξ-hydroxy-17-carboxylic acid	82
17α-Aza-3β-acetoxy-D-homo-5α-androstan-17-one	*Cunninghamella elegans*	9α-Hydroxy-17α-aza-3β-acetoxy-D-homo-5α-androstan-17-one	61
Methyl-3-oxo-pregna-4,17(20)-diene-20-carboxylate	*Rhodococcus equi*	9α-Hydroxymethyl-3-oxo-pregna-4,17(20)-diene-20-carboxylate	94
20α-Hydroxymethyl-pregn-4-en-3-one	*Rhodococcus equi*	9α,20α-Dihydroxymethylpregn-4-en-3-one	94
17α,21-Dihydroxypregn-4-ene-3,20-dione	*Rhodococcus equi*	9α,17α,21-Trihydroxypregn-4-ene-3,20-dione	94
Cholesterol	*Mycobacterium parafortuitum* MC 1-0801	9α-Hydroxyandrost-4-ene-3,17-dione	32
Androst-5-en-17-one	*Cunninghamella elegans*	9α-Hydroxyandrost-5-ene-7,17-dione	64
Sitosterol	*Mycobacterium parafortuitum* NRRL B8119	(a) 9α-Hydroxyandrost-4-ene-3,17-dione	50

Table 1 (*Continued*)

Substrate	Microorganism	Products	References
		(b) 9α-Hydroxy-3-oxo-23,24-bisnor-chol-4-en-22-oic acid	
		(c) 9α-Hydroxy-3-oxo-23,24-bisnor-chol-4-en-22-oic acid ester	
		(d) 9α-Hydroxy-3-oxo-23,24-bisnor-chol-4-en-22-ol	
9β-Hydroxylation			
9β,10α-Pregn-4-ene-3,20-dione	*Rhizopus arrhizus*	9β-Hydroxy-9β,10α-pregn-4-ene-3,20-dione	74
9β,10α-Androst-4-ene-3,17-dione	*Rhizopus arrhizus*	9β-Hydroxy-9β,10α-androst-4-ene-3,17-dione	74
9β,10α,17β-Hydroxyandrost-4-en-3-one	*Rhizopus arrhizus*	9β,17β-Dihydroxy-9β,10α-androst-4-en-3-one	74
11α-Hydroxylation			
6α-Fluoro-16α,17α-isopropylidene-dioxy-pregn-4-ene-21-hydroxy-3,20-dione	*Hyphoderma roseum*	11α,21-Dihydroxy-6α-fluoro-16α,17α-isopropylidene dioxy-pregn-4-ene-3,20-dione	95
Pregn-4-ene-3,20-dione	*Aspergillus ochraceus*	11α-Hydroxypregn-4-ene-3,20-dione	96
21-Acetoxy-3β-hydroxypregn-5-en-20-one	*Aspergillus ochraceus* and *Bacillus lentus* (mixed culture)	(a) 3β,21,11α-Trihydroxypregn-5-en-20-one (b) 11α,21-Dihydroxypregna-1,4-diene-3,20-dione	97
Pregn-4-ene-3,20-dione	*Aspergillus phoenicis* (immobilized)	11α-Hydroxypregn-4-ene-3,20-dione	42
Pregn-4-ene-3,20-dione	*Aspergillus niger*	11α-Hydroxypregn-4-ene-3,20-dione	98
6α-Methyl-11-deoxy-17α,21-dihydroxy-pregn-4-ene-3,20-dione	*Absidia orchidis*	11α,17α,21-Trihydroxy-6α-methyl-pregn-4-ene-3,20-dione	78
Pregn-4-ene-3,20-dione	*Rhizopus nigricans* (immobilized)	11α-Hydroxypregn-4-ene-3,20-dione	43
Pregna-1,4-diene-3,20-dione	*Aspergillus ochraceus*	11α-Hydroxypregna-1,4-diene-3,20-dione	99
11-Deoxy-17α,21-dihydroxypregn-4-ene-3,20-dione	*Cunninghamella elegans*	11α,17α,21-Trihydroxypregn-4-ene-3,20-dione	100
Pregn-4-ene-3,20-dione	*Aspergillus fumigatus*	11α,15β-Dihydroxypregn-4-ene-3,20-dione	86, 87
Pregn-4-ene-3,20-dione	*Cunninghamella echinulata*	(a) 11α-Hydroxypregn-4-ene-3,20-dione (b) 11α,17α-Dihydroxypregn-4-ene-3,20-dione	101
Pregn-4-ene-3,20-dione	*Aspergillus niger*	11α-Hydroxypregn-4-ene-3,20-dione	102
5α-Androstan-3-one	*Rhizopus nigricans*	(a) 11α,16β-Dihydroxy-5α-androstan-3-one (b) 5α-androstane-3β,11α,16β-triol	59
5α-Androstan-3-one	*Aspergillus ochraceus*	6β,11α-Dihydroxy-5α-androstan-3-one	59
16,16-Difluoro-5α-androstan-3-one	*Aspergillus ochraceus*	(a) 11α-Hydroxy-16,16-difluoro-5α-androstan-3-one (b) 6β,11α-Dihydroxy-16,16-difluoro-5α-androstan-3-one	59
17,17-Difluoro-5α-androstan-3-one	*Rhizopus nigricans*	(a) 11α,16β-Dihydroxy-17,17-difluoro-5α-androstan-3-one (b) 3β,11α,16β-Trihydroxy-17,17-difluoro-5α-androstan-3-one	59
3α-Fluoro-5α-androstan-16-one	*Calonectria decora*	(a) 6α,11α-Dihydroxy-3α-fluoro-5α-androstan-16-one (b) 11α-Hydroxy-3α-fluoro-5α-androstane-6,16-dione	59
3α-Fluoro-5α-androstan-16-one	*Aspergillus ochraceus*	(a) 7β,11α-Dihydroxy-3α-fluoro-5α-androstan-16-one (b) 6β,11α-Dihydroxy-3α-fluoro-5α-androstan-16-one (c) 11α-Hydroxy-3α-fluoro-5α-androstan-16-one	59
5α-Androstan-17-one	*Calonectria decora*	6α,11α-Dihydroxy-5α-androstan-17-one	59
5α-Androstan-17-one	*Rhizopus nigricans*	(a) 6α,11α-Dihydroxy-5α-androstan-17-one (b) 3α,11α-Dihydroxy-5α-androstan-17-one	59
5α-Androstan-17-one	*Aspergillus ochraceus*	(a) 7β,11α-Dihydroxy-5α-androstan-17-one (b) 11α-Hydroxy-5α-androstan-17-one (c) 6α,11α-Dihydroxy-5α-androstan-17-one	59

3,3-Difluoro-5α-androstan-17-one	*Calonectria decora*	6α,11α-Dihydroxy-3,3-difluoro-5α-androstan-17-one	59
3,3-Difluoro-5α-androstan-17-one	*Rhizopus nigricans*	6α,11α-Dihydroxy-3,3-difluoro-5α-androstan-17-one	59
3,3-Difluoro-5α-androstan-17-one	*Aspergillus ochraceus*	11α-Hydroxy-3,3-difluoro-5α-androstan-17-one	59
6α-Fluoro-5α-androstan-17-one	*Aspergillus ochraceus*	11α-Hydroxy-6α-fluoro-5α-androstan-17-one	59
7,7-Difluoro-5α-androstan-17-one	*Rhizopus nigricans*	(a) 3α,11α-Dihydroxy-7,7-difluoro-5α-androstan-17-one (b) 4α,11α-Dihydroxy-7,7-difluoro-5α-androstan-17-one	59
3β-Hydroxy-B-nor-androst-5-en-17-one	*Rhizopus arrhizus* ATCC 11145	3β,11α-Dihydroxy-B-nor-androst-5-en-17-one	68
3β-Hydroxyandrost-5-en-17-one	*Rhizopus arrhizus* ATCC 11145	3β,11α-Dihydroxy-androst-5-en-17-one	65
Androst-5-ene-3,17-dione	*Rhizopus arrhizus*	11α-Hydroxy-androst-4-ene-3,17-dione	65
D-Homo-pregn-4-ene-3-20-dione	*Aspergillus giganteus* ATCC 10059	11α-Hydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Aspergillus ochraceus* ATCC 1008	(a) 11α-Hydroxy-D-homo-pregn-4-ene-3,20-dione (b) 6β,11α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Rhizopus arrhizus* ATCC 10260	6β,11α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Cunninghamella echinulata* NRRL 1386	6β,11α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Glomerulus cingulata* ATCC 10534	11α,15α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Colletotrichum lini* CBS 11221	11α,15α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Penicillium janthinellum* ATCC 10455	(a) 11α-Hydroxy-D-homo-pregn-4-ene-3,20-dione (b) 7β,11α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
17a-Aza-D-homo-androst-4-ene-3,17-dione	*Cunninghamella elegans*	11α-Hydroxy-17a-aza-D-homo-androst-4-ene-3,17-dione	60
6β-Methylandrost-4-ene-3,17-dione	*Rhizopus arrhizus* ATCC 11145	11α-Hydroxy-6β-methylandrost-4-ene-3,17-dione	103
6α-Methylandrost-4-ene-3,17-dione	*Rhizopus arrhizus* ATCC 11145	11α-Hydroxy-6α-methylandrost-4-ene-3,17-dione	103
3-Acetoxy-6β-methylandrosta-3,5-diene-17-one	*Rhizopus arrhizus* ATCC 11145	11α-Hydroxy-6α-methylandrost-4-ene-3,17-dione	103
Androst-4-ene-3,17-dione	*Cunninghamella elegans*	3α,11α-Dihydroxy-4α,5-epoxy-5α-androstan-17-one	64
Pregn-4-ene-3,20-dione	*Aspergillus phoenicis*	(a) 11α-Hydroxypregn-4-ene-3,20-dione (b) 11α,15β-Dihydroxypregn-4-ene-3,20-dione	42
11-Deoxy-17α,21-Dihydroxypregn-4-ene-3,20-dione	*Cunninghamella blakesleeana*	11α,17α,21-Trihydroxy-pregn-4-ene-3,20-dione	104
11β-Hydroxylation			
(20*S*)-20-Carboxy-pregn-1,4-diene-3-one	*Cochliobolus lunatus*	11β-Hydroxy-(20*S*)-20-carboxypregn-1,4-diene-3-one	105
Pregn-4-ene-3,20-dione	*Aspergillus niger*	11β-Hydroxypregn-4-ene-3,20-dione	98
17α,21-(1-ethoxyethylidenedioxy)-pregn-4-ene-3,20-dione	*Curvularia lunata*	11β,17α,21-Trihydroxypregn-4-ene-3,20-dione	106, 107
6α-Fluoro-16α,17α-isopropylidenedihydroxypregn-4-ene-21-hydroxy-3,20-dione	*Curvularia lunata*	6α-Fluoro-16α,17α-isopropylidenedihydroxypregn-4-ene-11β,21-dihydroxy-3,20-dione	108
6α-Fluoro-16α,17α-isopropylidenedihydroxypregn-4-ene-21-hydroxy-3,20-dione	*Cunninghamella blakesleeana*	6α-Fluoro-16α,17α-isopropylidenedihydroxypregn-4-ene-11β,21-dihydroxy-3,20-dione	108
6α-Fluoro-16α,17α-isopropylidenedihydroxypregn-4-ene-21-hydroxy-3,20-dione	*Tieghemella orchidis*	6α-Fluoro-16α,17α-isopropylidenedihydroxypregn-4-ene-11β,21-dihydroxy-3,20-dione	108
3α-Acetoxy-5α-androstan-17-one	*Cunninghamella elegans*	6β,11β-Dihydroxy-3α-acetoxy-5α-androstan-17-one	108
11-Deoxy-17α,21-dihydroxypregn-4-ene-3,20-dione	*Cunninghamella elegans*	11β,17α,21-Trihydroxypregn-4-ene-3,20-dione	101
17aβ-Hydroxy-17aα-methyl-D-homoandrostane-3,17-dione	*Curvularia clavata*	(a) 11β-Hydroxy-17aβ-hydroxy-17aα-methyl-D-homoandrostane-3,17-dione (b) 3,11β-Dihydroxy-17aβ-hydroxy-17aα-methyl-D-homoandrostan-17-one	69
17α-Acetoxy-D-homo-pregn-4-ene-3,20-dione	*Curvularia lunata*	11β-Hydroxy-17α-acetoxy-D-homo-pregn-4-ene-3,20-dione	109
21-Hydroxy-17α-methoxy-methoxy-pregn-4-ene-3,20-dione	*Curvularia lunata*	11β,21-Dihydroxy-17α-methoxy-methoxy-pregn-4-ene-3,20-dione	110

Table 1 (*Continued*)

Substrate	Microorganism	Products	References
D-Homo-pregn-4-ene-3,20-dione	*Pellicularia filamentosa* ATCC 1328a	11β,17α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
11-Deoxy-17α,21-dihydroxypregn-4-ene-3,20-dione	*Cunninghamella blakesleeana*	11β,17α,21-Trihydroxypregn-4-ene-3,20-dione	104
11-Deoxy-17α,21-dihydroxypregn-4-ene-3,20-dione	*Curvularia lunata*	11β,17α,21-Trihydroxypregn-4-ene-3,20-dione	104
11-Deoxy-17α,21-dihydroxypregn-4-ene-3,20-dione	*Curvularia lunata* (immobilized)	11β,17α,21-Trihydroxypregn-4-ene-3,20-dione	111
Androst-4-ene-3,17-dione	*Rhizopus nigricans*	6,11β-Dihydroxyandrost-4-ene-3,17-dione	72
12α-Hydroxylation			
17α,21-Dihydroxypregn-4-ene-3,20-dione	*Cereospora kaki*	12α,17α,21-Trihydroxypregn-4-ene-3,20-dione	112
3β-Acetoxyandrost-5-en-17-one	*Cunninghamella elegans*	3β,12α-Dihydroxy-5,6β-epoxy-5α-androstan-17-one	64
12β-Hydroxylation			
5α-Androstan-3-one	*Calonectria decora*	(a) 3β,12β,15α-Trihydroxy-5α-androstan-3-one (b) 12β,15α-Dihydroxy-5α-androstan-3-one	59
7,7-Difluoro-5α-androstan-3-one	*Calonectria decora*	(a) 3β,12β,15α-Trihydroxy-7,7-difluoro-5α-androstan-3-one (b) 12β,15α-Dihydroxy-7,7-difluoro-5α-androstan-3-one	59
16,16-Difluoro-5α-androstan-3-one	*Calonectria decora*	(a) 7β,12β-Dihydroxy-16,16-difluoro-5α-androstan-3-one (b) 3β,7β,12β-Trihydroxy-16,16-difluoro-5α-androstan-3-one	59
17-Fluoroandrost-16-en-3-one	*Calonectria decora*	(a) 3β,12β,15α-Trihydroxy-17-fluoroandrost-16-en-3-one (b) 12β,15α-Dihydroxy-17-fluoroandrost-16-en-3-one	59
D-Homo-pregn-4-ene-3,20-dione	*Calonectria decora* ATCC 14767	12β,15α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Fusarium ciliatum* CBS 13235	12β,15α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
Androst-5-en-3β-ol	*Cunninghamella elegans*	(a) 3β,12β-Dihydroxyandrost-5-en-7-one (b) Androst-5-ene-3β,12β,7β-triol	64
(20*S*)-20-Carboxypregna-1,4-dien-3-one	*Cochliobolus lunatus*	12β-Hydroxy-(20*S*)-20-carboxypregna-1,4-dien-3-one	105
17α-Acetoxy-pregn-4-ene-3,20-dione	*Calonectria decora*	12β-Hydroxy-17α-acetoxypregn-4-ene-3,20-dione	113
14α-Hydroxylation			
D-Homo-pregn-4-ene-3,11,20-trione	*Curvularia lunata* NRRL 2380	14α-Hydroxy-D-Homo-pregn-4-ene-3,11,20-trione	79
11β-Fluoropregn-4-ene-3,20-dione	*Curvularia lunata*	(a) 14α,21-Dihydroxy-11β-fluoropregn-4-ene-3,20-dione (b) 14α-Hydroxy-11β-fluoropregn-4-ene-3,20-dione	114
Androst-4-ene-3,17-dione	*Cunninghamella elegans*	14α-Hydroxyandrost-4-ene-3,17-dione	64
3β-Acetoxy-androst-5-en-17-one	*Cunninghamella elegans*	3β,14α-Dihydroxyandrost-5-ene-7,17-dione	64
15α-Hydroxylation			
3β-Hydroxypregn-5-en-20-one	*Cladosporium herbarum*	3β,15α-Dihydroxypregn-5-en-20-one	81
D-Homo-pregn-4-ene-3,20-dione	*Fusarium lini* CBS 713	15α-Hydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Fusarium oxysporum* ATCC 7601	15α-Hydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Colletotrichum phomoides*	15α-Hydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Helminthosporium sativum*	15α-Hydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Glomerella cingulata* ATCC 10534	11α,15α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Colletotrichum lini* CBS 11221	11α,15α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Calonectria decora* ATCC 14767	12β,15α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Fusarium ciliatum*	12β,15α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Fusarium oxysporum f sp pisi* ATCC 9991	(a) 15α-Hydroxy-D-homo-pregn-4-ene-3,20-dione	79

D-Homo-pregn-4-ene-3,20-dione	*Giberella zeae* IFO 5269	(b) 15α,16α-Dihydroxypregn-4-ene-3,20-dione (a) 15α-Hydroxy-D-homo-pregn-4-ene-3,20-dione (b) 15α,16α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
5α-Androstan-3-one	*Calonectria decora*	(a) 3β,12β,15α-Trihydroxy-5α-androstan-3-one (b) 12β,15α-Dihydroxy-5α-androstan-3-one	59
7,7-Difluoro-5α-androstan-3-one	*Calonectria decora*	(a) 3β,12β,15α-Trihydroxy-7,7-difluoro-5α-androstan-3-one (b) 12β,15α-Dihydroxy-7,7-difluoro-5α-androstan-3-one	59
12,12-Difluoro-5α-androstan-3-one	*Calonectria decora*	3β,7β,15α-Trihydroxy-12,12-difluoro-5α-androstan-3-one	59
17-Fluoro-5α-androst-16-ene-3-one	*Calonectria decora*	(a) 3β,12β,15α-Trihydroxy-17-fluoro-5α-androst-16-ene-3-one (b) 12β,15α-Dihydroxy-17-fluoro-5α-androst-16-ene-3-one	59
12,12-Difluoro-5α-androstan-17-one	*Calonectria decora*	7β,15α,17β-Trihydroxy-12,12-difluoro-5α-androstan-17-one	59
15β-Hydroxylation			
17β-Hydroxyandrost-4-en-3-one	*Aspergillus fumigatus*	15β,17β-Dihydroxyandrost-4-en-3-one	115
Pregn-4-ene-3,20-dione	*Aspergillus fumigatus*	(a) 11α,15β-Dihydroxypregn-4-ene-3,20-dione (b) 7β,15β-Dihydroxypregn-4-ene-3,20-dione (c) 15β-Hydroxypregna-1,4-diene-3,20-dione	86, 87
Pregn-4-ene-3,20-dione	*Aspergillus phoenicis* (immobilized)	(a) 15β-Hydroxypregn-4-ene-3,20-dione (b) 11α,15β-Dihydroxypregn-4-ene-3,20-dione	42
Pregna-4-16-diene-3,20-dione	*Absidia orchidis*	(a) 15β-Hydroxypregna-4,16-diene-3,20-dione (b) 7β,15β-dihydroxypregna-4,16-diene-3,20-dione (c) 6β,15β-Dihydroxypregna-4-16-diene-3,20-dione	76
Pregn-4-ene-3,20-dione	*Curvularia lunata*	15β-Hydroxypregna-1,4-diene-3,20-dione	116
16α-Hydroxylation			
3β-Hydroxyandrost-5-en-17-one	*Streptomyces roseochromogenus* NRRL B-1233 (resting cells)	3β,16α-Dihydroxyandrost-5-en-17-one	117
3β-Hydroxypregn-5-en-20-one	*Streptomyces roseochromogenus* NRRL B-1233 (resting cells)	3β,16α-Dihydroxypregn-5-en-20-one	117
Androst-4-ene-3,17-dione	*Streptomyces roseochromogenus* NRRL B-1233 (resting cells)	16α-Hydroxyandrost-4-ene-3,17-dione	117
Androst-5-ene-3β,17β-diol	*Streptomyces roseochromogenus* NRRL B-1233 (resting cells)	Androst-5-ene-3β,16α,17β-triol	117
3β-Hydroxy-1,3,5-estratriene-17-one	*Streptomyces roseochromogenus* NRRL B-1233 (resting cells)	3β,16α-Dihydroxy-1,3,5-estratrien-17-one	117
9α-Fluoro-11β,17α-21-trihydroxypregn-4-ene-3,20-dione	*Streptomyces roseochromogenus* *Arthrobacter simplex* (mixed culture)	9α-Fluoro-11β,16α,17α,21-tetrahydroxypregn-4-ene-3,20-dione	45
18,21-Dihydroxydeoxypregn-4-ene-3,20-dione	*Streptomyces roseochromogenus*	16α,18,21-Trihydroxydeoxypregn-4-ene-3,20-dione	118
D-Homo-pregn-4-ene-3,20-dione	*Fusarium oxysporum* ATCC 9991	15α,16α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
D-Homo-pregn-4-ene-3,20-dione	*Giberella zeae* IFO 5269	15α,16α-Dihydroxypregn-4-ene-3,20-dione	79
16β-Hydroxylation			
Androst-5-en-3β-ol	*Cunninghamella elegans*	3β,16β-Dihydroxyandrost-5-en-7-one	64
5α-Androstan-3-one	*Rhizopus nigricans*	(a) 11α,16β-Dihydroxy-5α-androstan-3-one (b) 3β,11α,16β-Trihydroxy-5α-androstan-3-one	59
12,12-Difluoro-5α-androstan-3-one	*Rhizopus nigricans*	(a) 1β,16β-Dihydroxy-12,12-difluoro-5α-androstan-3-one (b) 4α,16β-Dihydroxy-12,12-difluoro-5α-androstan-3-one	59

Table 1 (*Continued*)

Substrate	Microorganism	Products	References
17,17-Difluoro-5α-androstan-3-one	*Rhizopus nigricans*	(a) 11α,16β-Dihydroxy-17,17-difluoro-5α-androstan-3-one (b) 3β,16β,11α-Trihydroxy-17,17-difluoro-5α-androstan-3-one	59
3α-Hydroxy-5α-androstan-6-one	*Leptoporus fissilis*	3α,16β,18-Trihydroxy-5α-androstan-6-one	119
17α-Hydroxylation			
Pregn-4-ene-3,20-dione	*Cladosporium herbarum*	17α-Hydroxypregn-4-ene-3,20-dione	82
Pregn-4-ene-3,20-dione	*Rhizopus nigricans*	17α-Hydroxypregn-4-ene-3,20-dione	98
Pregn-4-ene-3,20-dione	*Curvularia lunata*	3,17α-Dihydroxy-9,10-seco-1,3,5(10)-androstatrien-9-one	116
D-Homo-pregn-4-ene-3,20-dione	*Penicillium lilacinum* ATCC 10114	17aβ-Hydroxy-D-homo-pregn-4-ene-3,20-dione	79
16α-Hydroxypregn-4-ene-3,20-dione	*Eubacterium* sp 144	17α-Hydroxypregn-4-ene-3,20-dione	120
Pregn-4-ene-3,20-dione	*Cunninghamella echinulata*	(a) 17α-Hydroxypregn-4-ene-3,20-dione (b) 11α,17α-Dihydroxypregn-4-ene-3,20-dione	101
D-Homo-pregn-4-ene-3,20-dione	*Pellicularia filamentosa* ATCC 13289	(a) 17α-Hydroxy-D-homo-pregn-4-ene-3,11,20-trione (b) 11β,17α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione (c) 7β,17α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	79
18-Hydroxylation			
3α-Hydroxy-5α-androstan-6-one	*Leptoporus fissilis*	3α,16β,18-Trihydroxy-5α-androstan-6-one	119
19-Hydroxylation			
6β-chloro-17α-Hydroxy-1α,2α-methylenepregna-4,6-diene-3,20-dione (cyproterone)	*Nigrospora sphaerica*	17α,19-Dihydroxy-6β-chloro-1α,2α-methylenepregna-4,6-diene-3,20-dione	121
5α-Androstan-17-one	*Calonectria decora*	6α,19-Dihydroxy-5α-androstan-1,17-dione	59
21-Hydroxylation			
11β-Fluoropregn-4-ene-3,20-dione	*Curvularia lunata*	14α,21-Dihydroxy-11β-fluoropregn-4-ene-3,20-dione	114
22-Hydroxylation			
Sitosterol	*Mycobacterium fortuitum* NRRL B-8119	3-Oxo-23,24-bisnorchol-4-en-9α,22-diol	50

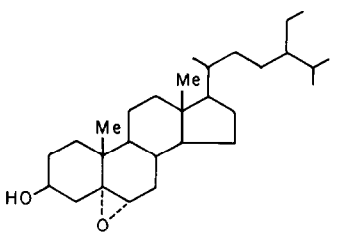
Hydroxylation reactions have been arranged according to increasing order of the carbon atom on which hydroxylations have taken place

terol derivative such as cholest-4-ene-3-(*O*-carboxymethyl)-oxime by *Mycobacterium phlei* has been achieved [26] The same androstane derivative was obtained by fermentation of sitosterol with a strain of *Mycobacterium fortuitum* [27] A mutant of *Mycobacterium vaccae* (MC-1-1102) grown on a medium containing soybean, sodium nitrate, soybean oil, rice bran, magnesium sulphate and cholesterol has been used for degradation of cholesterol to 9α-hydroxyandrostenedione [28] Another mutant (MC-1-1104) of the microorganism could consume cholesterol to produce ADD, AD and 1-dehydro-testosterone [29] Androstanes such as ADD, AD and 17β-hydroxyandrosta-1,4-diene-3-one have been obtained by fermentation of cholesterol with a natural mutant of *Rhodococcus terrae* (MC-1-1161) [30] Cholesterol has been converted to ADD, cholesta-1,4-diene-3-one and cholest-4-ene-3-one by *Arthrobacter simplex* and the resulting ADD has been separated from cholestanes by adsorbing it on active carbon Strains of *Mycobacterium flavum*, *M mucosum* and *M lacticola* metabolize 19-hydroxysitosterol and its acetate to 19-hydroxyandrost-4-ene-3,17-dione and estrone [31] The microbial preparation of a number of androstane derivatives (ADD, AD, 17β-hydroxyandrosta-1,4-diene-3-one, testosterone, 5α-androstane-3,6,17-trione, 5β-androst-1-ene-3,17-dione and 5α-androstane-3,17-dione) by a mutant of *Mycobacterium parafortuitum* (MC 1-0801) has been patented [32] The preparation of ADD, AD, 17β-hydroxyandrosta-1,4-diene-3-one and testosterone from cholesterol by a mutant of *Arthrobacter simplex* (MC-1-0803) has also been patented [33]

IMMOBILIZATION OF MICROBIAL CELLS

Immobilization of enzymes and cells as practical catalysts has been a subject of much interest in recent years The performance of enzymes and whole cells in commercial applications can often be improved by immobilization of the biocatalyst, for instance, by covalent attachment to or adsorption on solid supports, entrapment in polymeric gels, or by encapsulation and cross-linking Applications of immobilized enzymes and cells in the chemical, pharmaceutical and food industries have been briefly discussed in a recent article by Klibanov [34]

Considerable work has been done on the immobilization of microorganisms for the purpose of steroid transformation A review on transformation of steroids by immobilized living microorganisms has appeared [35] Transformation of steroids by gel entrapped *Nocardia rhodocrous* cells in organic solvents has been reported Whole cells of the microorganism were immobilized by entrapment with photo-cross linkable resin prepolymers or urethane prepolymers of either hydrophilic or hydro-



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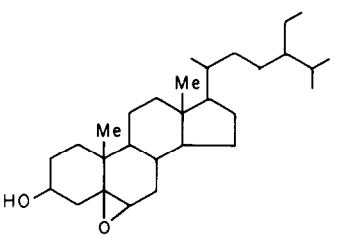

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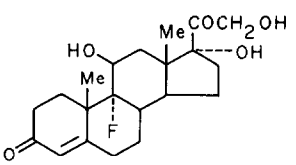

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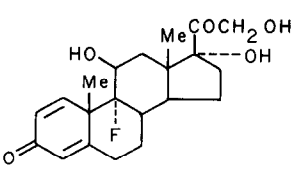

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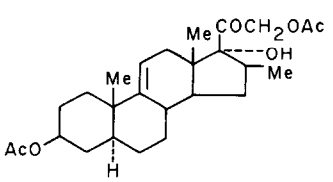

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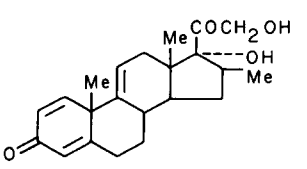

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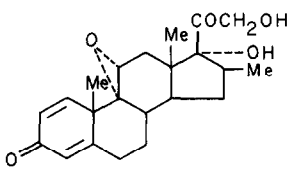
phobic character Both hydrophilic and hydrophobic gel entrapped cells transform 4-androstene-3,17-dione to dehydroepiandrosterone [36] Cortisol has been converted to prednisolone by *Arthrobacter simplex* immobilized in polyacrylamide gel [37] Cholesterol derivatives such as 3,3-ethylenedioxy-cholest-5-ene and 4-cholestene-3-(*O*-carboxymethyl)-oxime were transformed to the corresponding androstenedione derivatives by selective cleavage of the side chain with immobilized cells of *Mycobacterium phlei* and *Mycobacterium smegmatis* [38] Bioconversion of dehydroepiandrosterone to 4-androstene-3,17-dione, sitosterol to sitostenone, stigmasterol to stigmastenone, pregnenolone to progesterone and testosterone to Δ^1-dehydrotestosterone or 4-androstene-3,17-dione by *Nocardia rhodocrous* cells immobilized with photo-cross linkable resin prepolymers or urethane prepolymers has been reported [39] Side chain degradation of a cholesterol derivative, 4-cholesten-3-(*O*-carboxymethyl)-oxime was achieved by the employment of viable cells of *Mycobacterium phlei* immobilized in polyacrylamide gel [40] Transformation of cortisol to prednisolone by living cells of *Arthrobacter simplex* immobilized in calcium alginate has been reported [41] Progesterone was converted to its 11α-hydroxy, 15β-hydroxy and 11α,15β-dihydroxy derivatives by *Aspergillus phoenicis* immobilized by K-carrageenan, alginate, polyurethane, albumin foam or gelation [42] The production of 11α-hydroxyprogesterone from progesterone by *Rhizopus nigricans* immobilized in alginate and agar gels has been described [43]

MIXED CULTURE FERMENTATION

It is possible to conduct microbial two-step conversions in mixed cultures of two organisms Maximization of microbial two-step conversion of 9α-fluorohydrocortisone (**3**) to triamcinolone (**4**) in a mixed culture of two microorganisms has been described [44, 45] A mathematical model of the steroid transformation in the mixed culture was constructed with a different equation The kinetic parameters other than the Michaelis–Menten constants in the mathematical model varied with pH of the culture medium The model facilitated the simulation of the effect of pH on steroid conversions in the mixed culture Conversion of 5α-pregnane-3β,17α-diol-20-one-21-acetate to hydrocortisone by *Nocardia* sp and *Absidia coerulea* has been reported [46] The preparation of isoprogesterone from 16α-hydroxy progesterone by using two strains of bacteria has been described [47] A mixed culture of *Arthrobacter simplex* and *Nocardia* sp has been employed for conversion of 16β-methyl-5α-pregn-9(11)-ene-3β,17α,21-triol-20-one-3β, 21-diacetate (**5**) and 17α-methyl-17β-hydroxy-5α-androstane-3-one The products that have been obtained are **6** and **7** in the case of the former and **8** and **9** in the case of the latter [48]

Mixed substrates have also been used in microbial



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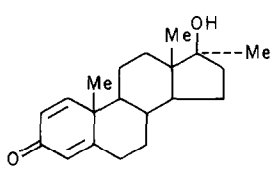

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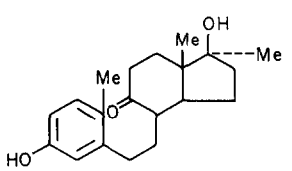

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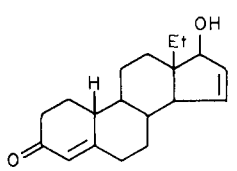

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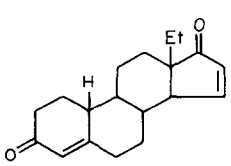

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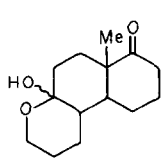

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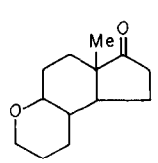

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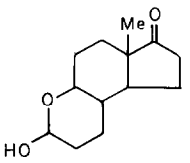
transformations for obtaining desired products The manufacture of androstanes, e g AD, ADD and 9α-hydroxyandrost-4-ene-3,17-dione from a mixture of sitosterol and campesterol by *Mycobacterium vaccae* (MC-1-1104) has been patented [49]

MEDICINALLY USEFUL STEROID DERIVATIVES

Microbial transformations have been used with advantage for preparation of medicinally useful steroid derivatives For example, a series of mutants which were blocked at various stages of the sterol degradative path were isolated from the potent sterol degrader, *Mycobacterium fortuitum* (ATCC-6842) Sitosterol bioconversion by these mutants resulted in the accumulation of a number of intermediate compounds, some of which are potentially useful as substrates in the manufacture of medicinally important steroids [50] 17β-Hydroxy-18-methyl-4,15-estradiene-3-one (**10**) having progestational, estrogenic and antihypercholesterolemic properties has been prepared from 18-methyl-4,15-estradiene-3,17-dione (**11**) by the use of the strains of *Sistotrema brinkmanni* or *Trechospora* sp [51] New steroid degradation products obtainable by microbial transformation may be medicinally useful

The complete degradation of the side chain of steroids for the preparation of useful steroid intermediates has received considerable attention Transformation of sitosterol to a hexahydroindanone derivative (**12**) and other steroid intermediates (**13–16**) by *Mycobacterium fortuitum* have been reported [52, 53] A similar type of conversion has been achieved with a mutant strain of *Mycobacterium fortuitum*, giving rise to four intermediate products (**14, 17–19**) [54] A mutant of *Nocardia corallina* (IFO-3338) accumulated several substances as cholesterol degradation products such as 3aα-H-4α-(3'-propionic acid)-5α-hydroxy-7aβ-methyl-hexahydro-1-indanone-δ-lactone (**20**), 3aα-H-4α-(3'-transacrylic acid)-5α-hydroxy-7aβ-methyl-hexahydro-1-indanone (**21**) and 3aα-H-4α-acetyl-5α-hydroxy-7aβ-methyl-hexahydro-1-indanone (**22**) These substances were also produced from 5β-cholestanol, sitosterol, cholest-4-en-3-one, lithocholic acid, cholic acid and progesterone [55]

Microbial hydroxylations of various steroid substrates are shown in Table 1 Hydroxylation reactions have been arranged according to increasing order of the carbon atom on which hydroxylations have taken place Table 2 shows the side chain degradations and the substrates have been classified alphabetically Dehydrogenations are shown in Table 3, and the miscellaneous reactions, e g acetylation,epoxidation, hydrogenation, hydrolysis, oxidation and reduction are given in Table 4



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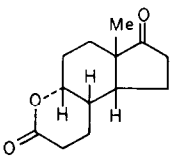

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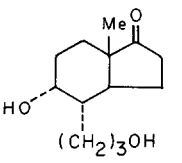

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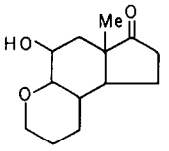

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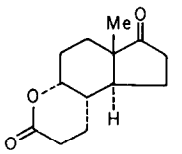

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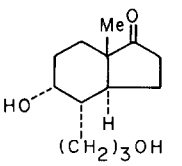

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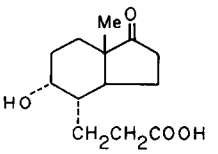

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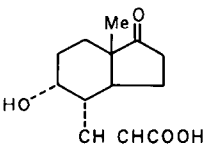

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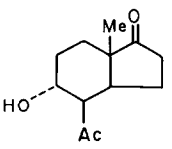

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Table 2 Side chain degradations

Steroid substrate	Microorganism	Products	References
Cholesterol and its derivatives			
Cholesterol	*Mycobacterium parafortuitum*	(a) 20α-Hydroxymethylpregna-1,4-dien-3-one (b) 20α-Hydroxymethylpregn-4-en-3-one	122
Cholesterol	*Arthrobacter simplex*	Androsta-1,4-diene-3,17-dione	123
Cholesterol	*Nocardia erythropolis*	20-Carboxy-pregn-4-en-3-one	124
Cholesterol	*Brevibacterium lipolyticum*	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione (c) 3β-Hydroxyandrost-5-en-17-one (d) 17β-Hydroxyandrosta-1,4-dien-3-one	125
Cholesterol	*Corynebacterium* sp ATCC 31385	(a) 20-Carboxy-pregna-1,4-dien-3-one (b) 20-Carboxy-pregn-4-en-3-one	126
Cholesterol	*Arthrobacter simplex*	(a) Pregna-1,3,5(10)-triene-20-carboxylic acid (b) 3β-Hydroxy-9,10-seco-androsta-1,3,5(10)-trien-17-one	127
Cholesterol	*Arthrobacter simplex*	(a) 17β-Hydroxyandrosta-1,4-dien-3-one (b) Androsta-1,4-diene-3,17-dione	128
Cholesterol	*Mycobacterium vaccae* MCI-1102	9α-Hydroxyandrost-4-ene-3,17-dione	28
Cholesterol	*Mycobacterium smegmatis*	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione	129
Cholesterol	*Mycobacterium parafortuitum*	9α-Hydroxyandrost-4-ene-3,17-dione	32
Cholesterol	*Mycobacterium diernoferi*	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione	130
Cholesterol	*Arthrobacter simplex*	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione (c) 17β-Hydroxyandrosta-1,4-dien-3-one (d) 17β-Hydroxyandrost-4-en-3-one	131
Cholesterol	*Brevibacterium steroidocidalis*	3-Oxopregn-4-ene-20-carboxylic acid	132
Cholesterol	*Arthrobacter simplex*	Androsta-1,4-diene-3,17-dione	133
Cholesterol	*Mycobacterium vaccae* MCI-1104	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione (c) 17β-Hydroxyandrosta-1,4-dien-3-one	29
Cholesterol	*Nocardia corallina* IFO 3338	(a) 3aα-H-4α-(3'-Propionic acid)-5α-hydroxy-7aβ-methyl-hexahydroindanone-δ-lactone (b) 3aα-H-4α-(3'-Transacrylic acid)-5α-hydroxy-7aβ-methyl-hexahydroindanone (c) 3aα-H-4α-Acetyl-5α-hydroxy-7aβ-methyl-hexahydro-1-indanone	55
Cholesterol	*Rhodococcus terrae* MC1-1161	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione (c) 17β-Hydroxyandrosta-1,4-dien-3-one	30
Cholesterol	*Mycobacterium fortuitum*	(a) 24-Nor-chola-1,4-diene-3,22-dione (b) 24-Nor-chol-4-ene-3,22-dione	134

Cholesterol	*Nocardia erythropolis*	20-Carboxy-pregna-1,4-dien-3-one	135, 136
Cholesterol	*Nocardia aliena*	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione	137, 138
Cholesterol	*Mycobacterium parafortuitum* MC1-0801	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione (c) 17β-Hydroxyandrosta-1,4-dien-3-one (d) 17β-Hydroxyandrost-4-en-3-one (e) 5α-Androstan-3,6,17-trione (f) 5β-Androst-1-ene-3,17-dione (g) 9α-Hydroxyandrost-4-ene-3,17-dione (h) 5α-Androstan-3,17-dione	32
Cholesterol	*Arthrobacter simplex* MC1-0803	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione (c) 17β-Hydroxyandrosta-1,4-dien-3-one (d) 17β-Hydroxyandrost-4-en-3-one	33
Cholesterol	*Brevibacterium lypolytica* IAM-1398	Androsta-1,4-diene-3,17-dione	139
Cholesterol	*Rhodococcus corallinus*	3β-Hydroxy-23,24-bisnor-chol-5-en-22-oic acid	140
Cholest-4-ene-3-(*O*-carboxy-methyl)-oxime	*Mycobacterium phlei*	Androst-4-ene-3,17-dione	26
Cholest-4-ene-3-(*O*-carboxy-methyl)-oxime	*Mycobacterium phlei* (immobilized)	Androst-4-ene-3-(*O*-carboxy-methyl)-oxime-17-one	38
Cholest-4-ene-3-(*O*-carboxy-methyl)-oxime	*Mycobacterium smegmatis* (immobilized)	Androst-4-ene-3-(*O*-carboxy-methyl)-oxime-17-one	38
3,3-Ethylenedioxycholest-5-ene	*Mycobacterium phlei* (immobilized)	3,3-Ethylenedioxyandrost-5-en-17-one	38
3,3-Ethylenedioxycholest-5-ene	*Mycobacterium smegmatis* (immobilized)	3,3-Ethylenedioxyandrost-5-en-17-one	38, 141
Cholest-4-ene-3-(*O*-carboxy-methyl)-oxime	*Mycobacterium phlei* (immobilized)	Androst-4-ene-3-(*O*-carboxy-methyl)-oxime-17-one	40
Progesterone and its derivatives			
Pregn-4-ene-3,20-dione	*Aspergillus aureofulgens*	(a) Androst-4-ene-3,17-dione (b) 17β-Acetoxyandrost-4-en-3-one (c) 17β-Hydroxyandrost-4-en-3-one (d) 5β-Androstan-3,17-dione (e) 3α-Hydroxy-5β-androstan-17-one	142
Pregn-4-ene-3,20-dione	*Curvularia lunata*	(a) Androsta-1,4-diene-3,17-dione (b) 3-Hydroxy-9,10-seco-1,3,5(10)-androstatriene-9,17-dione (c) 3,17-Dihydroxy-9,10-seco-1,3,5(10)-androstatrien-9-one	116
3β-Hydroxypregn-5-en-20-one	*Arthrobacter simplex*	Androst-4-ene-3,17-dione	143
D-Homo-pregn-4-ene-3,20-dione	*Penicillium lilacinum* ATCC 10114	17aβ-Hydroxy-D-homo-androst-4-en-3-one	79
20-Hydroxymethylpregn-4-en-3-one	*Mycobacterium parafortuitum*	Androst-4-ene-3,17-dione	144
20-Hydroxymethylpregna-1,4-dien-3-one	*Mycobacterium parafortuitum*	Androsta-1,4-diene-3,17-dione	144
11β,17α,21-Trihydroxypregn-4-ene-3,20-dione	*Pseudomonas testosteroni*	11β-Hydroxyandrosta-1,4-diene-3,17-dione	145
Sitosterol and its derivatives			
Sitosterol	*Mycobacterium fortuitum*	(a) 9α,17β-Dihydroxyandrost-4-en-3-one (b) 3-Oxo-bisnor-chol-4-ene-9α,22-diol (c) 9α-Hydroxy-3-oxo-bisnor-chol-4-en-22-oic acid methyl ester (d) 9α-Hydroxy-3-oxo-bisnor-chol-4-en-22-oic acid	88
Sitosterol	*Mycobacterium fortuitum*	Androst-4-ene-3,17-dione	27
Sitosterol	*Mycobacterium fortuitum*	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione	146, 147

Table 2 (*Continued*)

Steroid substrate	Microorganism	Products	References
Sitosterol	*Mutant bacterial* strain ATCC-31459	(a) 3-Oxopregna-1,4-diene-20-carboxylic acid (b) 3-Oxopregn-4-ene-20-carboxylic acid	148
Sitosterol	Strains of *Mycobacterium*	(a) Pregn-4-ene-20-carboxylic acid (b) Androst-4-ene-3,17-dione (c) Androsta-1,4-diene-3,17-dione	149
Sitosterol	*Mycobacterium flavum*	Androsta-1,4-diene-3,17-dione	149
Sitosterol and campesterol mixture	*Mycobacterium vaccae*	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione (c) 9α-Hydroxyandrost-4-ene-3,17-dione	49
Sitosterol	91 *Mycobacterium* strains	(a) 23,24-Bisnor-chola-1,4-diene-3-one-22-oic acid (b) Androst-4-ene-3,17-dione (c) Androsta-1,4-diene-3,17-dione	150
Sitosterol	*Mycobacterium fortuitum*	3aαH-4α-(3-Hydroxypropyl)-7aβ-methyl-hexahydro-1,5-indandione hemiketal	52
Sitosterol	*Mycobacterium fortuitum* NRRL B 8119	(a) 9α-Hydroxyandrost-4-ene-3,17-dione (b) 9α-Hydroxy-3-oxo-23,24-bisnor-chol-4-en-22-oic acid (c) 9α-Hydroxy-3-oxo-23,24-bisnor-chol-4-en-22-oic acid ester (d) 3-Oxo-23,24-bisnor-chol-4-ene-9α,22-diol	50
Sitosterol	*Mycobacterium* sp B 3683	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione	151
Sitosterol	*Mycobacterium* sp NRRL B 3805	(a) 21-Hydroxy-20-methyl-pregn-4-en-3-one (b) 21-Hydroxy-20-methyl-pregna-1,4-dien-3-one	152
Sitosterol	*Mycobacterium fortuitum* NRRL B 8153	(a) Androsta-1,4-diene-3,17-dione (b) Androst-4-ene-3,17-dione	153
Sitosterol	*Nocardia M* 29–40	3-(5α-Hydroxy-7aβ-methyl-1-oxo-3aα-H-hexahydroindan-4α-yl)-propionic acid	154
19-Hydroxysitosterol and its acetate	*Mycobacterium flavum*	(a) 19-Hydroxyandrost-4-ene-3,17-dione (b) 3β-Hydroxy-1,3,5-estratrien-17-one	31
19-Hydroxysitosterol and its acetate	*Mycobacterium mucosum*	(a) 19-Hydroxyandrost-4-ene-3,17-dione (b) 3β-Hydroxy-1,3,5-estratrien-17-one	31
19-Hydroxysitosterol and its acetate	*Mycobacterium lacticola*	(a) 19-Hydroxyandrost-4-ene-3,17-dione (b) 3β-Hydroxy-1,3,5-estratrien-17-one	31
19-Hydroxysitosterol and its acetate	*Protoaminobacter alboflavus*	(a) 19-Hydroxyandrost-4-ene-3,17-dione (b) 3β-Hydroxy-1,3,5-estratrien-17-one	31
Phytosterol	*Arthrobacter simplex*	Androsta-1,4-diene-3,17-dione	155

Substrates are classified alphabetically

Table 3 Dehydrogenations

Substrate	Microorganism	Products	References
Androstanes			
Androst-4-ene-3,17-dione	*Nocardia rhodocrous* (immobilized)	Androsta-1,4-diene-3,17-dione	156
Androst-4-ene-3,17-dione	*Mycobacterium* sp (immobilized)	Androsta-1,4-diene-3,17-dione	156
Androst-4-ene-3,17-dione	*Rhizopus* sp (immobilized)	Androsta-1,4-diene-3,17-dione	156
Androst-4-ene-3,17-dione	*Arthrobacter* sp (immobilized)	Androsta-1,4-diene-3,17-dione	156
Androst-4-ene-3,17-dione	*Corynebacterium* sp (immobilized)	Androsta-1,4-diene-3,17-dione	156
Androst-4-ene-3,17-dione	*Cunninghamella* sp (immobilized)	Androsta-1,4-diene-3,17-dione	156
Androst-4-ene-3,17-dione	*Curvularia* sp (immobilized)	Androsta-1,4-diene-3,17-dione	156
Androst-4-ene-3,17-dione	*Aspergillus* sp (immobilized)	Androsta-1,4-diene-3,17-dione	156
Androst-4-ene-3,17-dione	*Bacillus* sp (immobilized)	Androsta-1,4-diene-3,17-dione	156
Androst-4-ene-3,17-dione	*Nocardia rhodocrous*	Androsta-1,4-diene-3,17-dione	157
Androst-4-ene-3,17-dione	*Cunninghamella elegans*	Androsta-4,6-diene-3,17-dione	64
17β-Hydroxyandrost-4-en-3-one	*Nocardia rhodocrous* (immobilized)	17β-Hydroxyandrosta-1,4-dien-3-one	39
3β-Hydroxyandrost-5-en-17-one	*Nocardia rhodocrous* (immobilized)	Androst-4-ene-3,17-dione	39
17α-Cyanomethyl-19-nor-17β-hydroxy-androst-4,9-dien-3-one	*Mycobacterium smegmatis*	17α-Cyanomethyl-1,3,5(10)-estratriene-3,17-diol	158
6α-Hydroxyandrost-4-ene-3,17-dione	*Phytophthora infestans*	Androst-4-ene-3,6,17-trione	159
17β-Hydroxyandrost-4-en-3-one	*Phytophthora infestans*	Androst-4-ene-3,17-dione	159
17α-Methyl-17β-hydroxy-5α-androstan-3-one	*Arthrobacter simplex* and *Nocardia* sp (immobilized)	(a) 17α-Methyl-17β-hydroxyandrosta-1,4-dien-3-one (b) 17α-Methyl-3,17β-dihydroxy-9,10-seco-1,3,5-(10)-androstatrien-9-one	48
Cholestanes			
Cholesterol	*Nocardia rhodocrous* (immobilized)	Cholest-4-en-3-one	36
Cholesterol	*Nocardia* sp	Cholest-4-en-3-one	160
Cholesterol	*Nocardia* sp or *Mycobacterium* sp	Cholest-4-en-3-one	161
Cholesterol	*Arthrobacter simplex*	(a) Cholesta-1,4-dien-3-one (b) Cholest-4-en-3-one	162
Cholesterol	*Nocardia erythropolis* (immobilized)	Cholest-4-en-3-one	163
Cholesterol	*Phytophthora infestans*	Cholest-4-en-3-one	159
25-Hydroxycholesterol	*Rhizoctonia muneratii*	25-Hydroxycholest-4-en-3-one	66
21-Nor-cholesterol	*Tetrahymena pyriformis*	21-Nor-cholesta-5,7,22-trien-3β-ol	164
26(27)-Nor-cholesterol	*Tetrahymena pyriformis*	26(27)-Nor-cholesta-5,7,22-trien-3β-ol	164
Pregnanes			
Pregn-4-ene-3,20-dione	*Curvularia lunata*	Pregna-1,4-diene-3,20-dione	116
3β-Hydroxypregn-5-en-20-one	*Arthrobacter simplex*	Pregna-1,4-diene-3,20-dione	127
3β-Hydroxypregn-5-en-20-one	*Nocardia rhodocrous* (immobilized)	Pregn-4-ene-3,20-dione	39
3β-Hydroxypregn-5-en-20-one	*Phytophthora infestans*	Pregn-4-ene-3,20-dione	159
11α-Hydroxypregn-4-ene-3,20-dione	*Phytophthora infestans*	Pregn-4-ene-3,11,20-trione	159
16α-Hydroxypregn-4-ene-3,20-dione	2 strains of bacteria No 144 and No 146	Pregna-4,16-diene-3,20-dione	65

Table 3 (*Continued*)

Substrate	Microorganism	Products	References
16α-Hydroxypregn-4-ene-3,20-dione	*Eubacterium* sp No 144	Pregna-4,16-diene-3,20-dione	120
11β,17α,21-Trihydroxypregn-4-ene-3,20-dione	*Arthrobacter simplex* (immobilized)	11β,17α,21-Trihydroxypregna-1,4-diene-3,20-dione	37, 41
11β,17α,21-Trihydroxypregn-4-ene-3,20-dione (cortisol)	*Corynebacterium simplex*	11β,17α,21-Trihydroxypregna-1,4-diene-3,20-dione	165
11α,17α,21-Trihydroxypregn-4-ene-3,20-dione (epicortisol)	*Curvularia lunata*	11β,17α,21-Trihydroxypregna-1,4-diene-3,20-dione	105
11β,16α,17α,21-Tetrahydroxypregn-4-ene-3,20-dione	*Corynebacterium* sp	11β,16α,17α,21-Tetrahydroxypregna-1,4-diene-3,20-dione	166
9β,11β-Epoxy-17α-hydroxy-16β-methylpregn-4-ene-3,20-dione	*Arthrobacter simplex*	9β,11β-Epoxy-17α-hydroxy-16β-methylpregna-1,4-diene-3,20-dione	167
9α-Fluoro-11β,17α,21-Trihydroxypregn-4-ene-3,20-dione	*Arthrobacter simplex* and *Streptomyces roseochromogenus* (mixed culture)	9α-Fluoro-11β,17α,21-trihydroxypregna-1,4-diene-3,20-dione	44
16β-Methyl-5α-pregn-9(11)-ene-3β,17α,21-trihydroxy-20-one-3,21-diacetate	*Arthrobacter simplex* and *Nocardia* sp (mixed culture)	(a) 16β-Methylpregna-1,4,9(11)-triene-17α,21-dihydroxy-3,20-dione (b) 16β-Methylpregna-1,4-diene-9α,11α-epoxy-17α,21-dihydroxy-3,20-dione	48
D-Homo-pregn-4-ene-3,15,20-trione	*Bacillus lentus* ATCC 13805	D-Homo-pregna-1,4-diene-3,15,20-trione	79
11α-Hydroxy-D-homo-pregn-4-ene-3,20-dione	*Bacillus lentus* ATCC 13805	11α-Hydroxy-D-homo-pregna-1,4-diene-3,20-dione	79
6β,11α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	*Bacillus lentus* ATCC 13805	6β,11α-Dihydroxy-D-homo-pregna-1,4-diene-3,20-dione	79
11α,15α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	*Bacillus lentus* ATCC 13805	11α,15α-Dihydroxy-D-homo-pregna-1,4-diene-3,20-dione	79
11β,17α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	*Bacillus lentus* ATCC 13805	11β,17α-Dihydroxy-D-homo-pregna-1,4-diene-3,20-dione	79
12β,15α-Dihydroxy-D-homo-pregn-4-ene-3,20-dione	*Bacillus lentus* ATCC 13805	12β,15α-Dihydroxy-D-homo-pregna-1,4-diene-3,20-dione	79
3β,17α-Dihydroxy-5α-pregnan-20-one-21-acetate	*Nocardia* sp	17α-Hydroxypregn-4-ene-3,20-dione-21-acetate ester	46
3β,17α,21-Trihydroxy-5α-pregnan-20-one-21-acetate	*Nocardia* sp	17α,21-Dihydroxypregna-1,4-diene-3,20-dione	168
Sitostanes			
Sitosterol	*Nocardia rhodocrous* (immobilized)	Stigmast-4-en-3-one	36
Sitosterol	91 strains of *Mycobacterium*	Stigmast-4-en-3-one	144
Sitosterol	*Pseudomonas* sp	Stigmast-4-en-3-one	18
Sitosterol	*Nocardia rhodocrous* (immobilized)	Stigmast-4-en-3-one	39
Sitosterol	Strains of *Mycobacterium*	Stigmast-4-en-3-one	149
Sitosterol	*Phytophthora infestans*	Stigmast-4-en-3-one	159
Stigmasterol	*Nocardia rhodocrous* (immobilized)	Stigmast-4-en-3-one	36, 39
Stigmasterol	*Pseudomonas* sp	Stigmasta-4,22-dien-3-one	75
Stigmasterol	*Phytophthora infestans*	Stigmast-4-en-3-one	159
Fucosterol	*Nocardia restrictus*	(a) Fucostenone (b) Iso-fucostenone	169
Iso-fucosterol	*Nocardia restrictus*	(a) Fucostenone (b) Iso-fucostenone	169

Table 4 Miscellaneous reactions

Substrate	Microorganism	Products	References
Acetylation			
17aβ-Hydroxy-17aα-methyl-D-homo-androstane-3, 17-dione	*Curvularia clavata*	6α-Acetoxy-17aβ-hydroxy-17aα-methyl-D-homo-androstane-3,17-dione	69
Epoxidations			
3β,17α,21-Trihydroxy-16β-Methyl-5α-pregn-9(11)-en-20-one-3β,21-diacetate	*Arthrobacter simplex* and *Nocardia* sp (mixed culture)	9α,11α-Epoxy-17α,21-dihydroxy-16β-methylpregna-1,4-diene-3,20-dione	48
Androst-4-ene-3,17-dione	*Cunninghamella elegans*	(a) 3α-Hydroxy-4α,5-epoxy-5α-androstan-17-one (b) 3α,11α-Dihydroxy-4α,5-epoxy-5α-androstan-17-one	64
17a-Aza-D-homo-androst-4-ene-3,17-dione	*Cunninghamella elegans*	3α-Hydroxy-4α,5-epoxy-D-homo-5α-androstan-17-one	60
N-Acetyl-17a-aza-D-homo-androst-5-en-3β-yl acetate	*Cunninghamella elegans*	*N*-Acetyl-5,6β-epoxy-17a-aza-D-homo-5β-androstane-1β,3β-diol	60
Sitosterol	*Pseudomonas* sp	(a) 5,6α-Epoxy-5α-stigmastan-3β-ol (b) 5,6β-Epoxy-5β-stigmastan-3β-ol	24
3β-Acetoxyandrost-5-en-17-one	*Cunninghamella elegans*	3β,12α-Dihydroxy-5,6β-epoxy-5α-androstan-17-one	64
3β-Acetoxy-17a-aza-D-homo-androst-5-en-17-one	*Cunninghamella elegans*	3β-Hydroxy-5,6β-epoxy-17a-aza-D-homo-5β-androstan-17-one	60
Hydrogenations			
Androsta-1,4-diene-3,17-dione	*Streptococcus faecalis*	5β-Androst-1-ene-3,17-dione	170
Androst-4-ene-3,17-dione	*Clostridium paraputrificum*	5β-Androstane-3,17-dione	171
3β-Hydroxyandrost-5-en-17-one	*Eubacterium* sp	3β-Hydroxy-5β-androstan-17-one	171
Androst-4-ene-3,17-dione	*Clostridium paraputrificum*	3α-Hydroxy-5β-androstan-17-one	172
Cholest-4-en-3-one	*Eubacterium* sp	5β-cholestan-3β-ol	171
Cholest-4-en-3β-ol (Allocholesterol)	*Eubacterium* sp	5β-cholestan-3β-ol	171
Cholesterol	*Eubacterium* sp	5β-cholestan-3β-ol	173
24-Methylenecholesterol	*Saccharomyces cerevisiae*	24β-Methylcholesterol	174
Desmosterol	*Saccharomyces cerevisiae*	24-Methylcholesterol	174
Pregn-4-ene-3,20-dione	*Gymnoascus reesii*	3-Carboxy-4-oxo-3,4-seco-5α-pregnan-20-one	63
Cholest-4-en-3-one	*Nocardia corallina*	5α-Cholestan-3β-ol	175
Hydrolysis			
3β-Acetoxy-17a-aza-D-homo-androst-5-en-17-one	*Cunninghamella elegans*	(a) 3β-Hydroxy-5,6β-epoxy-17a-aza-D-homo-5β-androstan-17-one (b) 3β,7β-Dihydroxy-17a-aza-D-homo-androst-5-en-17-one (c) 3β,7α-Dihydroxy-17a-aza-D-homo-androst-5-en-17-one (d) 3β-Hydroxy-17a-aza-D-homo-androst-5-en-17-one (e) 3β-Hydroxyandrost-5-ene-7,17-dione	60
N-Acetyl-17a-aza-D-homo-androst-5-en-3β-yl acetate	*Cunninghamella elegans*	(a) *N*-Acetyl-17a-aza-D-homo-androst-5-ene-3β,7β-diol (b) *N*-Acetyl-17a-aza-D-homo-androst-5-ene-3β,7α-diol (c) *N*-Acetyl-17a-aza-D-homo-androst-5-ene-1β,3β-diol (d) *N*-Acetyl-5,6β-epoxy-17a-aza-D-homo-5β,androstane-1β,3β-diol (e) *N*-Acetyl-17a-aza-D-homo-androst-5-ene-1β,3β,7β-triol	60
N-Acetyl-17a-aza-D-homo-androst-5-en-3β-yl acetate	*Cunninghamella elegans*	(a) 3β-Hydroxy-*N*-acetyl-17a-aza-D-homo-androst-5-en-7-one (b) *N*-Acetyl-17a-aza-D-homo-androst-5-ene-3β,7β-diol (c) *N*-Acetyl-17a-aza-D-homo-androst-5-ene-3β,7α-diol	60

Table 4 (*Continued*)

Substrate	Microorganism	Products	References
3β,16β-Diacetoxy-androst-5-en-17-one	*Flavobacterium estero-aromaticum*	3β,16β-Dihydroxyandrost-5-en-17-one	176
3-Acetoxy-6-chloroandrosta-3,5-dien-17-one	*Rhizopus arrhizus* ATCC 11145	3β-Hydroxyandrost-4-ene-6,17-dione	103
3β-Hydroxyandrost-5-en-17-one acetate	*Cunninghamella elegans*	(a) 3β-Hydroxyandrost-5-ene-7,17-dione (b) 3β,14α-Dihydroxyandrost-5-ene-7,17-dione (c) 3β,7β-Dihydroxyandrost-5-en-17-one (d) 3β,7α-Dihydroxyandrost-5-en-17-one (e) 3β,12α-Dihydroxy-5,6β-epoxy-5α-androstan-17-one	64
Cholesteryl acetate	*Phytophthora infestans*	Cholesterol	159
Pregn-5-ene-3β,17α-dihydroxy-20-one-21-acetate	*Corynebacterium mediolanum*	17α,21-Dihydroxypregn-4-ene-3,20-dione	177
3β,21-Diacetoxy-17α-methoxypregn-5-en-20-one	*Flavobacterium dehydrogenans*	21-Hydroxy-17α-methoxypregn-4-ene-3,20-dione	110
21-Acetoxy-5α,6α-epoxy-3β-hydroxy-6β,16α-dimethylpregnan-20-one	*Flavobacterium dehydrogenans*	6α,21-Dihydroxy-6β,16α-dimethylpregn-4-ene-3,20-dione	71
21-Acetoxy-3β-hydroxypregn-5-en-20-one	*Aspergillus ochraceus*	3β,11α,21-Trihydroxypregn-5-en-20-one	97
21-Acetoxy-5α,6α-epoxy-3β-hydroxy-6β,16α-dimethylpregnan-20-one	*Flavobacterium dehydrogenans*	6α,21-Dihydroxy-6β,16α-dimethylpregn-4-ene-3,20-dione	70, 71
3β,17α-Dihydroxy-5α-pregnan-20-one-21-acetate	*Nocardia* sp	(a) 17α,21-Dihydroxypregn-4-ene-3,20-dione (Reichestein's compound 'S') (b) 17α,21-Dihydroxypregna-1,4-diene-3,20-dione	46
17α-Hydroxy-5α-pregnan-20-one-3β,21-diacetate	*Norcadia* sp	(a) 17α,21-Dihydroxypregn-4-ene-3,20-dione (b) 17α,21-Dihydroxypregna-1,4-diene-3,20-dione	46
Sitosteryl acetate	*Phytophthora infestans*	Sitosterol	159
Stigmasteryl acetate	*Phytophthora infestans*	Stigmasterol	159
Oxidations			
Pregn-4-ene-3,20-dione	*Caldariella acidophila*	Pregn-4-ene-3,6,20-trione	67
6α-Chloroandrost-4-ene-3,17-dione	*Rhizopus arrhizus* ATCC 11145	Androst-4-ene-3,6,17-trione	103
3-Acetoxy-6β-chloroandrosta-3,5-dien-17-one	*Rhizopus arrhizus* ATCC 11145	Androst-4-ene-3,6,17-trione	103
11-Deoxy-17α,21-dihydroxypregn-4-ene-3,20-dione	*Cunninghamella blakesleeana*	17α,21-Dihydroxypregn-4-ene-3,11,20-trione	105
3β-Acetoxyandrost-5-en-17-one	*Cunninghamella elegans*	(a) 3β-Hydroxyandrost-5-ene-7,17-dione (b) 3β,14α-Dihydroxyandrost-5-ene-7,17-dione	64
3β-Acetoxy-17a-aza-D-homo-androst-5-en-17-one	*Cunninghamella elegans*	3β-Hydroxyandrost-5-ene-7,17-dione	60
Oxidation cum hydrolysis			
3β-Acetoxypregna-5,16-dien-20-one	*Streptomyces albus*	(a) Pregna-4,16-diene-3,20-dione (b) 3β-Hydroxypregna-5,16-dien-20-one	178
3β-Acetoxypregn-5-en-20-one	*Streptomyces albus*	(a) Pregn-4-ene-3,20-dione (b) 3β-Hydroxypregn-5-en-20-one	178
3β-Acetoxyandrost-5-en-17-one	*Streptomyces albus*	(a) Androst-4-ene-3,17-dione (b) 3β-Hydroxyandrost-5-en-17-one	178
17β-Acetoxyandrost-4-en-3-one	*Streptomyces albus*	(a) 17β-Hydroxyandrost-4-en-3-one (b) Androst-4-ene-3,17-dione	178
Reduction of keto group			
18,21-Dihydroxy-11-deoxypregn-4-ene-3,20-dione	*Clostridium paraputrificum*	3α,18,21-Trihydroxy-11-deoxy-5β-pregnan-20-one	179

8,21-Dihydroxy-11-dehydropregn-4-ene-3,20-dione	*Clostridum paraputrificum*	3α,8,21-Trihydroxy-11-dehydropregn-4-en-20-one	179
11β,18,21-Trihydroxypregn-4-ene-3,20-dione	*Clostridium paraputrificum*	3α,11β,18,21-Tetrahydroxypregn-4-en-20-one	179
Androst-4-ene-3,17-dione	*Rhodotorula glutinis*	5α-Androstane-3α,17β-diol	180
17β-Hydroxyandrost-4-en-3-one	*Rhodotorula glutinis*	5α-Androstane-3α,17β-diol	180
Pregn-4-ene-3,20-dione	*Aspergillus aureofulgens*	3α-Hydroxy-5β-androstan-17-one	142
17α-Cyanomethyl-19-nor-17β-hydroxyandrost-4-en-3-one	*Mycobacterium smegmatis*	17α-Cynomethyl-3α,17β-dihydroxy-5α-estrane	158
Androst-4-ene-3,17-dione	*Clostridium paraputrificum*	3α-Hydroxy-5β-androstan-17-one	172
19-Hydroxyandrost-4-ene-3,17-dione	*Rhodotorula mucilaginosa*	3α,19-Dihydroxy-5α-androstan-17-one	181
7,7-Difluoro-5α-androstan-3-one	*Calonectria decora*	3β,12β,15α-Trihydroxy-7,7-difluoro-5α-androstane	59
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16,16-Difluoro-5α-androstan-3-one	*Calonectria decora*	3β,7β,12β-Trihydroxy-16,16-difluoro-5α-androstane	59
17β-Hydroxy-19-nor-5α-androstan-3-one	*Rhodotorula mucilaginosa*	(a) 3α-Hydroxy-19-nor-5α-androstan-17-one (b) 19-Nor-5α-androstane-3α,17β-diol	181
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