

**Test methods for determining the intracellular concentration of cyclic
nucleotides**

The invention relates to processes for the quantitative optical analysis of the
5 intracellular concentration of cyclic guanosine 3',5'-monophosphate (cGMP) or
cyclic adenosine 3',5'-monophosphate (cAMP). These processes may be useful for
identifying and evaluating the pharmacological properties of test substances which
influence the activity of receptors or enzymes involved in the synthesis or
degradation of the cyclic nucleotides cGMP and cAMP. As a result, the process is
10 suitable, for example, for finding modulators of soluble and membrane-bound
guanylate cyclases, phosphodiesterases (PDEs), NO synthases and G-protein-coupled
receptors (GPCRs).

The invention describes a process in which the intracellular concentrations of cGMP
15 or cAMP are measured with the aid of recombinant cell lines. These cell lines
express recombinantly a combination of particular ion channels activated by cyclic
nucleotides (CNG channels), a calcium-sensitive photoprotein and a receptor or an
enzyme for which modulators are to be found. The process is suitable for automation
and for high-throughput screening (HTS) and ultra high-throughput screening
20 (uHTS) for modulators.

Current processes for measuring the intracellular concentration of cGMP or cAMP
have the disadvantage of being very expensive, due to the use of radioactivity, being
only partially automatable, if at all, and being very complicated.

25 Conventional commercial systems for determining cGMP and cAMP are radioactive
techniques such as the radioimmunoassay (RIA; e.g. from IBL, Hamburg,
Germany), the scintillation proximity assay (SPA; Amersham Bioscience, UK) and
the non-radioactive enzymed-linked immunosorbent assay (ELISA; for example
30 from Amersham Bioscience, UK).

The above-described processes cannot be used for measuring the intracellular cGMP and cAMP concentrations in living cells "in situ". To carry out the measurements, the cells need to be disrupted and the cyclic nucleotides then be extracted.

- 5 Another process for measuring intracellular cAMP is the measurement with the aid of inducible promoter systems ("cAMP response element", CRE) and the enzyme luciferase (Goetz et al., J. Biomol. Screen. (2000) 5 377-384). The process has the disadvantage, however, that both transcription and translation need to take place in order for the signal to form, causing the measurement to last for hours. This method
10 is thus not suitable for rapid measurement of the actual cAMP concentrations in cells.

It is the object of the invention to find an improved, non-radioactive process for measuring the intracellular concentrations of cGMP and cAMP. The intention here is
15 to be able to carry out the measurements very rapidly and also with high sensitivity. The process should be automatable and suitable for high-throughput screening of samples or test compounds (HTS and uHTS).

Test compounds in accordance with the invention are preferably small-molecule
20 chemical compounds having a molecular weight of from 100 to 500 or 100 to 1000 or else higher than that. These compounds may be used individually or else as a mixture in the processes according to the invention. Test compounds in accordance with the invention also include antibodies, natural substances, extracts of natural substances, peptides, proteins and nucleic acids. This list is to be regarded only by
25 way of example and not as finite.

In order to establish a screening system for enzymes and receptors which influence the intracellular cAMP or cGMP level, various ion channels activated by cyclic nucleotides (CNG channels) are transfected, alone or in various combinations, into
30 cells which additionally express a calcium-sensitive photoprotein in a recombinant manner. These cells are subsequently transfected with various enzymes or receptors in order to test the suitability of the cells for high-throughput screening. This involves using, for example, soluble guanylate cyclase, since it is capable of

producing intracellular cGMP after stimulation. An example of a receptor which may be used is the β -adrenergic receptor which, after an activation, induces an increase in intracellular cAMP concentration.

- 5 CNG channels are integral membrane proteins which are opened by the cyclic nucleotides cGMP and cAMP. This family of ion channels are non-selective cation channels which are permeable to sodium, potassium and calcium ions. The functional channels are composed of four identical or else different subunits (homo- or heterotetramers). The sensitivities to cGMP and cAMP can be influenced by
10 combining various subunits (Biel et al. TCM (1996) 6, 274-280; Kaupp and Seifert, Physiol. Rev. (2002) 82, 769-824). The channel subunits CNG1-CNG6 which, according to a more recent nomenclature, are also referred to as CNGA1-CNB3, have been cloned and published (Bradley et al., Science (2001) 294, 2095-2096). There exist also splice variants such as CNG4.3, for example (Sauter et al., PNAS
15 (1998) 95, 4696-4701).

The increase in intracellular cGMP or cAMP concentration results in the opening of the CNG channels and thereby in an influx of calcium ions. The calcium flowing in may then be detected with the aid of calcium-sensitive fluorescent indicators, such
20 as, for example, FURA, Fluo-3 etc., or with the aid of calcium-sensitive photoproteins such as aequorin or obelin.

The photoprotein aequorin which is derived from the jellyfish *Aequorea victoria* is a highly sensitive calcium indicator in cells. The aequorin complex consists of the
25 protein apoaequorin, molecular oxygen and the luminophore coelenterazine. This complex emits blue light in the presence of calcium (Ca^{2+} ions), with maximum emission at 466 nm (Jones et al., Trends Biotechnol. (1999) 17, 477-481).

Another photoprotein is obelin which has been cloned from various hydrozoa such as
30 *Obelia longissima*, for example. It consists of apoobelin, O_2 and the luminophore coelenterazine. Likewise, blue light is emitted in the presence of calcium (Illarionov et al., Methods Enzymol. (2000) 305, 223-49).

Guanylate cyclases are responsible for producing cGMP from GTP. A distinction is made between soluble and membrane-bound guanylate cyclases. Soluble guanylate cyclase is a heterodimer composed of an α subunit and a β subunit. It is the natural receptor for nitrogen monoxide (NO) produced by the endothelial NO synthase and can therefore also be activated pharmacologically by NO-releasing substances such as, for example, SIN-1. Since the cGMP produced by guanylate cyclase induces relaxation of blood vessels, the enzyme is a highly interesting pharmacological target (Hobbs AJ., TIPS (1997) 18, 484-491). The membrane-bound guanylate cyclases possess a transmembrane segment and are activated by various agonists such as ANP, BNP, CNP or guanylin (Wedel and Garbers, Annual Rev. Physiol. (2001) 63, 215-233).

Another pharmacologically interesting protein family are the "G-protein-coupled receptors" (GPCRs). These are integral membrane proteins which can transduce the action of an extracellular hormone into the cell interior. The intracellular levels of cAMP or calcium are influenced via coupling of these receptors to various G proteins. The activation of "Gq-coupled receptors" results in a release of calcium from internal stores and thus in an increase in cytoplasmic calcium concentration. The activation of "Gs-coupled receptors" results in an increase in cAMP concentration, whereas activation of the "Gi-coupled receptors" reduces the intracellular cAMP content (Gurrath M., Curr. Med. Chem. (2001) 8, 1605-1548). An example of Gs-coupled receptors are the " β -adrenergic receptors" which can be stimulated with the aid of agonists such as isoprenaline (Dzimiri N., Pharmakol. Rev. (1999) 51, 465-501).

The cyclic nucleotides cGMP and cAMP produced by guanylate cyclases and GPCRs, respectively, are hydrolyzed by "phosphodiesterases" (PDEs) to give GMP and AMP, respectively. The phosphodiesterases are an enzyme family whose members are distinctly different with regard to substrate specificity, regulation and expression patterns in the body (Francis et al., Prog. Nucleic Acid Res. Mol. Biol. (2001) 65, 1-52). PDEs play a decisive part in controlling the intracellular cAMP and cGMP levels and are therefore likewise important targets for pharmacological intervention.

Surprisingly, combining the CNG3 channel (SEQ ID NO: 5, Acc. No. X 89600) or, in particular, the CNG2 channel (SEQ ID NO: 1, Acc. No. X55010) with a photoprotein proved to be particularly suitable for detecting changes in intracellular cGMP concentrations (Figure 1).

A similar surprise was a combination of CNG2/CNG4.3/CNG5 (SEQ ID NO: 1/ SEQ ID NO: 2, Acc. No. AJ000515/SEQ ID NO: 3, Acc. No. U12623) and a photoprotein, which proved to be very suitable for detecting changes in intracellular cAMP concentration (Figure 3). The combination of CNG2(T537A)/CNG4.3/CNG5 (SEQ ID NO: 4/ SEQ ID NO: 2/ SEQ ID NO: 3) with a photoprotein proved to be particularly suitable for cAMP measurement. In the CNG2 mutant CNG2(T537A) (SEQ ID NO: 4), the amino acid threonine-537 has been replaced with alanine (Altenhofen et al., PNAS (1991) 88, 9868-9872).

The recombinant cell lines may be prepared using common vectors such as pcDNA1.1 Amp or pcDNA3 (Invitrogen Life Technologies). Common transfection reagents such as, for example, lipofectamine (Invitrogen Life Technologies) may be used for transfecting the corresponding plasmid constructs.

The cells are seeded for the measurements on 384-well microtitre plates (MTPs) at 1500 cells per well and on 1536-well MTPs at 250 cells per well. After 1-2 days of growth at 37°C/5% CO₂, the cell culture medium (DMEM/F12 containing 10% foetal calf serum) is removed and the cells are charged with coelenterazine (0.8 µg/ml) in calcium-free Tyrode's at 37°C/5% CO₂ for 3 h. Subsequently, test substances and appropriate control substances (e.g. SIN-1 or isoprenaline) are added in calcium-free Tyrode's and incubated on the cells for 5-10 min. The extra measurement is then carried out in a light-tight box by adding calcium-containing Tyrode's via a comb (final calcium concentration: 3 mM), with the aid of a charge-coupled device camera.

To measure the effects of substances directly, the cells are charged with coelenterazine in calcium-containing Tyrode's. The substances are then added within

the light-tight box and measurement commences immediately with addition of the substances (Figure 5).

5 The advantages of this process are the high sensitivity of the measurement, the low costs per measuring point and the suitability for HTS and uHTS. The process has an excellent signal-to-noise ratio, and it is possible to achieve stimulation factors of 50-150. It is moreover possible to apply test substances for very short periods of time, since a signal can already be observed after a few seconds (Figure 5). This has the advantage of unspecific effects of test substances (e.g. due to cytotoxicity) on the
10 cells used being minimized. The process is moreover suitable for characterizing "orphan receptors" (receptors whose natural ligand is unknown), since it is possible to observe both changes in the cAMP level (Gs coupling and Gi coupling) and changes in intracellular calcium concentration (Gq coupling) by means of luminescence or fluorescence measurement.

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The invention relates to processes for determining the intracellular concentration of cyclic nucleotides, characterized in that a cell expressing a CNG channel together with a photoprotein is prepared and used, and the intracellular concentration of cyclic nucleotides is determined by means of the luminescence signal of the photoprotein.

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The invention likewise relates to processes as described above, wherein the CNG channel is the CNG2 or the CNG3 channel.

25 The invention comprises processes as described above, wherein the cyclic nucleotide is cGMP.

The invention likewise relates to processes as described above, wherein the cyclic nucleotide is cAMP and a cell expressing a combination of the CNG2/CNG4.3/CNG5 channels is prepared and used.

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The invention also relates to the above-described processes, wherein the cyclic nucleotide is cAMP and a cell expressing a combination of the CNG2(T537A)/CNG4.3/CNG5 channels is prepared and used.

The invention relates to the processes as described above, wherein the photoprotein is aequorin.

- 5 The invention also relates to processes as described above, wherein the photoprotein is obelin.

The invention relates to a method of screening test compounds for identifying receptor ligands, wherein any of the above-described processes is used in which the
10 cell used expresses the receptor and possesses an intracellular messenger system which allows a receptor-ligand bond to cause measurable modulation of the ion flow through the ion channel, the said cell is incubated with test substances of which those modulating the luminescence are selected.

- 15 The invention also relates to a method of this type, wherein the receptor is a G-protein-coupled receptor.

The invention also relates to a corresponding method, wherein the G-protein-coupled
20 receptor is an orphan receptor.

The invention furthermore relates to a method of screening test compounds for identifying modulators of phosphodiesterases, wherein any of the above-described processes is used in which the cell used expresses the phosphodiesterase, the said cell
25 is incubated with test substances of which those modulating the luminescence are selected.

The invention likewise relates to a method of screening test compounds for identifying modulators of guanylate cyclases, wherein any of the above-described processes is used in which the cell used expresses the guanylate cyclase, the said cell
30 is incubated with test substances of which those modulating the luminescence are selected.

The invention also comprises a method of screening test compounds for identifying modulators of NO synthase, wherein any of the above-described processes is used in which the cell used expresses the NO synthase and soluble guanylate cyclase, the said cell is incubated with test substances of which those modulating the luminescence are selected.

The invention also relates to a corresponding method, wherein the NO synthase and the soluble guanylate cyclase are expressed in different cells.

The invention also relates to a cell prepared by any of the processes illustrated above.

Description of the figures

Figure 1: Schematic representation of the process for determining intracellular cGMP concentration.

Figure 2: Luminescence measurement after activation of soluble guanylate cyclase with SIN-1. The "relative light units" (RLUs) were measured for 1 min. The amount of light measured at the SIN-1 concentration indicated over this period is shown.

Figure 3: Schematic representation of the process for determining intracellular cAMP concentration.

Figure 4: Luminescence measurement after activation of the β -adrenergic receptor with isoprenaline. The incubation time with isoprenaline is 10 min in calcium-free Tyrode's. Measurement is started by adding calcium. The relative light units (RLUs) are measured in second intervals. The time course of the luminescence signal after addition of calcium and previous incubation with 0 M (stars), 10^{-7} M (squares) and 10^{-6} M (triangles) isoprenaline is shown.

Figure 5: Kinetics of the luminescence signal after activation of the β -adrenergic receptor with isoprenaline in calcium-containing Tyrode's. The measurement is started with the addition of the agonist isoprenaline (10^{-6} M) within the light-tight box.

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Examples

If, for example, soluble guanylate cyclase is additionally expressed in a cell line which expresses, as a cGMP measuring system, the CNG2 channel (SEQ ID NO: 1) together with a calcium-sensitive photoprotein, it is possible to increase the intercellular cGMP concentration with the aid of the guanylate cyclase stimulator SIN-1 in a dose-dependent manner and to detect an enhanced luminescence signal (Figure 2).

15

If, for example, the β -adrenergic receptor is additionally expressed in cells which, as a cAMP-measuring system, express a calcium-sensitive photoprotein together with the CNG-channel subunits CNG2(T537A)/CNG4.3/CNG5 (SEQ ID NO: 4/SEQ ID NO: 2/ SEQ ID NO: 3), activation of this receptor by means of isoprenaline results in a dose-dependent manner in an increased cAMP concentration and an enhanced luminescence signal (Figure 4). If the cells are charged with coelenterazine in calcium-containing Tyrode's, the agonist isoprenaline may also be added directly to the cells within the light-tight box. A luminescence signal will then be observed within a few seconds (Figure 5).

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Claims

1. Process for determining the intracellular concentration of cyclic nucleotides, characterized in that
 - 5 i) a cell expressing a CNG channel together with a photoprotein is prepared and used, and
 - 10 ii) the intracellular concentration of cyclic nucleotides is determined by means of the luminescence signal of the photoprotein.
2. Process according to Claim 1, wherein the CNG channel is the CNG2 or the CNG3 channel.
- 15 3. Process according to Claim 1 or 2, wherein the cyclic nucleotide is cGMP.
4. Process according to Claim 1, wherein the cyclic nucleotide is cAMP and a cell expressing a combination of the CNG2/CNG4.3/CNG5 channels is prepared and used.
- 20 5. Process according to Claim 1, wherein the cyclic nucleotide is cAMP and a cell expressing a combination of the CNG2(T537A)/CNG4.3/CNG5 channels is prepared and used.
- 25 6. Method according to Claims 1-5, wherein the photoprotein is aequorin.
7. Process according to Claims 1-5, wherein the photoprotein is obelin.
- 30 8. A method of screening test compounds for identifying receptor ligands, wherein a process according to any of claims 1-7 is used in which the cell used expresses the receptor and possesses an intracellular messenger system which allows a receptor-ligand bond to cause measurable modulation of the

ion flow through the ion channel, the said cell is incubated with test substances of which those modulating the luminescence are selected.

- 5 9. A method according to Claim 8, wherein the receptor is a G-protein-coupled receptor.
10. A method according to Claim 9, wherein the G-protein-coupled receptor is an orphan receptor.
- 10 11. A method of screening test compounds for identifying modulators of phosphodiesterases, wherein a process according to any of Claims 1-7 is used in which the cell used expresses the phosphodiesterase, the said cell is incubated with test substances of which those modulating the luminescence are selected.
- 15 12. A method of screening test compounds for identifying modulators of guanylate cyclases, wherein a process according to any of Claims 1-7 is used in which the cell used expresses the guanylate cyclase, the said cell is incubated with test substances of which those modulating the luminescence are selected.
- 20 13. A method of screening test compounds for identifying modulators of NO synthase, wherein a process according to any of Claims 1-7 is used in which the cell used expresses the NO synthase and the soluble guanylate cyclase, the said cell is incubated with test substances of which those modulating the luminescence are selected.
- 25 14. A method according to Claim 13, wherein the NO synthase and the soluble guanylate cyclase are expressed in different cells.
- 30 15. Cell, prepared according to any of Claims 1-14.

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