

21-Hydroxylation of steroids

5

Description:

Generally, the present invention relates to the field of steroid hydroxylation. More specifically, the present invention relates to a method for the 21-hydroxylation of steroids in cells. It also
10 relates to cells expressing a steroid 21-hydroxylating enzyme or steroid 21-hydroxylase, expression vectors comprising a nucleic acid encoding for a steroid 21-hydroxylase and a kit for carrying out the method for the 21-hydroxylation of steroids in cells.

Synthetic glucocorticoids are descendent from the natural occurring stress hormone cortisol
15 and play a crucial role in pharmaceutical industry because of their anti-inflammatory and immune suppressive effects. Moreover, synthetic molecules often act more effective than cortisol.

Currently, the synthesis of some pharmaceutically active steroids involves a 21-hydroxylation
20 of their precursor (see Figure 1 for an example), which consists of a long lasting chemical multistep synthesis. By means of synthetic chemistry this hydroxylation is also difficult, as the chemical oxidants are not selective to position 21. For this reason, other functional groups have to be protected to avoid their oxidation and to direct the hydroxylation reaction towards position 21. Furthermore, the synthesis is not environmentally friendly because of the use of
25 reagents such as iodine. Therefore, a cheap and sustainable production of pharmaceutically active steroids is highly desirable to satisfy the high demand for these important drugs.

This problem has been addressed by the present inventors by the development of whole cell biotransformation of steroids in a one-step synthesis by the enzyme CYP21A2, which is a
30 member of the protein family of the cytochrome P450 monooxygenases and which is able to perform a highly selective hydroxylation of steroids at the 21-position of the steroid scaffold (see Figure 2 for a scheme of the process). CYP21A2 is a mammalian membrane anchored enzyme which is located in the endoplasmic reticulum and which plays a crucial role in the steroid hormone biosynthesis. The inventors have shown that the biocatalytic system of the
35 invention is a promising candidate to replace the established chemical synthesis. In particular, they have shown that steroids could be modified within one single hydroxylation step, leading to the one desired product, which is saving time, is environmentally friendly (no by-products were observed) and facilitates downstream processing. Furthermore and

advantageously, for the steroid production in whole cells according to the invention, enzymes do not have to be purified, remain stable in the host and the addition of costly redox equivalents like NADPH is not necessary, because the cell itself serves as a donor.

5 Before the present invention is described in detail below, it is to be understood that this invention is not limited to the particular methodology, protocols and reagents described herein as these may vary. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to limit the scope of the present invention which will be limited only by the appended claims. Unless defined
10 otherwise, all technical and scientific terms used herein have the same meanings as commonly understood by one of ordinary skill in the art.

Preferably, the terms used herein are defined as described in "A multilingual glossary of biotechnological terms: (IUPAC Recommendations)", Leuenberger, H.G.W, Nagel, B. and
15 Kölbl, H. eds. (1995), Helvetica Chimica Acta, CH-4010 Basel, Switzerland).

Several documents are cited throughout the text of this specification. Each of the documents cited herein (including all patents, patent applications, scientific publications, manufacturer's specifications, instructions etc.), whether supra or infra, is hereby incorporated by reference
20 in its entirety. Nothing herein is to be construed as an admission that the invention is not entitled to antedate such disclosure by virtue of prior invention.

In the following, the elements of the present invention will be described. These elements are listed with specific embodiments, however, it should be understood that they may be
25 combined in any manner and in any number to create additional embodiments. The variously described examples and preferred embodiments should not be construed to limit the present invention to only the explicitly described embodiments. This description should be understood to support and encompass embodiments which combine the explicitly described embodiments with any number of the disclosed and/or preferred elements. Furthermore, any
30 permutations and combinations of all described elements in this application should be considered disclosed by the description of the present application unless the context indicates otherwise.

Throughout this specification and the claims which follow, unless the context requires
35 otherwise, the word "comprise", and variations such as "comprises" and "comprising", are to be understood to imply the inclusion of a stated integer or step or group of integers or steps but not the exclusion of any other integer or step or group of integer or step. As used in this

specification and the appended claims, the singular forms “a”, “an”, and “the” include plural referents, unless the content clearly dictates otherwise.

In a first aspect, the present invention relates to a process for the hydroxylation of the carbon atom 21 of a steroid, comprising the steps of:

a) providing a cell expressing

(i) a heterologous CYP21A2 protein or a functional variant thereof,

(ii) at least one heterologous electron transfer system capable of transferring electrons to CYP21A2, and

(iii) one or more chaperones facilitating folding of CYP21A2; and

b) adding the steroid to the cell.

A steroid is a type of organic compound that contains a characteristic arrangement of four cycloalkane rings that are joined to each other (shown below). The core of steroids is composed of seventeen carbon atoms bonded together that take the form of four fused rings: three cyclohexane rings (designated as rings A, B and C) and one cyclopentane ring (the D ring). The steroids vary by the functional groups attached to this four-ring core and by the oxidation state of the rings.

The hydroxylation of the carbon atom 21 of a steroid is the addition of an -OH group at position 21 as shown in the above-shown ABCD steroid ring system. The numbering of the carbon atoms is according to the IUPAC (International Union of Pure and Applied Chemistry)-approved ring lettering and atom numbering. The 21-hydroxylation of a steroid is shown in Figure 1.

25

In a particular embodiment of the process of the first aspect of the invention, the steroid is a 3-keto steroid. More particularly, the steroid is a non-natural steroid, i.e. a steroid that is not produced and/or 21-hydroxylated in cells, especially human or bovine cells, which are not genetically altered.

30

In one embodiment, the steroid is selected from the group consisting of medrane, deltamedrane, progesterone, 17OH-progesterone, medroxyprogesterone, and 5- α -dihydroprogesterone. The 21-hydroxylation converts these particular steroids to premedrol, medrol, 11-deoxycorticosterone, 11-deoxycortisol, 21OH-medroxyprogesterone and 21OH-(5 α -dihydroprogesterone), respectively. In one particular embodiment, in which the steroid is a non-natural steroid, the steroid is selected from the group consisting of medrane, deltamedrane, medroxyprogesterone, and 5- α -dihydroprogesterone.

The cell is in particular a cultured cell, cultured in any cell medium, e.g. in a growth medium, and is, in a particular embodiment, in a resting state. According to this embodiment, the cell is comprised in a buffer or medium capable of maintaining the cell rather than in a growth medium. The composition of the buffer depends on the particular cell and suitable buffers are well-known in the art. Depending on the cell-type, the cell is a suspension cell or an adherent cell. A suspension cell is a cell that may naturally live in suspension (i.e. without being attached to a surface), or a cell that has been modified to be able to survive in suspension cultures, for example to be grown to higher densities than adherent conditions would allow.

10 An adherent cell is a cell that requires a surface, such as tissue culture plastic or microcarrier, which may be coated with extracellular matrix (such as collagen and laminin) components to increase adhesion properties and provide other signals needed for growth and differentiation. In one embodiment, the adherent cell is a monolayer cell.

15 Generally, the cell may be a prokaryotic cell or a eukaryotic cell. A particular example of a prokaryotic cell to be used in the process of the first aspect is an *E. coli* cell, e.g. of the *E. coli* strain C43(DE3) of the examples. A particular example of a eukaryotic cell is a yeast cell, e.g. a *S. cerevisiae* cell or a *Schizosaccharomyces pombe* cell. However, the process of the first aspect is not limited to any particular cell type and any cell type may be used, in particular any cell type that can be grown and maintained in culture and that can be used as a recombinant expression system, like insect cells or mammalian cells in addition to the above-mentioned cells.

20

The term "heterologous" means that a protein is expressed in cell that does not normally (i.e. without human intervention) express that protein. CYP21A2, for example is an enzyme also called 21-hydroxylase, which is part of the cytochrome P450 family of enzymes. Cytochrome P450 enzymes are involved in many processes in the body, such as assisting with reactions that break down drugs and helping to produce cholesterol, certain hormones, and fats (lipids). The 21-hydroxylase enzyme is found in the adrenal glands, which are located on top of the kidneys and produce a variety of hormones that regulate many essential functions in the body. Therefore, with respect to heterologous expression, the CYP21A2 protein can be considered heterologous regarding any cell which is not an adrenal gland cell.

25

30

In particular, the term "heterologous" can also refer to the species a protein or gene is derived from in comparison to the cell in which it is expressed, in particular recombinantly expressed. A heterologous protein is then a protein that is derived from a different species than the cell it is expressed in, i.e. the cell of the process of the first aspect of the invention.

35

For example, the present inventors expressed mammalian, in particular human or bovine proteins in an *E. coli* cell, making these proteins heterologous with respect to the cell.

In a particular embodiment of the process of the first aspect of the invention, the CYP21A2 protein is of human or bovine origin. Human CYP21A2 (UniProt accession number P08686) has the sequence according to SEQ ID NO: 1 of the sequence listing. Bovine CYP21A2 (UniProt accession number P00191) has the sequence according to SEQ ID NO: 2 of the sequence listing. See also Figure 8. Homologous genes, however, do also exist in other mammalian species, such as *Canis lupus* (dog), *Macaca mulata* (rhesus monkey), *Rattus norvegicus* (rat), *Gallus gallus* (chicken), *Danio rerio* (zebra fish), *Mus musculus* (mouse), or *Pan troglodytes* (chimpanzee). Therefore, it is emphasized that any CYP21A2 protein can be used, in particular any mammalian CYP21A2 protein. A modified human or bovine CYP21A2 according to SEQ ID NO: 3 and SEQ ID NO: 4, respectively, can also be used. See also Figure 8.

15

The term “functional variant” is a protein variant that has at least 20% (e.g., at least: 20%; 30%; 40%; 50%; 60%; 70%; 80%; 90%; 95%; 98%; 99%; 99.5%; or 100% or even more) of the ability of the unaltered or CYP21A2 protein to 21-hydroxylate a steroid. This ability can be determined by the skilled person without undue burden using, for example, the methods shown in Examples 1 and 2 herein.

A “protein variant” is a protein that has an amino acid sequence that is at least 70%, 80%, 85%, 90%, 95%, 96%, 97%, 98% or 99% identical to the amino acid sequence of the CYP21A2 it is derived from, for example SEQ ID NO: 1 or 3 in case of human CYP21A2 or SEQ ID NO: 2 or 4 in case of bovine CYP21A2. The determination of percent identity between two sequences is accomplished using the mathematical algorithm of Karlin and Altschul, *Proc. Natl. Acad. Sci. USA* 90, 5873-5877, 1993. Such an algorithm is incorporated into the BLASTN and BLASTP programs of Altschul et al. (1990) *J. Mol. Biol.* 215, 403-410. To obtain gapped alignments for comparative purposes, Gapped BLAST is utilized as described in Altschul et al. (1997) *Nucleic Acids Res.* 25, 3389-3402. When utilizing BLAST and Gapped BLAST programs, the default parameters of the respective programs are used.

Alternatively, a protein variant can also be defined as having up to 100, 90, 80, 70, 60, 50, 40, 30, 20, 10, 5, 4, 3, 2, or 1 amino acid substitutions, in particular conservative amino acid substitutions. Conservative substitution tables are well known in the art (see for example Creighton (1984) *Proteins*. W.H. Freeman and Company). An overview of physical and chemical properties of amino acids is given in Table 1 below. In a particular embodiment,

35

conservative substitutions are substitution made with amino acids have the same properties according to Table 1.

Table 1: Properties of naturally occurring proteins.

5

Charge properties / hydrophobicity	Side group	Amino Acid
nonpolar hydrophobic	aliphatic aliphatic, S-containing aromatic imino	Ala, Ile, Leu, Val Met Phe, Trp Pro
polar uncharged	aliphatic amide aromatic hydroxyl sulfhydryl	Gly Asn, Gln Tyr Ser, Thr Cys
positively charged	basic	Arg, His, Lys
negatively charged	acidic	Asp, Gly

The term “variant” also includes protein fragments. A fragment of CYP21A2 has an N-terminal and/or C-terminal deletion of up to 100, 90, 80, 70, 60, 50, 40, 30, 20, 10, 5, 4, 3, 2, or 1 amino acids in total. In a particular embodiment, the functional variant is a fragment of 10 CYP21A2 lacking the hydrophobic anchor region, i.e. a truncation of 29 N-terminal amino acid residues (Figure 8).

In addition, the CYP21A2 protein may be modified, for example by N-terminal or C-terminal amino acid additions, such as tags or N-terminal modifications for improved bacterial 15 expression. For example, the tag may be a C-terminal His-tag, e.g. 6 x His-tag and the N-terminal modification an addition of ten amino acids from the N-terminus of CYP2C3 (see Figure 8 and SEQ ID Nos 3 and 4).

An electron transfer system is a series of compounds that transfer electrons from electron 20 donors to electron acceptors via redox reactions. The term “capable of transferring electrons to CYP21A2” thereby means that CYP21A2 is the electron acceptor of this series. The term “series” herein may include CYP21A2 and, thus, the electron transfer system may consist of only one protein in addition to CYP21A2. For the process of the first aspect of the invention, it is not crucial which members the electron transfer system consists of, as long as the 25 system is capable of transferring electrons to CYP21A2. Suitable systems are well-known in the art. In a particular embodiment of the process of the first aspect of the invention, the at

least one electron transfer system comprises (i) a CYP21A2 reductase, or (ii) a ferredoxin reductase, preferably an NADPH-dependent ferredoxin reductase (adrenodoxin reductase) and a ferredoxin. For example, the at least one electron transfer protein can be selected from the group consisting of an NADPH-dependent cytochrome P450 reductase (CPR, e.g. human or bovine), the combination of an adrenodoxin reductase (AdR, e.g. human or bovine) and an adrenodoxin (Adx4-108, e.g. human or bovine), the combination of a flavodoxin reductase (Fpr, e.g. from *E. coli*) and an adrenodoxin (Adx4-108, e.g. human or bovine), the combination of an adrenodoxin reductase homolog (Arh), e.g. *S. pombe* adrenodoxin reductase homolog (Arh1), and an adrenodoxin (Adx4-108, e.g. human or bovine), the combination of an adrenodoxin reductase homolog (Arh), e.g. *S. pombe* adrenodoxin reductase homolog (Arh1), and the ferredoxin domain of an electron transfer domain (etp^{fd}), e.g. the ferredoxin domain of the *S. pombe* electron transfer domain (etp1^{fd}), and the combination of a flavodoxin reductase (Fpr, e.g. from *E. coli*) and the ferredoxin domain of an electron transfer domain (etp^{fd}), e.g. the ferredoxin domain of the *S. pombe* electron transfer domain (etp1^{fd}).

In a particular embodiment, exogenous NADPH is not added to the cell. In this embodiment, NADPH is produced by the cell. In a specific embodiment, the NADPH-production in the cell may be increased by recombinant means, e.g. the heterologous expression of enzymes involved in NADPH production (e.g. one or more of glucose-6-phosphate dehydrogenase (G6PD), phosphogluconate dehydrogenase (PGD), malate dehydrogenase (MDH), and/or isocitrate dehydrogenase (ICDH)), and/or it may be increased by providing hormonal signals, i.e. adding hormones such as estradiol that enhance the level of endogenous NADPH production.

25

Similarly, the chaperone can be any chaperone as long as it is capable of facilitating folding of CYP21A2. The present inventors found that the process of the first aspect of the invention can rely only on endogenous chaperones, i.e. additional expression of suitable chaperones is not essential. However, an additional expression improves the production of functional CYP21A2 in the cell and can therefore be beneficial. Thus, in one embodiment of the process of the first aspect of the invention, the one or more chaperones are recombinantly expressed chaperones. In particular, the one or more chaperones may be heterologous chaperones. Exemplary chaperones are the *E. coli* chaperones GroEL and GroES or other chaperones like DnaK, DnaJ, GrpE, and ClpB as well as small heat shock proteins (sHSP) such as IbpA and IbpB (IbpAB),.

35

Optionally, the same chaperone or one or more additional chaperone(s) to be expressed in the cell is/are capable of folding one or more of above electron transfer proteins.

Recombinant expression refers to the expression of a recombinant gene. Such a gene can be any gene introduced into the cell by methods of genetic engineering and is usually a heterologous gene and/or a gene regulated differently than a possible endogenous counterpart gene in terms of expression. In one embodiment, the recombinant expression is inducible.

In one embodiment of the process of the first aspect of the invention, the process further comprises adding one or more cell permeabilizing agents to the suspension of cells, for example after step b). Cell permeabilizing agents are reagents which increase the permeability of membranes. Examples are organic solvents, such as methanol, acetone or DMSO, detergents such as saponin, Triton X-100 or Tween-20, and EDTA. In particular, polymyxin B can be used as a cell permeabilizing agent. This agent proved to work particularly well in the process of the invention.

In another embodiment of the process of the first aspect of the invention, the process further comprises a step c) of extracting the 21-hydroxylated steroid from the cell and/or the supernatant of the cell (i.e. the buffer or medium the cell is comprised in), for example from a whole cell suspension. The extraction can be done with any solvents or extraction methods known in the art for extracting undissolved compounds. For example, a solvent such as 1-butanol, 2-butanone or chloroform may be used.

In a specific embodiment of the process of the first aspect of the invention, the expression of at least one tryptophanase gene is reduced or abolished in the cell. A tryptophanase or L-tryptophan indole-lyase (EC number 4.1.99.1.) is an enzyme catalyzing the reaction $L\text{-tryptophan} + H_2O = \text{indole} + \text{pyruvate} + NH_3$. Accordingly, the reduction or abolishment will lead to the decrease of indol production by the cell, which can improve the process, since indol is an inhibitor of CYP enzymes such as CYP21A2. As tryptophanase genes are generally (but not exclusively) found in prokaryotes, e.g. *E. coli*, this specific embodiment applies in particular to the embodiment of the process of the first aspect of the invention in which the cell is a prokaryotic cell. In one embodiment, the species of a cell expressing a tryptophanase gene is selected from the group consisting of *Aeromonas hydrophila*, *Bacillus* sp., *Bacteroides* sp., *Corynebacterium* sp., *Enterobacter aerogenes*, *Enterobacter aerogenes* SM-18, *Enterobacter* sp., *Erwinia* sp., *Escherichia aureescens*, *Escherichia coli*, *Fusobacterium necrophorum* subsp. *Funduliforme*, *Kluyvera* sp., *Micrococcus aerogenes*,

Morganella morganii, *Paenibacillus alvei*, *Paracolobactrum coliforme*, *Paracolobactrum sp.*, *Pasteurella sp.*, *Photobacterium profundum*, *Porphyromonas gingivalis*, *Prevotella intermedia*, *Proteus vulgaris*, *Providencia rettgeri*, *Shigella alkalescens*, *Sphaerophorus sp.*, *Symbiobacterium thermophilum*, *Vibrio sp.* and a mammalian species such as *Homo sapiens*
5 and *Rattus norvegicus*,

In a further embodiment of the process of the first aspect of the invention, the cell further expresses a heterologous or recombinant gene encoding for an enzyme catalyzing a step in the heme biosynthesis pathway, in particular a heterologous hemA (glutamyl tRNA
10 reductase) gene. An example for such cells is *E. coli*. This will advantageously reduce the need for feeding precursors for the synthesis of the CYP heme, such as the heme precursor δ -aminolevulinic acid, and reduce the costs for the biotransformation of steroids in such cells.

In a particular embodiment of the process of the first aspect of the invention, the nucleic
15 acids encoding for (i) a heterologous CYP21A2 protein or a functional variant thereof, (ii) at least one heterologous electron transfer system capable of transferring electrons to CYP21A2, and optionally (iii) one or more chaperones facilitating folding of CYP21A2 are comprised in one or more expression cassette(s) which is/are integrated into the cell, in particular into its genome. The term "expression cassette" refers to a DNA fragment which
20 comprises a gene operably linked to a regulatory sequence such as a promoter, necessary for gene expression. "Operably linked" refers to the linking of nucleotide regions encoding specific genetic information such that the nucleotide regions are contiguous, the functionality of the region is preserved and will perform relative to the other regions as part of a functional unit. The nucleic acids (i), (ii) and optionally (iii) may each be comprised in individual
25 expression cassettes or in one or more multicistronic expression cassettes. As used herein, the term "multicistronic" means that multiple cistrons, namely, multiple nucleic acids or genes, are operably linked to the same regulatory sequence, e.g. a promoter.

In one embodiment, the nucleic acids encoding for (i) a heterologous CYP21A2 protein or a
30 functional variant thereof, (ii) at least one heterologous electron transfer system capable of transferring electrons to CYP21A2, and optionally (iii) one or more chaperones facilitating folding of CYP21A2 are comprised in an expression vector comprised in the cell. An "expression vector" is a vehicle by means of which DNA fragments that contain nucleic acids encoding for a protein can be introduced into host cells where the nucleic acids can be
35 expressed by the host cell. The nucleic acids (i), (ii) and optionally (iii) may each be comprised in individual expression vectors or in one or more multicistronic expression vectors.

Also, one or more of the nucleic acids (i), (ii) and optionally (iii) may be comprised in an expression cassette which is integrated into the cell genome, whereas the remaining nucleic acids (i), (ii) or optionally (iii) are comprised in an expression expression vector, both as set
5 out above.

In a second aspect, the present invention relates to cell expressing
(i) a heterologous CYP21A2 protein or a functional variant thereof,
(ii) at least one heterologous electron transfer system capable of transferring electrons to
10 CYP21A2, and
(iii) one or more chaperones facilitating folding of CYP21A2.

This cell as well as the cell of the process of the first aspect of the invention can also be described as a cell comprising one or more nucleic acids encoding for
15 (i) a heterologous CYP21A2 protein or a functional variant thereof,
(ii) at least one heterologous electron transfer system capable of transferring electrons to CYP21A2, and
(iii) one or more chaperones facilitating folding of CYP21A2.

20 In a particular embodiment, these nucleic acids are comprised in one or more expression cassettes.

The cell of the second aspect is in essence the cell used in the process of the first aspect of the invention and, therefore, further embodiments of the cell of the second aspect of the
25 invention are as described above with respect to the process of the first aspect .

In a third aspect, the present invention relates to a multicistronic expression vector comprising (i) a nucleic acid encoding for a CYP21A2 protein or a functional variant thereof,
(ii) one or more nucleic acids encoding for at least one heterologous electron transfer system
30 capable of transferring electrons to CYP21A2, and optionally (iii) one or more nucleic acids encoding for chaperones facilitating folding of CYP21A2.

In a fourth aspect, the present invention relates to a kit comprising
- a cell of the second aspect,
35 - a multicistronic expression vector of the third aspect, or
- (i) an expression vector comprising a nucleic acid encoding for a CYP21A2 protein or a functional variant thereof, (ii) one or more expression vectors comprising one or more nucleic

acids encoding for at least one heterologous electron transfer system capable of transferring electrons to CYP21A2, and optionally (iii) one or more expression vectors comprising one or more nucleic acids encoding for chaperones facilitating folding of CYP21A2.

5 The term "kit" is used herein to mean a collection of all or some of the reagents, materials, and instructions necessary to carry out the process of the first aspect. This includes cell culture medium or buffer (both in dry or liquid form), one or more cell permeabilizing agents, solvents for extracting the steroid and, in particular, the steroid to be hydroxylated, in particular a 3-keto steroid, for example one or more of medrane, deltamedrane,
10 progesterone, 17OH-progesterone, medroxyprogesterone, or 5 α -dihydroprogesterone. Furthermore, it is envisaged that all reagents or materials described herein with relation to the process of the first aspect can be part of the kit of the fourth aspect.

In a particular embodiment, the process of the first aspect, the cell of the second aspect, the
15 expression vector of the third aspect and the kit of the fourth aspect do not comprise a further step or component as applicable, especially a heterologous gene or protein, for steroid conversion or production which is not related to the 21-hydroxylation of steroids, particularly as described herein. Optionally, an exception of this may be downstream steps or components related to the further processing of the 21-hydroxylated steroid (such as the
20 conversion from premedrol to medrol) or upstream steps or components related to the production of the steroid to be 21-hydroxylated (such as the production of medrane).

In the following figures and examples, some particular embodiments of the invention are described in more detail. Yet, no limitation of the invention is intended by the details of the
25 particular embodiments. In contrast, the invention pertains to any embodiment which comprises details which are not explicitly mentioned in the embodiments herein, but which the skilled person finds without undue effort.

Description of the Figures:

30

Figure 1: Hydroxylation of a steroid (here progesterone) at carbon atom 21.

Figure 2: Scheme of a whole cell biotransformation of a steroid by CYP21A2 and the needed electron transfer proteins in *E. coli*.

35

Figure 3: left: CO difference spectrum of purified bovine CYP21; right: SDS-PAGE of bCYP21 samples taken after indicated purification steps (IMAC/DEAE/SP).

Figure 4: HPLC chromatogram of the *in vitro* 21-hydroxylation of medrane to premedrol by human CYP21 and described electron transfer proteins, here AdR and Adx (system 2).

5 Figure 5: Constructed vectors for whole cell biotransformation using human or bovine CYP21 with different electron transfer proteins.

Figure 6: HPLC chromatogram of the whole cell 21-hydroxylation of medrane to premedrol (A), delta-medrane to medrol (B), medroxyprogesterone to 21OH-medroxyprogesterone (C),
10 and 17OH-progesterone to 11-deoxycortisol (D) by bovine CYP21 and described electron transfer proteins, here Fpr and Adx.

Figure 7: Time-dependent whole cell conversion of medrane to premedrol by bovine CYP21 and described electron transfer proteins, here Fpr and Adx.

15

Figure 8: Amino acid sequences of wildtype and modified human (A) and bovine (B) CYP21A2.

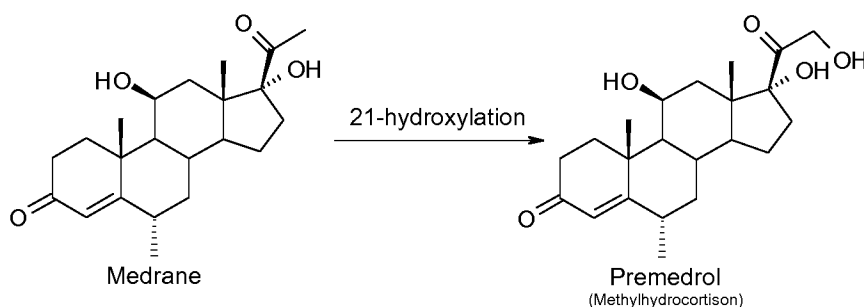
Description of the examples:

20

Example 1: *In vitro* hydroxylation

1.1 Expression / purification of hCYP21 / bCYP21

25 To show that both human and bovine CYP21 are able to hydroxylate steroids at position 21, *in vitro* studies with both enzymes were performed. As an exemplary 21-hydroxylation process, medrane was converted to premedrol:



30

Premedrol (methylhydrocortisone) is a precursor of a highly effective pharmaceutical steroid medrol (methylprednisolone). Medrol is an important drug in therapy of autoimmune

diseases, multiple sclerosis and in general for local and systematic treatment of inflammations.

Both enzymes were expressed in the *E. coli* strain C43(DE3) by coexpression of the *E. coli* 5 chaperones GroEL/GroES encoded in the vector pGro12. These chaperones ensure a correct protein folding which is important for an incorporation of the heme prosthetic group. In Figure 3 an SDS-PAGE and a CO difference spectrum of purified bovine CYP21 are shown. As the CO difference spectrum shows, the enzyme was purified in an active form. To determine the binding of medrane to both isozymes the binding constants (K_D -values) were 10 determined.

1.2 Expression of electron delivering redox partners

For an efficient substrate conversion, both isoforms require an electron transfer system 15 which consists of two parts, the cytochrome P450 enzyme itself and one or two electron transfer proteins which are essential for a hydroxylation reaction. Without these transfer proteins, no reaction will take place. Electrons can be transferred to CYP21 for example by the six electron transfer systems listed in Table 2:

20 Table 2: Electron delivering proteins applied in CYP21-dependent substrate conversions and corresponding expression plasmids for whole-cell systems. hCYP21 or bCYP21 were combined in reconstituted systems or whole-cell systems with the indicated redox partners bCPR (bovine NADPH-dependent cytochrome P450 reductase), bAdR (bovine adrenodoxin reductase), bAdx₄₋₁₀₈ (bovine adrenodoxin), Fpr (*E. coli* flavodoxin reductase), Arh1 (*S.* 25 *pombe* adrenodoxin reductase homolog), etp1^{fd} (*S. pombe* electron transfer protein, ferredoxin domain).

	Protein combinations in reconstituted <i>in vitro</i> systems		Corresponding plasmids in whole-cell systems
	Reductase	Ferredoxin	
1	CPR		p21h_bRED / p21b_bRED
2	AdR	Adx ₄₋₁₀₈	p21h_AdAx / p21b_AdAx
3	Fpr	Adx ₄₋₁₀₈	p21h_FrAx / p21b_FrAx
4	Arh	Adx ₄₋₁₀₈	p21h_ArAx / p21b_ArAx
5	Arh	etp1 ^{fd}	p21h_ArET / p21b_ArET
6	Fpr	etp1 ^{fd}	p21h_FrET / p21b_FrET

For *in vitro* studies and a verification of a substrate conversion, all redox partners were purified.

1.3 Reconstitution of cytochrome P450 systems *in vitro*

5

In vitro substrate conversions with purified enzymes in a defined buffer and with an NADPH regeneration system revealed that both isoforms together with the here listed electron transfer proteins are able to convert medrane to premedrol very efficiently. Figure 4 shows the *in vitro* conversion of medrane by human CYP21 together with electron transfer system
10 2. This result indicates that steroids as exemplified by premedrol can be produced enzymatically by CYP21 together with a suitable redox system, e.g. as shown in Table 2.

Example 2: Whole-cell systems

15 In view of the successful *in vitro* conversion of steroids, a biotransformation in whole cells was developed.

Generally, in order to perform the hydroxylation in whole cells, the CYP21 as well as the necessary electron transfer proteins were expressed heterologously in *Escherichia coli* strain
20 C43(DE3). For expression and following conversion, bi- or tricistronic vectors based on the plasmid pET17b were constructed, which carry the genes for the particular CYP21 and the particular redox system. Figure 5 shows all constructed vectors. To facilitate correct protein folding, the *E. coli* chaperones GroEL and GroES were co-expressed on a second vector. The transformed *E. coli* cells were able to produce the CYP21 enzyme as well as the needed
25 redox partners. After the protein expression, a substrate conversion took place which was started by the addition of the steroid to be hydroxylated (exemplified by medrane) as a substrate.

In particular, *E. coli* strain C43(DE3) was transformed with vector for whole cell biocatalysis
30 (e.g. p21b_ArET) and the pGro12 which encodes the chaperones GroEL/ES. The culture comprised 200 mL TB medium (+ antibiotics ampicillin and kanamycin) in a 2 L Erlenmeyer flask, inoculated with 2 mL seed culture, and was grown at 37°C. Expression was induced at OD 0.5 by addition of 1 mM IPTG, 1mM δ -aminolevulinic acid, 4 mg/mL arabinose and maintained for 28 h at 27 °C. For whole cell biotransformation, cells were harvested by
35 centrifugation and washed with 50 mM potassium phosphate buffer (pH 7.4). Substrate conversion was started with the addition of 400 μ M substrate with resting cells in 25 mL potassium phosphate buffer (50 mM) including 2% glycerol, 1 mM IPTG, 1mM δ -

aminolevulinic acid, 4 mg/mL arabinose in 300 mL baffled flasks for 24 h at a cell density of ca. 24 g/L (wet weight). Samples were taken after, e.g., 24 h and measurement was performed via RP-HPLC after steroid extraction with chloroform.

5 Figure 6 shows that the steroid was converted to its 21-hydroxylated derivative and that the appearance of by-products was not observed, in contrast to a chemical synthesis. Time-dependent product formation was studied in whole cells with the six redox systems for each CYP21 isoform to determine not only an endpoint yield but also the velocity of the reaction which is of high interest regarding a biotechnological process (Figure 7).

10

Next to the medrane-to-premedrol conversion, both human and bovine CYP21 were able to hydroxylate all tested 3-ketosteroids which are not yet hydroxylated at position 21. In particular, the following steroid conversions could be shown:

- Medrane to premadrol (non-natural substrate)

15 - Deltamedrane to medrol (non-natural substrate)

- Progesterone to 11-deoxycorticosterone (natural substrate)

- 17OH-progesterone to 11-deoxycortisol (natural substrate)

- Medroxyprogesterone to 21OH-medroxyprogesterone (non-natural substrate)

- 5 α -dihydroprogesterone to 21OH-(5 α -dihydroprogesterone).

20

Claims:

1. A process for the hydroxylation of the carbon atom 21 of a steroid, comprising the steps of:
 - 5 a) providing a cell expressing
 - (i) a heterologous mammalian CYP21A2 protein or a functional variant thereof, wherein the functional variant has at least 20% of the ability of the unaltered CYP21A2 protein to 21-hydroxylate a steroid,
 - (ii) at least one heterologous electron transfer system capable of transferring electrons
 - 10 to CYP21A2, and
 - (iii) one or more chaperones facilitating folding of CYP21A2; and
 - b) adding the steroid to the cell,
 wherein the steroid is medrane or deltamedrane.
- 15 2. The process of claim 1, further comprising a step c) of extracting the 21-hydroxylated steroid from the supernatant of the cell.
3. The process of any one of claims 1-2, further comprising adding one or more cell permeabilizing agents to the cell after step b).
- 20 4. The process of any one of claims 1-3, wherein the cell is a resting cell.
5. The process of any one of claims 1-4, wherein the cell is a prokaryotic cell or a eukaryotic cell.
- 25 6. The process of claim 5, wherein the prokaryotic cell is *E. coli* cell or the eukaryotic cell is a yeast cell.
7. The process of any one of claims 1-6, wherein the at least one electron transfer system comprises
 - 30 (i) a CYP21A2 reductase, and/or
 - (ii) a ferredoxin reductase and a ferredoxin.
8. The process of any one of claims 1-7, wherein the one or more chaperones are
 - 35 recombinantly expressed chaperones.

9. The process of any one of claims 1-8, wherein the expression of at least one tryptophanase gene is reduced or abolished in the cell.

10. The process of any one of claims 1-9, wherein the cell further expresses a heterologous gene encoding for an enzyme catalyzing a step in the heme biosynthesis pathway.

11. The process of claim 10, wherein the heterologous gene is a hemA gene.

12. The process of any one of claims 1-11, wherein the genes encoding for (i), (ii) and optionally (iii) are comprised in one or more expression cassettes which is/are integrated into the cell genome.

13. Use of a cell expressing

(i) a heterologous mammalian CYP21A2 protein or a functional variant thereof, wherein the functional variant has at least 20% of the ability of the unaltered CYP21A2 protein to 21-hydroxylate a steroid,

(ii) at least one heterologous electron transfer system capable of transferring electrons to CYP21A2, and

(iii) one or more chaperones facilitating folding of CYP21A2 for the hydroxylation of the carbon atom 21 of a steroid, wherein the steroid is medrane or deltamedrane.

14. Use of a multicistronic expression vector comprising (i) a nucleic acid encoding for a mammalian CYP21A2 protein or a functional variant thereof, wherein the functional variant has at least 20% of the ability of the unaltered CYP21A2 protein to 21-hydroxylate a steroid,

(ii) one or more nucleic acids encoding for at least one heterologous electron transfer system capable of transferring electrons to CYP21A2, and optionally (iii) one or more nucleic acids encoding for chaperones facilitating folding of CYP21A2

for the hydroxylation of the carbon atom 21 of a steroid, wherein the steroid is medrane or deltamedrane.

15. Use of a kit comprising any one of:

- a cell as defined in claim 13, or

- a multicistronic expression vector as defined in claim 14, or

- (i) an expression vector comprising a nucleic acid encoding for a mammalian CYP21A2 protein or a functional variant thereof, wherein the functional variant has at least 20% of the

ability of the unaltered CYP21A2 protein to 21-hydroxylate a steroid, (ii) one or more expression vectors comprising one or more nucleic acids encoding for at least one heterologous electron transfer system capable of transferring electrons to CYP21A2, and optionally (iii) one or more expression vectors comprising one or more nucleic acids encoding
5 for chaperones facilitating folding of CYP21A2
for the hydroxylation of the carbon atom 21 of a steroid, wherein the steroid is medrane or deltamedrane.