Molecular cloning and functional characterization of a type-I neurotensin receptor (NTR) and a novel NTR from the bullfrog brain

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Abstract

Neurotensin (NT) is a tridecapeptide that functions as a neurotransmitter and neuromodulator in the nervous system. To date, three different types of NT receptor (NTR), NTR1, NTR2 and NTR3, have been identified only in mammalian species. In the present study we isolated the cDNAs for an NTR1 and a novel NTR in the bullfrog brain, designated bfNTR1 and bfNTR4 respectively. bfNTR1 and bfNTR4 encode 422- and 399-amino acid residue proteins respectively. bfNTR1 has a 64% amino acid identity with mammalian NTR1, and 34–37% identity with mammalian NTR2. bfNTR4 exhibits 43% and 45–47% identity with mammalian NTR1 and NTR2 respectively. Both receptors are mainly expressed in the brain and pituitary. bfNTR1 triggers both CRE-luc, a protein kinase A (PKA)-specific reporter, and c-fos-luc, a PKC-specific reporter, activities, indicating that bfNTR1 can activate PKA- and PKC-linked signaling pathways. However, bfNTR4 appears to be preferentially coupled to the PKA-linked pathway as it induces a higher CRE-luc activity than c-fos-luc activity. bfNTRs exhibit different pharmacological properties as compared with mammalian NTRs. Mammalian NTR1 but not NTR2 responds to NT, whereas both bfNTR1 and bfNTR4 show a high sensitivity to NT. SR 48692 and SR 142948A, antagonists for mammalian NTR1 but agonists for mammalian NTR2, function as antagonists for both bfNTR1 and bfNTR4. In conclusion, this report provides the first molecular, pharmacological and functional characterization of two NTRs in a non-mammalian vertebrate. These data should help to elucidate the phylogenetic history of the G protein-coupled NTRs in the vertebrate lineage as well as the structural features that determine their pharmacological properties.

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Introduction

Neurotensin (NT) is a brain and gastrointestinal tridecapeptide that was originally isolated from the bovine hypothalamus (Carraway & Leeman 1973) and subsequently from bovine intestine (Kitabgi et al. 1976). NT exhibits a dual function as a neurotransmitter or neuromodulator in the central nervous system and as a local hormone at the periphery. Central administration of NT induces various effects including modulation of dopaminergic transmission, naloxone-independent analgesia, inhibition of food intake and modulation of pituitary hormone release (Rostène & Alexander 1997, Kitabgi 2002). There is also increasing evidence that NT plays a role in neuropsychiatric diseases, notably in schizophrenia and Parkinson’s disease (McMahon et al. 2002). At the periphery, NT induces hypotension, decrease in gastric acid secretion, lipod digestion, proinflammatory response and proliferation of gut and cancer cells (Kitabgi 2002, Somai et al. 2002).

NT exerts its action through its own membrane receptors. To date, three distinct types of NT receptor, termed NTR1 (Tanaka et al. 1990, Vita et al. 1993), NTR2 (Chalon et al. 1996, Mazella et al. 1996) and NTR3 (Vita et al. 1998), have been identified in mammals. NTR1 and NTR2 have seven transmembrane helices (TMHs), a typical structure of G protein-coupled receptors (GPCRs), while NTR3 possesses a single transmembrane domain and belongs to a Vps10p domain receptor family (Mazella et al. 1998). Compared with NTR1, NTR2 has a relatively short extracellular N-terminal region and a long third intracellular loop (ICL3) (Vincent et al. 1999). Moreover, in NTR2, Asp at position 250 in TMH2 and Asn at position 7–49 in TMH7, the most conserved residues...
among rhodopsin-like GPCRs, are replaced by Ala/Gly and Thr respectively (Vincent et al. 1999). NTR1 exhibits a high affinity for NT but is insensitive to levocabastine, a non-peptide H1 histamine antagonist (Tanaka et al. 1990, Vita et al. 1993), while NTR2 has a very low affinity for NT and is sensitive to levocabastine (Chalon et al. 1996, Mazella et al. 1996). The non-peptide NTR antagonist SR 48692 has a higher affinity to NTR1 than to NTR2 (Gully et al. 1993). A second-generation antagonist, SR 142948A, exhibits a similar binding affinity to mammalian NTR1 and NTR2 (Gully et al. 1997, Betancur et al. 1998). However, it is known that SR 48692 and SR 142948A act as agonists for NTR2 when expressed in Xenopus oocytes (Botto et al. 1997, Mazella et al. 1998). Recently, β-lactotensin has been suggested as a specific agonist for NTR2 (Yamauchi et al. 1998). However, the functional relevance of NT as a ligand of NTR2 is still controversial. NT acts as an agonist for mouse NTR2 (mNTR2) when expressed in Xenopus oocyte (Mazella et al. 1996) and rat cerebellar granule cells (Sarret et al. 2002), while NT is unable to activate any second messenger systems from mNTR2 expressed in human embryonic kidney 293 (HEK293) cells, although radiolabeled NT can bind mNTR2 (Botto et al. 1998). Further, it has been suggested that NT acts as a natural agonist for human NTR2 (hNTR2) when expressed in COS7 and CHO cells (Vita et al. 1998, Richard et al. 2001).

The signal transduction pathways associated with NTRs have been studied in various cell lines. Activation of rat NTR1 (rNTR1) induces an increase in inositol trisphosphate (IP_3) and Ca^{2+} mobilization through an activation of G_{q/11} (Watson et al. 1992, Chabry et al. 1994, Hermans et al. 1994). It has also been reported that stimulation of NTR1 evokes the production of arachidonic acid and cAMP through G_{q/11} and G_{s} activation respectively (Yamada et al. 1993, Carraway & Mitra 1998, Gailly et al. 2000). Furthermore, levocabastine and SR 48692 trigger Ca^{2+} mobilization, IP production, arachidonic acid release and mitogen-activated protein kinase activity in CHO cells expressing rNTR2 or hNTR2 (Vita et al. 1998, Yamada et al. 1998).

Although the three types of NTRs have now been cloned, the physiological roles of these NTRs are still poorly understood. Using an NTR1-knockout mouse model, it has been found that NTR1 is involved in the control of food consumption and body weight, but not in NT-induced analgesia (Remaury et al. 2002). On the other hand, NTR2 seems to account for the SR 48692-insensitive analgesic effect (Dubuc et al. 1999, Maeno et al. 2004). Recent studies have shown that NTR3 may control proliferation of human cancer cells (Dal Farra et al. 2001), migration of human microglia (Martin et al. 2003) and proNGF-induced neuronal cell death (Nykjaer et al. 2004).

In non-mammalian species, the primary structure of NT has been characterized in chicken (Carraway & Bhatnagar 1980), alligator (Bello et al. 1993), python (Conlon et al. 1997) and two species of frog (Shaw et al. 1992, Desrues et al. 1998). It has also been reported that frog NT (fNT) stimulates the secretion of corticosteroids from perifused frog adrenal slices (Sicard et al. 2000) and the release of α-melanocyte-stimulating hormone from perifused frog pars intermedia cells (Desrues et al. 1998). The latter process appears to be mediated by a receptor which shares pharmacological characteristics with both mammalian NTR1 and NTR2 (Belmeguenai et al. 2000). However, to date, NTRs have not been characterized in any non-mammalian vertebrate species.

In the present study using the bullfrog, we have cloned and characterized an NTR1 like receptor (bNTR1) and a novel NTR (bNTR4) that is structurally and functionally different from mammalian NTR2.

Materials and methods

Materials

Oligonucleotides were purchased from GenoTech Co. (Seoul, Korea). The pcDNA3 expression vector was purchased from Invitrogen. All constructs of mammalian NTRs were a generous gift from Dr J Mazella (CNRS, Valbonne, France). The pCMVβ-gal was purchased from Clontech. The CRE-luc vector that contains four copies of the cAMP response element (CRE, TGACGTCA) was obtained from Stratagene (La Jolla, CA, USA). The c-fos-luc vector containing the −711~+45 sequence of the human c-fos promoter constructed in the pFLASH vector, was a kind gift from Dr R Prywes (Columbia University, NY, USA). Taq DNA polymerase was purchased from Promega. Vent polymerase was obtained from New England Biotech (Beverly, MA, USA). Frog (Rana ridibunda) NT (Table 2) was synthesized by the solid phase methodology on an Applied Biosystem model 432 synthesizer (St Quentin en Yvelines, France), using an Fmoc-Leu-PEG-PS resin, by the standard Fmoc procedure as previously described (Desrues et al. 1998). hNT, porcine NMN (pMNN) and NT(8–13) were obtained from Sigma. The NT analogs JMV 431, JMV 457, JMV 458 and JMV 510 (Table 2) were kindly provided by Dr Jean Martinez (CNRS UMR 5810, University of Montpellier 2, France). Levocabastine was a generous gift from Janssen Pharmaceutica (Beerse, Belgium). SR 48692 and SR 142948A (Table 2) were generously given by Sanofi-Synthelabo (Montpellier, France).

Animals and tissue preparation

Adult bullfrogs were purchased from a local supplier (BCPC, Taen, Korea) and housed in flow-through tanks...
under simulated natural conditions. Frogs were killed by decapitation. The tissues of interest were quickly dissected and immediately frozen in liquid nitrogen, and stored at $-80^\circ$C until use. Animal experiments were conducted in accordance with the Guidelines for the Care and Use of Experimental Animals at Chonnam National University.

RNA isolation

Total RNA was extracted from frozen tissues by Tri reagent (MRC, Inc., Cincinnati, OH, USA) according to the manufacturer’s instructions. RNA quality was examined by electrophoresis on 1% formaldehyde agarose gels. The RNA, which showed two sharp bands of 18S and 28S, was stored at $-80^\circ$C until use. Poly (A)$^+$ RNA was prepared by using an RNeasy mini kit (Qiagen).

Isolation of partial fragments for bfNTR1 and bfNTR4

One microgram of total RNA isolated from the brain was reverse transcribed at 42$^\circ$C for 1 h followed by an incubation at 52$^\circ$C for 30 min in 20 µl of reaction buffer containing 1 mM of each dNTP, 200 U of AMV reverse transcriptase (Promega), 20 U of RNAGard Rnase Inhibitor (Amersham Pharmacia Biotech) and 0.5 µg oligo-deoxymyidine primer. Synthesized cDNA was amplified with the primer sets NTR-F4 and NTR-R1 (for bfNTR1) or dNTR4-F1 and NTR-R3 (for bfNTR4) (Table 1) under 35 cycles of denaturation at 94$^\circ$C for 30 s, annealing at 50$^\circ$C for 50 s and extension at 72$^\circ$C for 1 min. For bfNTR4, a nest PCR was performed with primers dNTR4-F and NTR-R2 in the same PCR condition. PCR products were cloned into the pGEM-T easy vector (Promega). Positive clones were sequenced by a sequenase version 2.0 DNA sequencing kit (USB Corporation, Cleveland, OH, USA).

5’- and 3’-rapid amplification of cDNA ends (RACE)

A cDNA library was constructed from brain Poly (A)$^+$ RNA using a Marathon cDNA amplification kit (Clontech) according to the manufacturer’s instruction. 5’-RACE was performed by using adapter primer 1 (Ap1) combined with the gene-specific primers bfNT1–5’GSP1 (bfNTR1) or bfNT4–5’GSP1 (bfNTR4) (Table 1). The PCR products were diluted and further amplified with adapter primer 2 (Ap2) combined with the gene-specific primers bfNT1–3’GSP2 (bfNTR1) or bfNT4–3’GSP3 (bfNTR4) (Table 1). 3’-RACE was performed by using Ap1 combined with the gene-specific primers bfNT1–3’GSP1 (bfNTR1) or bfNT4–3’GSP1 (bfNTR4) (Table 1). The PCR products were diluted and further amplified with Ap2 combined with the gene-specific primers bfNT1–3’GSP2 (bfNTR1) or bfNT4–3’GSP2 (bfNTR4) (Table 1). RACE products were cloned into the pGEM-T easy vector and transformed into DH5α competent cells. White colonies containing the right sized PCR product were sequenced via free access.
Cloning of the full-length open-reading frame (ORF) of bfNTRs

The ORFs of bfNTR1 and bfNTR4 were amplified with Vent DNA Taq polymerase using primer sets bfNTR1-F (including EcoRI and Kozak site) and bfNTR1-R (including XbaI) or bfNTR4-F (including HindIII and Kozak site) and bfNTR4-R (including XbaI) (Table 1). The PCR products of anticipated size were digested with the corresponding restriction enzymes and ligated into pcDNA3. The selected colonies were analyzed by PCR with their corresponding primer sets and further confirmed by sequencing.

Tissue distribution of bfNTRs mRNA

One microgram of total RNA prepared from various tissues was reverse transcribed as described above. One microliter out of 20 µl RT samples was subjected to PCR. For bfNTR1 and bfNTR4, the following pairs of primers were used respectively: bfNT1–3/GSP1 and bfNT1–5/GSP1; bfNT4–3/GSP1 and bfNT4–5/GSP1 (Table 1). The PCR products and 100 bp DNA size marker (Elpis Biotech, Daejeon, Korea) were analyzed on a 1·5% agarose gel containing ethidium bromide (0·5 µg/ml).

Establishment of stable cell lines expressing bfNTRs

The pcDNA3 containing the ORF of bfNTR1 or bfNTR4 was transfected into CHO-K1 cells using the SuperFect transfection kit (Qiagen). For each transfection, 100 ng construct cDNA and 200 ng c-fos-luc (or CRE-luc) along with 200 ng of the internal control plasmid pCMVβ-gal were used. The empty vector pcDNA3 was used to adjust the total amount of transfected DNA. Cells were incubated in serum-free DMEM for 18 h before treatment with NT, NT analogs and/or NT antagonists (Table 2). Six hours after drug treatment, cells were harvested and the luciferase activity in the cell extract was determined as previously described (Oh et al. 2005). The luciferase activities were normalized using the β-galactosidase values. Transfection experiments were performed in triplicate and repeated three to five times.

IP assay

Forty-eight hours before assay, CHO-K1 cells stably expressing bfNTR1 or bfNTR4 were stored in liquid nitrogen until use.

Table 2 NTR ligands used in this study

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<thead>
<tr>
<th>Compounds</th>
<th>Amino acid sequence or chemical formula</th>
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<tr>
<td>Frog NT</td>
<td>pGlu Ala His Ile Ser Lys Ala Arg Pro Tyr Ile Leu</td>
</tr>
<tr>
<td>Human NT</td>
<td>pGlu Leu Tyr Glu Asn Lys Pro Arg Pro Tyr Ile Leu</td>
</tr>
<tr>
<td>Porcine NMN</td>
<td>Lys Ile Pro Tyr Ile Leu</td>
</tr>
<tr>
<td>NT(8–13)</td>
<td>Arg Pro Tyr Ile Leu</td>
</tr>
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<td>Boc-Trp11NT(8–13) (JMV 458)</td>
<td>Boc Arg Arg Pro Trp Ile Leu</td>
</tr>
<tr>
<td>Boc-D-Trp11NT(8–13) (JMV 457)</td>
<td>Boc Arg Arg Pro D-Trp Ile Leu</td>
</tr>
<tr>
<td>Boc-Lys6,9,Nal11NT(8–13) (JMV 510)</td>
<td>Boc Lys Lys Pro Nal Ile Leu</td>
</tr>
<tr>
<td>Boc-psi11,12NT(8–13) (JMV 431)</td>
<td>Boc Arg Arg Pro Tyr psi (CH2NH) Ile Leu</td>
</tr>
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<td>SR 48692</td>
<td>2’[(1-(7-chloro-4-quinolinyl)-5-[2,6-dimethoxyphenyl]pyrazol-3-yl]carbonylamina]ticyclo-(3.3.1.1)decan-2-carboxylic acid</td>
</tr>
<tr>
<td>SR 14948A</td>
<td>2’-[5-[2,6-dimethoxyphenyl]-4-[N-[3-dimethylamina propyl]-N-methylcarbamoyl]2-isopropylphenyl]-1H-pyrazole-3-carbonyl]amino]adamantane-2-carboxylic acid hydrochloride</td>
</tr>
</tbody>
</table>
Measurement of intracellular Ca²⁺ concentration ([Ca²⁺]ᵢ)

CHO-K1 cells stably expressing bfNTR1 or bfNTR4 were grown on cover slip slides for 48 h. The medium was removed and washed with Ca²⁺ buffer (138 mM NaCl, 6 mM KCl, 1 mM MgSO₄, 2 mM CaCl₂, 1 mM Na₂HPO₄, 5 mM NaHCO₃, 5 mM glucose, 10 mM Hepes, pH 7.4). The membrane preparation (20 µg) was incubated at 16 °C for 25 min. Then, NT was added and incubated at 37 °C for 25 min. The reaction was terminated by replacing the solution with 0.5 ml ice-cold formic acid (10 mM). IPs were extracted by incubating at 4 °C for 30 min and separated using a Dowex ion exchange resin. Total IPs were eluted with buffer containing 1 M ammonium formate and 0.1 M formic acid. The radioactivity was counted using a liquid scintillation counter.

Radiolabeled ligand binding assay

hNT was radioiodinated by the chloramine-T method and purified by chromatography on a Sephadex G-25 column as described previously (Sadoul et al. 1984). Cell membranes were prepared from CHO-K1 cells stably expressing bfNTR1, bfNTR4 or rNTR1 and suspended in binding buffer (50 mM Tris, 2 mM MgCl₂, 1 mM dithiothreitol, 0.1% BSA and protease inhibitor, pH 7.4). The membrane preparation (20 µg) was incubated at 16 °C for 1 h with increasing concentrations of ¹²⁵I-hNT in the presence (non-specific binding) or absence (total binding) of 10 µM unlabeled hNT. Specifically bound ligand was separated by rapid filtration through GF/C filters (Brandel, Gaithersburg, MD, USA) presoaked in binding buffer containing 0.01% polyethylenimine (Sigma) and washed twice with ice-cold washing buffer (40 mM Tris, 2 mM MgCl₂, 0.1% BSA, pH 7.4). Competition binding assay was carried out with intact cells in 12-well plates at 16 °C for 1 h. Cells stably expressing bfNTR1 or bfNTR4 were incubated with 100 000 c.p.m. ¹²⁵I-hNT and increasing concentrations of unlabeled competitor in 500 µl DMEM containing 0.1% BSA. Non-specific binding was determined in the presence of 10 µM unlabeled hNT.

Data analysis

All data are expressed as means ± S.E.M. of three independent experiments. Data were analyzed using non-linear regression and plotted as sigmoid dose–response curves. Ligand concentrations inducing half-maximal stimulation (EC₅₀), half-maximal inhibition (IC₅₀) and/or maximal fold increase (E₅₀) were calculated using GraphPad PRISM3.0 software (GraphPad, San Diego, CA, USA). Statistical analysis was performed by one-way ANOVA followed by a Bonferroni test. Data were considered as significant at P<0.05.

Results

Primary structure of bfNTRs

Using degenerate PCR combined with 5'– and 3'–RACE, we isolated full-length cDNAs for bfNTR1 (1467 nucleotides accession No. AY613326) and bfNTR4 (1779 nucleotides accession No. AY613327). The bfNTR1 and bfNTR4 cDNAs were predicted to encode putative receptors with 422 and 400 amino acids respectively (Fig. 1). bfNTR1 and bfNTR4 exhibited the typical characteristics of GPCRs with seven hydrophobic TMHs (Fig. 1). Sequence alignment showed that bfNTR1 had a 64% amino acid identity with mammalian NTR1 and a 34–37% identity with mammalian NTR2. bfNTR4 had a 43–47% identity with mammalian NTR2 and a 43% identity with mammalian NTR1. bfNTR1 and bfNTR4 showed 43% sequence identity to each other. bfNTR1 contained two potential N-glycosylation sites in the N-terminal domain, one potential protein kinase A (PKA) phosphorylation site in ICL1 and two potential protein kinase C (PKC) phosphorylation sites in ICL3 and the intracellular C-terminal tail (Fig. 1). While mammalian NTR2 does not possess N-glycosylation sites, bfNTR4 had two potential N-glycosylation sites in the N-terminal domain (Fig. 1). bfNTR4 contained multiple potential PKC phosphorylation sites in ICL2, ICL3 and the C-terminal tail (Fig. 1).

Tissue distribution of bfNTRs mRNA

The tissue distribution of bfNTR1 and bfNTR4 mRNAs was determined by RT-PCR using the primer pairs bfNT1–3/GSP1 and bfNT1–5/GSP1 (for bfNTR1) or bfNT4–3/GSP1 and bfNT4–5/GSP1 (for bfNTR4) (Table 1). The mRNA for bfNTR1 was abundant in various brain regions including the olfactory lobe,
cerebral cortex and hypothalamus, as well as in the spinal cord (Fig. 2). The mRNA for bNTR4 was abundant in the cerebral cortex and hypothalamus, but weakly expressed in the olfactory lobe and spinal cord (Fig. 2). In the distal and neurointermediate lobes of the pituitary, bNTR1 mRNA was highly expressed, while bNTR4 mRNA was moderately expressed. At the periphery, weak signals for bNTR1 were detected in the heart, kidney and small intestine. An intense signal for bNTR4 was observed in the ovary (Fig. 2).

**Differential signal transduction for mammalian and bullfrog NTRs**

To investigate the signaling pathways of bNTRs, CV-1 cells or CHO-K1 cells were co-transfected with either bNTR1, bNTR4, rNTR1 or hNTR2 in combination with the c-fos-luc (or CRE-luc) reporter vector. We have previously shown that c-fos-luc and CRE-luc reporter are sensitive to phospholipase C (PLC)/PKC- and adenylate cyclase (AC)/PKA-linked signaling pathways respectively. The predicted seven transmembrane helices (TMHs) are indicated above the aligned sequences. Asp in TMH2 and Asn in TMH7 are highly conserved in rhodopsin-like GPCRs are indicated by dots. Two conserved motifs D/ERY and NPXXY are indicated by asterisks. GenBank accession Nos are hNTR1: P30989; hNTR2: O95665; rNTR1: P20789; rNTR2: Q63384.
Activation of bfNTR1 by hNT strongly increased both c-fos-luc and CRE-luc reporter activity with similar strength. bfNTR4 slightly induced c-fos-luc and CRE-luc activity when expressed in CV1 cells. When expressed in CHO-K1 cells, bfNTR4 was able to induce a 9-fold increase in CRE-luc activity but only a 4-fold increase in c-fos-luc activity (Fig. 3). rNTR1 induced both CRE-luc and c-fos-luc reporter activity in CV1 and CHO-K1 cells. In contrast, no significant increase in CRE-luc and c-fos-luc reporter activity was observed in either CV1 or CHO-K1 cells expressing hNTR2 (Fig. 3) or mNTR2 (data not shown).

NT-induced IP production and $[Ca^{2+}]_i$ elevation were determined in CHO-K1 cells stably expressing bfNTR1 or bfNTR4. In agreement with the c-fos-luc assay results, hNT induced a 3-fold increase in IP production in cells expressing bfNTR1 and only a 1.5-fold increase in cells expressing bfNTR4 (Fig. 4). Exposure of CHO-K1 cells expressing bfNTR1 or bfNTR4 to hNT provoked an immediate elevation of $[Ca^{2+}]_i$, and the $Ca^{2+}$ signal lasted for at least 45 s (Fig. 5A and B). In mock-transfected cells, hNT did not induce $[Ca^{2+}]_i$ increase although thapsigargin, an inhibitor of sarcoendoplasmic $Ca^{2+}$ ATPase, was able to increase $[Ca^{2+}]_i$, indicating that Fura-2 was successfully loaded (Fig. 5C).

**Effect of peptide agonists on NTRs**

Ligand selectivity was examined using the c-fos-luc and CRE-luc reporter systems. In the c-fos-luc assay system, bfNTR1 and rNTR1 exhibited similar patterns of ligand
sensitivity toward NTs and different pseudopeptide analogs. fNT showed the highest potency for both bfNTR1 and rNTR1, followed by hNT/p93 JMV 458/p93 NT(8–13) > pNMN > JMV 510/p93 JMV 457/p93 JMV 431 (Fig. 6 and Table 3). Compared with rNTR1 and bfNTR1, bfNTR4 showed slightly lower sensitivity to these compounds (Fig. 6 and Table 3). In the CRE-luc assay system, rNTR1 and bfNTR1 exhibited a similar pattern of ligand sensitivity as observed in the c-fos-luc assay system. It is of interest to note that bfNTR4 showed a slightly higher sensitivity to all NT analogs, except pNMN, than bfNTR1 (Fig. 7 and Table 3).

**Effect of non-peptide ligands on NTRs**

SR 48692 and SR 142948A are known to function as antagonists for mammalian NTR1 and agonists for mammalian NTR2 (Botto et al. 1997, Gully et al. 1997, Vita et al. 1998). Indeed, SR 142948A and SR 48692 showed antagonistic activity to rNTR1, the former having a higher potency than the latter (Fig. 8A and Table 4). SR 142948A completely inhibited hNT-induced CRE-luc activity in bfNTR1-expressing cells, while SR 48692 marginally inhibited hNT-induced CRE-luc activity in these cells (Fig. 8B and Table 4). Both SR 142948A and SR 48692 showed an antagonistic property for bfNTR4 (Fig. 8C). In particular, SR 142948A was a potent antagonist (IC50 = 9·1 ± 0·2) for bfNTR4. Levocabastine, at high concentrations, induced CRE-luc activity in cells expressing bfNTR1 and bfNTR4, but not in rNTR1-transfected cells (Fig. 8D and Table 4).

**Binding affinity of bfNTR1 and bfNTR4**

The binding properties of bfNTR1 and bfNTR4 were examined using 125I-hNT as a radioligand. Specific binding to membranes prepared from CHO-K1 cells expressing bfNTR1, bfNTR4 or rNTR1 was observed while only background binding occurred in mock-transfected CHO-K1 cells. Saturation experiments revealed that hNT had a high affinity to each NTR (Fig. 9A and B): 

\[
K_d = 0.88\pm 0.12 \text{ nM for bfNTR1, 1.29}\pm 0.23 \text{ nM for bfNTR4 and 0.83}\pm 0.14 \text{ nM for rNTR1).}
\]

Maximum binding (B max) was as follows: 7.61 ± 0.49, 12.24 ± 1.15 and 10.6 ± 0.84 pmol/mg protein for bfNTR1, bfNTR4 and rNTR1 respectively. Displacement experiments showed that hNT could efficiently inhibit the binding of 125I-hNT to bfNTR1 and to bfNTR4, indicating hNT has a high affinity for both receptors. In bfNTR1-expressing cells, SR 142948A showed a 100-times lower affinity than hNT, while in bfNTR4-expressing cells, SR 142948A had similar affinity to hNT. Levocabastine exhibited very low affinity for both bfNTR4 and bfNTR1 (Fig. 9C and D and Table 4).

![Figure 4](image1.png)

**Figure 4** IP accumulation in cells expressing bullfrog (bf) NTRs. CHO-K1 cells stably expressing each bfNTR or mock-transfected cells were seeded in 12-well plates (1x10^5 per well). One day after seeding, cells were grown in inositol-free DMEM containing 1 µCi myo-[3H]inositol/well and 2% FBS for 24 h and then treated with 1 µM hNT for 6 h. IP production was expressed as fold-induction over basal. Data shown are the means±S.E.M. of three independent experiments. (*P<0.01, **P<0.001).

![Figure 5](image2.png)

**Figure 5** Effect of NT on intracellular Ca^{2+} concentration ([Ca^{2+}]_i) in CHO-K1 cells expressing bullfrog (bf) NTRs. CHO-K1 cells stably expressing bfNTR1 (A) or bfNTR4 (B) and mock-transfected cells (C) were challenged with 1 µM hNT. Data show the means±S.E.M. of ~15 individual recordings of [Ca^{2+}]_i during 100 s. Cells were exposed to thapsigargin (1 mM) to confirm Fura-2 loading (C).
Figure 6 Differential ligand selectivity of rat (r) NTR1, bullfrog (bf) NTR1 and bfNTR4. CV1 cells were transfected with 200 ng CMVβ-gal and 200 ng c-fos-luc plus 100 ng rNTR1, bNTR1 or bNTR4. One day after transfection, cells were serum-starved for another 24 h, then treated for 6 h with graded concentrations of various agonists and luciferase activity was measured. Data are means±S.E.M. of one representative experiment from three to five experiments.

Table 3 Ligand selectivity of NTRs. Cells were transfected with NTR in combination with c-fos-luc reporter (CV1 cells) or CRE-luc reporter (CHO-K1 cells). EC_{50} (log M) and E_{max} (fold-increase over basal) values are obtained from c-fos-luc or CRE-luc reporter assay systems. Each value indicates the mean±S.E.M. from three independent experiments.

<table>
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<th>rNTR1</th>
<th>bfNTR1</th>
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<td></td>
<td>EC_{50}</td>
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<td><strong>c-fos-luc activity (CV1 cells)</strong></td>
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<td>fNT</td>
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<td>hNT</td>
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<td>25.3±0.8</td>
<td>−8.8±0.2</td>
</tr>
<tr>
<td>pNMN</td>
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<td>35.0±1.1</td>
<td>−7.8±0.2</td>
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<tr>
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<td>39.0±1.0</td>
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</tr>
<tr>
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<td>35.3±2.0</td>
<td>−7.1±0.2</td>
</tr>
<tr>
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<td>27.7±1.1</td>
<td>−8.4±0.2</td>
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<tr>
<td>JMV431</td>
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<td>44.2±1.2</td>
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<tr>
<td>JMV510</td>
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<td>−6.7±0.4</td>
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<tr>
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<td>53.7±2.3</td>
<td>−8.4±0.1</td>
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</tr>
<tr>
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<td>29.2±1.2</td>
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<tr>
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<td>−7.9±0.1</td>
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</tr>
<tr>
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<td>8.3±0.3</td>
<td>−8.1±0.2</td>
</tr>
<tr>
<td>Levocabastine</td>
<td>ND</td>
<td>ND</td>
<td>−6.4±0.2</td>
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</tbody>
</table>

ND, not detected.
Discussion

This report has described for the first time the identification and functional characterization of two non-mammalian NTRs. As previously described for mammalian NTRs, bfNTR1 and bfNTR4 were mainly expressed in the brain and pituitary. bfNTR1 has a high degree of sequence identity with mammalian NTR1 while bfNTR4 exhibits a relatively low similarity to either mammalian NTR1 or NTR2. They differed in signal transduction pathways and ligand affinity from each other. Further, they exhibited distinct pharmacological characteristics from those of the mammalian receptors.

bfNTR1 exhibited a high degree of sequence identity and structural similarity with the corresponding mammalian receptor NTR1. Like mammalian NTR1, bfNTR1 has a long extracellular N-terminal domain and a short extracellular loop 3 (ECL3). A Thr-X-Tyr motif in the C-terminal domain, which is critical for internalization of mammalian NTR1 (Chabry et al. 1995), was also found in bfNTR1. bfNTR4 has a short extracellular N-terminal domain and a relatively long ECL3, characteristics of mammalian NTR2. bfNTR4, however, showed some structural differences with mammalian NTR2. First, mammalian NTR2 does not contain glycosylation sites in the extracellular N-terminal domain while bfNTR4 possesses two putative glycosylation sites in the N-terminal region as found in mammalian NTR1. Secondly, the sequence of ICL1 in bfNTR4 is different from that of mammalian NTR2 but similar to that of mammalian NTR1 and bfNTR1. As the ICLs are involved in G protein coupling and signal transduction, it could be anticipated that differences in the signaling pathways occur between mammalian NTR2 and bfNTR4. Thirdly, the two conserved residues Asp^{2.50}/Asn^{7.49} in TMH2/TMH7, which are characteristic of the rhodopsin-like GPCR family, are absent in the mammalian NTR2 but present in bfNTR4. The presence of Asp^{2.50}/Asn^{7.49} residues is important for receptor conformation as they are involved in a hydrogen bond interaction responsible for the close association of TMH2 and TMH7 (Sealfon et al. 1997). It has been reported that the conserved Asp^{2.50} residue in TMH2 accounts for the Na^+ sensitivity and/or receptor activation in rNTR1 as in other GPCRs (Kong et al. 1993, Martin et al. 1999, Belmeguenai et al. 2000). Indeed, the mutation on these residues critically affects receptor activation (Awara et al. 1996). Further, the Asn^{7.49} residue followed by the Pro-X-X-Tyr motif is known to be involved in coupling with the small G protein ARF and RhoA (Mitchell et al. 1999).
Thus, the presence of the Asp<sup>2·50</sup>/Asn<sup>7·49</sup> residues in bfNTR4 may be responsible for differential signal transduction coupling and ligand sensitivity, as compared with mammalian NTR2. However, we do not exclude the possibility that bfNTR4 and mammalian NTR2 originate from the same ancestral gene as they show a global similarity in structure to some extent.

Table 4 IC<sub>50</sub> of SR 48692, SR 142948A and levocabastine to various NTRs. For the CRE-luc assay, CHO-K1 cells transiently expressing NTRs together with CRE-luc reporter were used. For the binding assay, CHO-K1 cells stably expressing NTRs were used. IC<sub>50</sub> (log M) more values obtained from the CRE-luc assay and competition binding assay respectively. Values are the mean±S.E.M. from three independent experiments.

<table>
<thead>
<tr>
<th></th>
<th>rNTR1</th>
<th>bNTR1</th>
<th>bfNTR4</th>
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<td><strong>CRE-luc assay</strong></td>
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</tr>
<tr>
<td>SR 48692</td>
<td>−7·2±0·2</td>
<td>PI</td>
<td>−7·2±0·2</td>
</tr>
<tr>
<td>SR 142948A</td>
<td>−8·6±0·1</td>
<td>−6·1±0·2</td>
<td>−9·1±0·2</td>
</tr>
<tr>
<td><strong>Binding assay</strong></td>
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<td>−9·2±0·2</td>
<td></td>
</tr>
<tr>
<td>Sr 142948A</td>
<td>−6·6±0·1</td>
<td>−8·8±0·2</td>
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<tr>
<td>Levocabastine</td>
<td>ND</td>
<td>−5·8±0·3</td>
<td></td>
</tr>
</tbody>
</table>

PI, partial inhibition; ND, not determined.

Table 4 IC<sub>50</sub> of SR 48692, SR 142948A and levocabastine to various NTRs. For the CRE-luc assay, CHO-K1 cells transiently expressing NTRs together with CRE-luc reporter were used. For the binding assay, CHO-K1 cells stably expressing NTRs were used. IC<sub>50</sub> (log M) more values obtained from the CRE-luc assay and competition binding assay respectively. Values are the mean±S.E.M. from three independent experiments.

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<tr>
<td><strong>Binding assay</strong></td>
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<td>−9·1±0·2</td>
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<tr>
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<td>−6·6±0·1</td>
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<tr>
<td>Levocabastine</td>
<td>ND</td>
<td>−5·8±0·3</td>
<td></td>
</tr>
</tbody>
</table>

Plastic inhibition; ND, not determined.

Figure 8 Effects of antagonists on rat (r) NTR1, bullfrog (bf) NTR1 and bfNTR4. CHO-K1 cells were transfected with 200 ng CMVβ-gal and 200 ng CRE-luc plus 100 ng rNTR1 (A), bNTR1 (B) or bfNTR4 (C). One day after transfection, cells were serum-starved for another 24 h, then treated for 6 h with graded concentrations of SR 48692 (SR) or SR 142948A (SRA) in the presence of 1 nM hNT. (D) Effect of graded concentrations of levocabastine on bNTR1-, bNTR4- and NTR1-expressing cells. Data are means±S.E.M. of one representative experiment from three to five experiments.

1998). Thus, the presence of the Asp<sup>2·50</sup>/Asn<sup>7·49</sup> residues in bfNTR4 may be responsible for differential signal transduction coupling and ligand sensitivity, as compared with mammalian NTR2. However, we do not exclude the possibility that bfNTR4 and mammalian NTR2 originate from the same ancestral gene as they show a global similarity in structure to some extent.

Consistent with a previous report showing that mNTR2 stably expressed in HEK293 cells is able to bind radioiodinated NT but cannot induce any signaling cascade, including PLC and AC activation (Botto et al. 1998), we found that NT did not induce CRE-luc and c-fos-luc reporter activity in CV1 or CHO-K1 cells expressing hNTR2 or mNTR2. Therefore, although mammalian NTR2 can bind NT and NT agonists, its ability to induce signal transduction is very low. Unlike mammalian NTR2, bfNTR4 was able to induce CRE-luc and c-fos-luc reporter activities as well as IP production and elevation of [Ca<sup>2+</sup>]. The fact that bfNTR4 has a better signaling activity than mammalian NTR2 is consistent with the structural differences described above. bfNTR4 could induce both CRE-luc and c-fos-luc reporter activity but their fold-increases depended on the cell line in which the receptor was transfected. Thus, in CV1 cells, bfNTR4 induced a
similar fold increase in CRE-luc and c-fos-luc reporter activity, while in CHO-K1 cells bNTR4 produced a 2·0-fold higher increase in CRE-luc activity (9-fold) than in c-fos-luc activity (4-fold). Since bNTR1 provoked a similar induction of c-fos-luc and CRE-luc reporter activity, it appears that bNTR1 may trigger both the AC/PKA- and PLC/PKC-linked signaling pathways with similar strength, at least in CHO-K1 cells, while bNTR4 may activate preferentially the AC/PKA-linked signaling pathway. Consistent with this observation, bNTR4-expressing CHO-K1 cells exhibited only a 1·5-fold increase in IP production, while bNTR1-expressing CHO-K1 cells showed approximately a 3-fold increase in IP production. However, results obtained from these cellular tools cannot simply be extrapolated to a normal physiological situation, which is very complicated as tissues contain the target receptor but also its isoforms as well as a variety of splice variants. Further, the coupling efficiency to the effectors is largely dependent on the cellular context (Oh et al. 2003).

There is now clear evidence that NT is an important neuroendocrine regulator of the hypothalamo–pituitary system (McCann & Vijayan 1992, Rostène & Alexander 1997). In particular, in the frog, fNT stimulates the electrical and secretory activity of melanotrope cells through an activation of a receptor whose pharmacological profile shares similarities with mammalian NTR1 (Labbé-Jullié et al. 1994, Desrues et al. 1998, Belmeguenai et al. 2000). In this model, the most potent agonist is JMV 458 followed by JMV 457, JMV 510 and JMV 431 (Belmeguenai et al. 2000). The specific NTR1 antagonist SR 48692 does not inhibit fNT-evoked stimulation of melanotrope cells, while the
wide-spectrum antagonist SR 142948A completely blocks the response (Belmeguenai et al. 2000). Consistent with this observation, the present study showed that JMV 458 exhibited the highest potency to stimulate bfNTR1 followed by JMV 457, JMV 510 and JMV 431 and that SR 142948A but not SR 48692 completely blocked bfNTR1 activation induced by NT. These pharmacological data strongly suggest that NT-induced stimulation of frog melanotropes cells is mediated through the NTR1 receptor subtype. In support of this hypothesis, we found that, in the bullfrog neurointermediate lobe, bfNTR1 mRNA was actively expressed whereas bfNTR4 was hardly detectable.

Strong evolutionary pressure has acted to conserve the structure of the C-terminal hexapeptide of NT(8–13) from amphibians to mammals (Table 2) and this region is known to bear the biological activity of the peptide (Rostène & Alexander 1997). In accord, NT(8–13) was found to have the same potency as hNT and fNT in inducing activation of bfNTR1 and bfNTR4. The low potency of pNMN, JMV 457, JMV 510 and JMV 431 might be ascribed to replacement of the Arg9 by an Ile or Lys residue and/or by substitution for a bulky amino acid at position 11, which are known to affect ligand binding (Pang et al. 1996). It is noteworthy that, in the c-fos-luc assay system, bfNTR1 showed a higher sensitivity than bfNTR4 to all agonists used in the present study whereas, in the CRE-luc reporter assay system, bfNTR4 responded better to these agonists, except for pNMN, than did bfNTR1. The reason for the differential sensitivity toward each signaling pathway is currently unknown. It may be due to differential coupling efficiency of the receptors or differential receptor trafficking (Kenakin 2001).

One serendipitous finding of this study is that bfNTRs exhibited distinct pharmacological properties as compared with mammalian NTRs. SR 142948A completely inhibited NT-induced rNTR1 activation with a higher potency than SR 48692, which is in good agreement with a previous report (Gully et al. 1997). SR 48692 and SR 142948A, however, showed a relatively low potency to inhibit the activity of bfNTR1, the bullfrog counterpart of mammalian NTR1. Surprisingly, SR 48692 and SR 142948A, which act as agonists on mammalian NTR2 (Botto et al. 1997), strongly inhibited NT-induced bfNTR4 activity. The residues Met208 in TMH4, Tyr324, Arg327 and Phe331 in TMH6 and Tyr351, Thr354, Phe358, Tyr359 in TMH7 of rNTR1 play a crucial role in SR 48692 binding (Labbé-Jullié et al. 1998). As these residues are conserved in bfNTR1 and bfNTR4, it is assumed that other nearby residues are involved in the differential selectivity of bfNTR1 and bfNTR4 for SR 142948A and SR 48692. Levocabastine, an agonist for mammalian NTR2 but not for NTR1, induced CRE-luc reporter activity in both bfNTR1- and bfNTR4-expressing cells. Altogether, these data indicate that, despite the high sequence similarity among bfNTRs and mammalian NTRs, bfNTRs have different characteristics compared with mammalian NTRs in terms of ligand selectivity and signal transduction. As the agonists and antagonists for mammalian NTRs exhibit different functionalities on the amphibian NTRs, one should be careful when using these NT analogs to characterize NTRs in non-mammalian vertebrates.

The characterization of two fNTRs provides novel information regarding the phylogenetic history of G protein-coupled NTRs in the vertebrate lineage. The fact that bfNTR4 has clearly retained NT as a natural agonist, mNTR2 and hNTR2 are insensitive to NT, suggesting that, in the mammalian phylogeny, NTR2 may have adopted a novel, yet unknown, peptide ligand. Finally, comparison of the sequences of amphibian and mammalian receptors will provide important clues as to the structural determinants that are responsible for ligand selectivity and signal transduction coupling.

In conclusion, this report provides the first molecular, pharmacological and functional characterization of two NTRs in a non-mammalian vertebrate. The data show that bfNTRs exhibit differential ligand selectivity and signal coupling mechanisms from each other, as well as distinct functional characteristics as compared with their mammalian counterparts. These data should help to elucidate the evolutionary history of NTRs in the vertebrate lineage and to identify the structural motifs that determine their pharmacological and physiological properties.

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