Molecular identification and characterization of three isoforms of tachykinin NK1-like receptors in the cane toad *Bufo marinus*

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Liu, Lu, Irit Markus, Robert J. Vandenberg, Brett A. Neilan, Michael Murray, and Elizabeth Burcher. Molecular identification and characterization of three isoforms of tachykinin NK1-like receptors in the cane toad *Bufo marinus*. Am J Physiol Regul Integr Comp Physiol 287: R575–R585, 2004. First published May 20, 2004; 10.1152/ajpregu.00051.2004.—The tachykinin peptide bufokinin, isolated from the small intestine of the cane toad *Bufo marinus*, was inactive, whereas bNK1-A and bNK1-C produced changes in chloride current when stimulated by tachykinins (minimum concentrations: bufokinin, 0.1 nM; SP, 1 nM; and NKA, 10 nM). A marked desensitization of the response was seen to subsequent applications of tachykinins, as experienced by the mammalian NK1 receptor. In summary, our study describing three isoforms of NK1-like receptor from the toad suggests that the alternative splicing of NK1 receptors may be an alternate signaling transduction pathway in nonneural tissues (27). The tachykinin family is phylogenetically ancient and has been well conserved throughout evolution, with numerous structurally related tachykinins isolated from a wide range of vertebrates and invertebrates (15). The amino acid sequences of tachykinins from mammals, birds, and reptiles are similar, whereas those from amphibians and fish are quite divergent, possibly reflecting their evolutionary position (15, 31).

The three mammalian tachykinin receptors have been cloned and intensively studied, mainly in mammalian species (2). They belong to a G protein-coupled receptor (GPCR) superfamily with the seven membrane-spanning domain structure typical for receptors of this family. After activation by agonist, the intracellular loops of the receptors interact with a GαGq-protein, leading to phospholipase C (PLC) activation, inositol 1,4,5-triphosphate (IP3) formation, and an increase in intracellular calcium. Stimulation of cAMP production via Gαs-protein may be an alternate signaling transduction pathway in certain systems (25).

Because mammalian and nonmammalian tachykinins have broadly similar actions on both nonmammalian and mammalian species (31), it is likely that the sequences of the receptors may also be conserved across different vertebrate groups. However, there is limited information on tachykinin receptor structure or signal transduction mechanisms in nonmammals. NK1-like receptors cloned from chicken (GenBank AF131057) and from fugu *Fugu rubripes* (GenBank AY327862) show 78 and 65% identity, respectively, at the amino acid level, to their human counterpart. In the bullfrog *Rana catesbeiana*, an SP-prefering receptor isolated from sympathetic ganglion exhibits 70% identity to mammalian NK1 receptors (32). Across these diverse vertebrate species, cytoplasmic loop 1 and transmembrane (TM) regions II and VII are highly conserved (92–100% identity), whereas the extracellular NH2 terminus and extracellular loops 2 and 3 are the least conserved regions (15–61% identity). Tachykinin-like receptors have also been cloned from several different invertebrate species, including the echiurid worm *Urechis unicinctus* (19), and it is notable that the second messenger systems activated by *Urechis* receptors (PLC-IP3-calcium signal transduction cascade, cAMP) are the same as those induced in mammalian tachykinin-dependent signaling processes (35, 36).

We have previously isolated an SP-like undecapeptide, bufokinin, from the small intestine of the cane toad *Bufo marinus* (6). Bufokinin exhibits high affinity at all three tachykinin receptors in the rat, where it shows even greater affinity than its mammalian counterpart, SP, for the NK1 receptor (6). Our TACHYKININS are multifunctional brain, gut, and skin peptides that possess a variety of biological roles in the central and peripheral nervous systems as well as in the cardiovascular and immune systems. Their actions include vasodilatation, plasma extravasation, smooth muscle contraction, secretion, neuronal excitation, and processing of sensory information; in addition, they have extensive proinflammatory properties (13). In mammals, substance P (SP), neurokinin A (NKA), and neurokinin B are the best known members of this family and act preferentially through tachykinin NK1, NK2, and NK3 receptors, respectively (27). Most recently, several new mammalian tachykinins (hemokinin and the endokinins) have been isolated from nonneural tissues (27). The tachykinin family is phylogenetically ancient and has been well conserved throughout evolution, with numerous structurally related tachykinins isolated from a wide range of vertebrates and invertebrates (15). The amino acid sequences of tachykinins from mammals, birds, and reptiles are similar, whereas those from amphibians and fish are quite divergent, possibly reflecting their evolutionary position (15, 31).

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earlier studies have shown that bufokinin is a potent spasmogen of intestinal smooth muscle and is also a potent vasodilator in the toad (21, 22). Binding and functional studies in toad intestinal smooth muscle have described a bufokinin-prefering NK₁-like receptor that couples to the G protein phosphoinositide hydrolysis pathway (22). However, this NK₁-like receptor shows negligible affinity for selective NK₁ receptor agonists and antagonists (3, 22), suggesting that key amino acids in the binding domains for these ligands are not well conserved in nonmammals.

From an evolutionary point of view, it is important to gain more information about the tachykinin receptors in nonmammalian species. Amphibians are extant representatives of the first terrestrial vertebrates and therefore occupy an extremely important position in phylogeny. Moreover, amphibians such as the cane toad Bufo marinus are convenient and low-cost experimental animals, extensively used in biological studies. Thus it is necessary to know the extent to which they can serve as models for the study of genetic or physiological processes.

We have therefore extended our earlier pharmacological studies of tachykinin receptors in Bufo marinus to better understand the molecular basis of the biological functions and evolutionary and phylogenetic relationships of tachykinin receptors. In this study, we report the cloning of three NK₁ receptor isoforms, bNK₁-A, bNK₁-B, and bNK₁-C [GenBank accession nos.: bNK₁-A (BFR-A), AF289083; bNK₁-B (BFR-B), AF416731; and bNK₁-C (BFR-C), AF482695], from the toad brain and gut, and the tissue distribution and expression level of these isoforms. Their pharmacological profiles were studied in transfected heterologous expression systems.

### MATERIALS AND METHODS

#### Isolation of RNA

Toads of both sexes, weight 150–200 g, were purchased from P. Douch, North Queensland, Australia, and housed in captivity at room temperature for up to 1 wk. Toads were anesthetized by immersion in 0.25% tricaine methanesulfonate (MS222, Sigma) and killed by decapitation, and their organs were removed. Total RNA was extracted from small intestinal smooth muscle, brain, spinal cord, lung, aorta, atrium, ventricle, bladder, skin, skeletal muscle, stomach, testis, and liver using RNAsTotal RNA Isolation System (Promega) and treated with RNase-Free DNase to remove traces of chromosomal DNA. RT-PCR amplification of the β-actin gene using Access RT-PCR System (Promega) was performed in the presence and absence of AMV reverse transcriptase, to monitor the quality of RNA and the presence of Partial cDNAs by RT-PCR

Total RNA from intestinal smooth muscle and brain was reverse-transcribed and PCR amplified using TM-2 and TM-7 primers (Table 1), which were derived from the conserved TM II and VII regions of the bullfrog NK₁-like receptor cDNA sequence (32). cDNA was created and amplified as per the manufacturer’s instructions (Access RT-PCR System, Promega). The reaction mixture contained 1 μg total RNA, 0.2 μM of each primer, 0.2 mM dNTPs, 1.5 mM MgSO₄, 2.5 U AMV reverse transcriptase, and 2.5 U Tdf DNA polymerase. The RT-PCR reaction was performed at 40°C for 45 min, 94°C for 2 min, and 40 cycles of 94°C for 30 s, 48°C for 1 min, and 70°C for 2 min, followed by one cycle of 48°C for 3 min, 70°C for 10 min. PCR products of the expected size (720 bp) were excised, purified, and cloned into pGEM-T vector (Promega). Positive clones were se-
Rapid Amplification of 5'- and 3'-cDNA Ends

Gene-specific primers used in rapid amplification of 5'- and 3'-cDNA ends (5'- and 3'-RACE) were designed based on the sequence information generated from the partial cDNA sequence. 5'-RACE was conducted as per the previously published method (34). In brief, reverse transcription (RT) occurred in the presence of 1 μg total RNA, 0.2 μM of the gene-specific primer 5'-GSP, 0.2 mM dNTPs, 1 mM dithiothreitol (DTT), and 200 U SuperScript II reverse transcriptase (Life Technologies) at 42°C for 30 min, followed by 5 cycles at 50°C for 1 min, 53°C for 1 min, and 56°C for 1 min. After removal of the RNA by alkaline hydrolysis cleavage with EDTA, an anchor oligonucleotide, DR88, was ligated to the 5'-end of the single-stranded cDNA by T4 RNA ligase. The anchor-ligated cDNA was then amplified by a touchdown PCR using the anchor-specific primer DT89 and 5'-GSP, which is internal to the primer 5'-GSP. The PCR was set to 90°C for 2 min, followed by 30 cycles of 95°C for 5 s and 68°C for 1 min. A single distinct PCR product (~500 bp) was subsequently purified, cloned, and sequenced as mentioned above.

The 3'-end of the full-length cDNA was amplified using the 3'-RACE System Kit (Life Technologies). Total RNA was reverse transcribed using (dT)17-adapter primer and SuperScript II reverse transcriptase following the manufacturer’s protocol. The poly(dA)-tailed double-strand cDNA was obtained by PCR using the gene-specific primer 3'-GSP and the abridged universal amplification primer (AUAP) at 94°C for 2 min, 30 cycles of 94°C for 30 s, 45°C for 1 min, and 70°C for 2 min, and one cycle of 45°C for 30 s, 70°C for 10 min. The hemi-PCR product was performed based on 100-fold dilution of first-round PCR products using primers 3'-NGSP I and AUAP with PCR parameters similar to those described above except that annealing was conducted at 50°C instead of 45°C. Three products of size of ~820 bp, ~730 bp and ~540 bp were generated. The hemi-PCR product was repeated with primers 3'-NGSP II and AUAP. Again three products of ~670, ~580, and ~390 bp were produced. All products were purified, cloned, and sequenced as above.

Synthesis of Open Reading Frame cDNAs and Construction of Plasmid DNAs

cDNAs corresponding to the open reading frame (ORF) were synthesized by RT-PCR, using RNA extracted from toad brain. The annealing temperature for RT-PCR reaction was changed from 48°C to 55°C; otherwise the conditions were identical to those described above (see Amplification of Partial cDNAs by RT-PCR). Primers 5'-BFR and 3'-BFR-AI were used for synthesis of the bNK1-A ORF, which was cloned into mammalian expression vector pTargetT using a TA cloning kit (Promega). A sense primer, 5'-BFR-Mfai, and antisense primer, 3'-BFR-BI-SalI and 3'-BFR-CI-SalI, were used to perform the amplification of bNK1-B and bNK1-C ORF, respectively. The products were digested with Mfai and SalI, and cloned into pTargetT. The plasmid DNAs were sequenced to confirm the nucleotide sequence of the inserts and used for expression in COS-7 cells and Xenopus oocytes.

Cell Line Transfection and Binding Assay

Transient transfections. The COS-7 (African, Green monkey kidney fibroblast, SV40 transformed) cell line was revived from liquid nitrogen storage and maintained in complete media consisting of DMEM (ThermoTrace), 10% FCS, penicillin/streptomycin (50 U/ml), and 1-glutamine (2 mM). Cells (1.5 × 10⁶ per well) were seeded in six-well plates and grown in complete media for 24 h and then transfected with 2.5 μg plasmid DNAs using 7.5 μl Tfx-20 Reagent (Promega). To maximize plasmid transfer, a second round of transfection was carried out after 6 h, using only half the amount of Tfx-20 and plasmid DNA (38). Transfected cells were cultured for an additional 48 h before radioligand binding studies were performed.

Stable transfections. Transfected COS-7 cell cultures were maintained in complete DMEM media supplemented with 0.5 mg/ml of G-418 (Promega). Cultures were washed with DMEM to remove dead cells and passedaged weekly for 4 wk. Surviving cells were cloned out in 96-well plates, propagated, and screened for receptor expression by radioligand binding. Positive clones were seeded in six-well plates (2-3 × 10⁵ cells/well) and incubated overnight before radioligand binding.

Radioligand binding. Radioligand binding studies were performed on monolayer transient or stably transfected COS-7 cells using [125I]-labeled Bolton-Hunter bufokinin ([125I]BH-bufokinin) and a method modified from the membrane binding assay (22). The medium was aspirated, and the cells were washed twice with 2 ml Tris·HCl buffer (50 mM, pH 7.4, 25°C) containing BSA (1 mg/ml). Cells were incubated with 200–300 pM [125I]BH-bufokinin in incubation buffer containing Tris·HCl (50 mM), BSA (1 mg/ml), MnCl₂ (3 mM), and peptide inhibitors bacitracin (40 μg/ml), leupeptin (4 μg/ml), and chymostatin (4 μg/ml) in a volume of 0.5 ml (2). Nonspecific binding was defined by 1 μM unlabeled bufokinin. After incubation at 25°C for 45 min, cells were rinsed with 3 × 1 ml wash buffer consisting of Tris·HCl (50 mM), MnCl₂ (3 mM), and BSA (0.2 mg/ml), and then solubilized in 1 ml 1 M NaOH. The bound radioactivity was quantified in a Wizard gamma counter (78% efficiency). No significant difference was observed for binding to transiently or stably transfected cells.

Functional Expression of Receptors in Xenopus Oocytes

pTargetT-cDNA constructs were linearized with the restriction enzyme NotI and transcribed using the mMessage mMachIne In Vitro Transcription Kit (Ambion) with the T7 RNA polymerase. Oocytes from Xenopus laevis were isolated and injected with cRNA as previously described (37). Oocytes were placed in a recording chamber and superfused with 96 mM NaCl, 2 mM KCl, 1.8 mM CaCl₂, 1 mM MgCl₂, and 5 mM HEPES, pH 7.5 (ND96) at a rate of 8.5–10 ml/min. Whole cell currents were measured by standard two-electrode voltage-clamp technique using a Geneclamp 5000 amplifier (Axon Instruments, Foster City, CA) interfaced with a MacLab2e chart recorder (ADInstruments, Sydney, NSW, Australia) using a Digidata 1200 (Axon Instruments) controlled by an IBM-compatible computer using the pClamp software (version 7.0, Axon Instruments). Oocytes were voltage clamped at −50 mV. Peptides (dissolved in 0.05% BSA to minimize adherence to surfaces) were applied at concentrations starting at 10 nM and then increasing by a factor of 10 until an inward current was detected.

The current-voltage relationships for peptide-elicited conductances were determined as follows. Steady-state current measurements in the absence of peptide were obtained during 200-ms voltage pulses from −30 mV to potentials between −100 and +40 mV in 10-mV steps. These were subtracted from corresponding current measurements in the presence of peptide. The current-voltage relationship was measured at both the peak response and after desensitization.

Tissue-Specific Expression of bNK₁ Receptor mRNA Isoforms by RT-PCR

Total RNAs from different tissues were reverse-transcribed with SuperScript II reverse transcriptase using oligo(dT) adapter (Life Technologies). The reaction was performed in 20-μl volume containing 2 μg total RNA, 0.5 μM (dT)₇-adapter, 0.5 mM dNTPs, 10 mM DTT, and 200 U SuperScript II at 42°C for 50 min and heated at 70°C.
for 15 min. RNA was then removed by digestion with RNase H. One-twentieth of the RT product (equivalent to 100 ng total RNA) from each sample was used for PCR to amplify bNK1-A, NK1-B, NK1-C, and β-actin. The sense primer was based on a region common to all three isoforms. The antisense primer 3′-BFR-AII for bNK1-A was based on the unique region of this isoform; 3′-BFR-BII for bNK1-B was chosen from the bNK1-C deletion region, whereas 3′-BFR-CII primer for bNK1-C was designed to span the deletion site so that it could be detected separately. PCR reactions using these primers on plasmids containing individual isoform full-length cDNAs showed no cross amplification, confirming that the primers were isospecific. RT products were PCR amplified using hot start Taq polymerase (Bioline): 94°C for 2 min, followed by 30 cycles of 94°C for 30 s, 55°C (for bNK1-A and β-actin) or 60°C (for bNK1-B and bNK1-C) for 1 min, and 70°C for 2 min, and a final elongation period at 70°C for 10 min.

**Statistical Analysis**

The COS-7 cell line binding data were analyzed using the nonlinear regression analysis program of Graph Pad Prism (version 3, Graph Pad Software, San Diego, CA) and expressed as IC50 and 95% confidence intervals of the mean (95% CI). Comparisons of competition curves were carried out using two-way ANOVA statistical analyses.

**Animal Ethics**

All procedures were in accordance with the Australian National Health and Medical Research Council “Guidelines for the Prevention of Cruelty to Animals.” These studies were approved by the Animal Ethics Committees of the University of New South Wales (00/110) and Sydney University (K21/5–2001/3/3394).

**RESULTS**

**Cloning and Identification of Three Isoforms of bNK1 Receptor**

Our experimental approach using the RT-PCR and 5′- and 3′-RACE techniques produced five different clones that spanned the ORF locus as well as the 5′- and 3′-untranslated regions of the *Bufo marinus* NK1 receptor (bNK1). Each clone was sequenced in both directions from at least four transformed colonies, generated from different PCR reactions using toad brain and small intestinal RNA extracts as templates. Clone 1 consisted of a 720-bp partial cDNA, which was obtained by RT-PCR using a pair of primers based on the nucleotide sequence of the bullfrog NK1 receptor. This clone included a fragment of receptor protein spanning TM II to VII. Clone 2 was a 5′-RACE product of 500 bp, containing the 5′-end of the receptor protein and its untranslated region. 3′-RACE generated three clones, possessing 815-, 738-, and 545-bp cDNA inserts, respectively. Each of these clones contained individual 3′-end translated and untranslated regions of the receptor gene locus. To exclude potential PCR artifacts, RT-PCR and PCR were conducted with fresh RNA extracts and cDNAs using several gene-specific primers coding for the 5′- and 3′-ends of the nontranslated regions. The existence of three receptor isoforms (bNK1-A, bNK1-B, and bNK1-C) was thereby confirmed to be authentic.

The bNK1-A isoform has the longest cDNA, comprising 1,854 nucleotides encoding a 309-amino acid protein; bNK1-B consists of 1,777 nucleotides encoding a protein of 390 amino acids; and bNK1-C is the shortest cDNA, with 1,585 nucleotides encoding a 371-amino acid ORF.

Figure 1 shows the complete sequences of the full-length cDNAs and the deduced amino acid sequences for the three toad NK1 receptor isoforms. These isoforms share a common nucleotide sequence between the 5′-untranslated region to the guanine at position 1219, but downstream regions are unique to each receptor. At position 1220, bNK1-A contains a stop codon, which results in a highly truncated COOH terminus for this receptor, extending only three amino acids beyond TM VII. The immediate 3′-untranslated region of mRNA encoding for bNK1-A also differs from those of bNK1-B and bNK1-C. The stop codon of bNK1-B occurs at position 1462, forming the longest COOH terminus, which is 81 amino acids longer than bNK1-A. The nucleotide sequence of bNK1-C is identical to that of bNK1-B except for a 192-bp deletion between positions 1272 and 1463. This resulted in a frame shift that gave rise to another ORF of 137 bp in bNK1-C and an alternative COOH terminus to bNK1-B. Thus, the first 309 amino acids are common to all three receptor isoforms, which then differ in their intracellular COOH-terminal regions. A comparison of amino acid sequences of toad, bullfrog, and human is shown in Fig. 1. The phylogenetic tree constructed from the amino acid sequences of tachykinin receptors using the ClustalX analysis program revealed that the three toad tachykinin receptor isoforms identified in this study belonged to the NK1 receptor group (Fig. 3).

**Ligand Binding Assay**

Competition binding experiments using [125I]BH-bufokinin were carried out using COS-7 cells transfected with ORF cDNAs to confirm that the cDNA clones isolated in the present study encoded proteins that are able to interact with tachykinins. All three cell lines expressing bNK1-A, bNK1-B, and bNK1-C, respectively, bound with high affinity to [125I]BH-bufokinin. The rank order of affinity for competing [125I]BH-
bufokinin binding was, for bNK1-A, bufokinin $\gg$ SP $\geq$ NKA; for bNK1-B, bufokinin $>$ SP $>$ NKA; and for bNK1-C, bufokinin $> NKA \geq SP$ (Fig. 4). Bufokinin was almost equipotent (IC$_{50}$, 0.6–0.8 nM) in all three isoforms, although these showed different affinities for SP and NKA (Table 2). SP and NKA were very weak competitors for bNK1-A; SP showed highest affinity for bNK1-B, whereas NKA showed highest affinity for bNK1-C (Table 2). In most cases, the slope factors...
of competition curves in all isoforms were below unity (0.5–0.7, data not shown), suggesting binding to more than one site.

When the binding data from the present study were compared with the data obtained in homogenate binding in the toad small intestine using the same radioligand (22), differences were noted (Table 2). Although the affinity order in the small intestine binding and in a functional study using isolated longitudinal ileal segments (Table 2) was bufokin > SP > NKA, similar to that for bNK1-B, a major discrepancy was observed with NKA. NKA was 34- to 42-fold weaker than bufokin in the native tissue compared with 228-fold weaker in COS-7 cells expressing bNK1-B.

**Functional Expression in Xenopus Oocytes**

Application of bufokin, SP, and NKA to oocytes expressing bNK1-B and bNK1-C generated current responses (Fig. 5A), but no responses were detected in oocytes expressing bNK1-A. The minimal doses required to elicit a response for the three peptides were bufokin (0.1 nM), SP (1 nM), and NKA (10 nM) for both bNK1-B and bNK1-C. The current response showed significant desensitization in the continued presence of the peptide, and subsequent applications of the same dose of peptide generated greatly attenuated responses (see Fig. 5A), which precluded obtaining accurate dose responses. The marked desensitization of the current measured in the continued presence of agonist is characteristic of activation of the endogenous calcium-dependent chloride channel (24). The reversal potential of the conductance was 20 mV, whether measured at the peak response or after desensitization (Fig. 5B), which corresponds with the reversal potential of chloride ions in *Xenopus* oocytes. Application of the chloride channel blocker niflumic acid before bufokin application greatly attenuated the current response to the subsequent bufokin application (Fig. 5C).

**Tissue-Specific Expression of bNK1 Receptor mRNA Isoforms**

RT-PCR analysis was carried out to determine the expression of the three isoform mRNAs in a number of toad tissues, using unique primers (Table 1). As expected, the control β-actin mRNA was ubiquitously expressed in all tissues ex-
amined (Fig. 6). Expression of the individual receptor isoforms varied between tissues. The bNK₁-B mRNA was detected in all tissues, being the predominant isoform, except in the skeletal muscle, where bNK₁-A showed the highest expression. The bNK₁-A and bNK₁-C mRNAs were also found in a wide range of tissues, although bNK₁-A was barely detected in liver and aorta, and bNK₁-C was not detectable in aorta, atrium, and skin. On the whole, the bNK₁ receptor gene was expressed abundantly in the spinal cord, small intestine, skeletal muscle, lung, and brain. A substantial expression was also seen in the stomach and testis. Low expression was observed in aorta, atrium, ventricle, bladder, skin, and liver (Fig. 6).

DISCUSSION

In this study, we report the isolation from toad brain and small intestine of three different isoforms of an NK₁-like receptor. At the amino acid level, the three isoforms differ only at the intracellular COOH terminus. Isoform A has 70% identity to the truncated mammalian NK₁ receptor (311 amino acids), and B shows moderate (~67%) levels of identity with the full-length human, rat, and guinea pig NK₁ receptor (407 amino acid) and the chicken NK₁ receptor (69%), with greatest similarity to the bullfrog receptor (85%). Thus bNK₁-A and bNK₁-B are counterparts of the mammalian truncated and full-length NK₁ receptors. In contrast, bNK₁-C is a new isoform with a unique intracellular COOH terminus, showing only 21% identity to bNK₁-B and 17% to the full-length human NK₁ receptor in the COOH-terminal region. The counterparts of bNK₁-C have not been reported in any other species to date.

All tachykinin receptors are encoded by a five-exon gene structure interrupted by four introns and are likely to have evolved from a common ancestral gene (12, 14, 19, 20, 33). The phylogenetic analysis indicates that the separation of NK₂ from the NK₁/NK₃ cluster occurred in an earlier evolutionary period than the split of NK₁ and NK₃ into two different genera (Ref. 27; Fig. 3). The short forms of human and guinea pig...
Fig. 4. A–C: competition binding of bufokinin, SP, and NKA against [125I]BH-bufokinin in COS-7 cells expressing bNK1-A (A), bNK1-B (B), and bNK1-C (C). Data represent means ± SE of duplicate determination in 3–5 different experiments. A: bufokinin showed significantly higher affinity than SP and NKA (P < 0.001), but there was no difference between SP and NKA (P = 0.48). B: bufokinin showed higher affinity than SP and NKA (P < 0.001), and SP showed higher affinity than NKA (P < 0.05). C: bufokinin showed higher affinity than NKA and SP (P < 0.01), and the difference between NKA and SP was not significant (P = 0.27). Two-way ANOVA was used for the statistical analyses.

Table 2. IC_50 values of tachykinins in competing for [125I]BH-bufokinin binding in COS-7 cells expressing toad NK_1 isoforms compared with data obtained in toad small intestine.

<table>
<thead>
<tr>
<th>Tachykinin</th>
<th>IC_50, nM (95% CI)</th>
<th>Ratio</th>
<th>IC_50, nM (95% CI)</th>
<th>Ratio</th>
<th>IC_50, nM (95% CI)</th>
<th>Ratio</th>
<th>Small Intestine Binding*</th>
<th>Small Intestine Functional†</th>
</tr>
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<tbody>
<tr>
<td>Bufokinin</td>
<td>0.66 (0.24–1.8)</td>
<td>100</td>
<td>0.60 (0.19–1.9)</td>
<td>100</td>
<td>0.75 (0.25–2.2)</td>
<td>5</td>
<td>1.7</td>
<td>100</td>
</tr>
<tr>
<td>SP†</td>
<td>910 (240–3,470)</td>
<td>0.07</td>
<td>7.3 (1.3–41)</td>
<td>8.2</td>
<td>30 (8.6–99)</td>
<td>4</td>
<td>10.7</td>
<td>16</td>
</tr>
<tr>
<td>NKA§</td>
<td>1660 (690–3,980)</td>
<td>0.04</td>
<td>137 (28–660)</td>
<td>0.43</td>
<td>8.1 (2.2–30)</td>
<td>9.0</td>
<td>57.8</td>
<td>14.2</td>
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</table>

95% CI, 95% confidence interval of the IC_50 estimation; n, numbers of experiments performed. Ratio, IC_50 relative to bufokinin. *Data from Liu et al. (22). †Functional data are from longitudinal segments of intestine. ‡Substance P (SP) showed significantly higher affinity for isoform B than for C (P < 0.05) and lower affinity for isoform A (P < 0.001 compared with B and C). Two-way ANOVA was used for the statistical analyses. §Neurokinin A (NKA) showed significantly higher affinity for isoform C than for B (P < 0.05) and lower affinity for isoform A (P < 0.01, 0.001 compared with B and C, respectively). Two-way ANOVA was used for the statistical analyses.
NK₁ receptors (1, 9) and bNK₁-A terminate three residues after TM VII and are truncated at the exact position where intron D is inserted between exon 4 and exon 5 (Fig. 7). The cDNA encoding bNK₁-C is created by a 192-bp nucleotide deletion of the bNK₁-B cDNA within the exon 5 region, causing a frame shift. Since there is no current evidence for the existence of multiple genes encoding the NK₁ receptor in the same species, it is probable that the multiple isoforms of the toad NK₁ receptor are derived from a single gene and undergo pre-mRNA alternative splicing.

This study provides direct evidence, at a molecular level, for sequence conservation and divergence between amphibian and mammalian receptors and may explain some specific characteristics of the toad receptor. The three residues (Glu78 in TM II, and Tyr205 and Tyr216 in TM V regions) required for activation of the human NK₁ receptor (17, 18) are fully conserved in amphibian receptors (see Fig. 2). Another four residues (Asn85, Asn89, Tyr92, and Asn96) in TM II, which are also fully conserved in amphibian receptors, were suggested to be important for conformational changes of the mammalian receptor (29). Other fully conserved residues (Asn23 and Phe25) at the NH₂ terminus are important for agonist binding (10, 11, 18). Therefore, the conservation of these key amino acids in toad NK₁ receptor would explain the high affinity of bufokinin at mammalian NK₁ receptors (6) and the potency of mammalian and other native amphibian tachykinins in the toad (3, 22). On the other hand, synthetic analogs of SP such as [Pro⁹]SP, [Sar⁹]SP, and [Sar⁹, Met(O₂)¹¹]SP showed weak or negligible ability to bind and activate the toad NK₁ receptor (3, 22), and this may result from substitution of mammalian Gln24 and Gln165 by Pro23 and Leu164 in the toad receptor protein. Other residues occurring in mammalian receptors (see Fig. 2) but not conserved in toad or bullfrog are important in the binding of nonpeptide NK₁ antagonists (5, 10, 33).

Fig. 6. Representative gels showing expression of each toad NK₁ receptor isoforms in different toad tissues. β-Actin expression in the same tissue was used as an internal control. Two to four other experiments for each isoform gave similar results. LU, lung; AO, aorta; AT, atrium; V, ventricle; BL, bladder; BR, brain; SC, spinal cord; SK, skin; SI, small intestine; SmM, skeletal muscle; ST, stomach; TE, testis; LI, liver.

Fig. 7. Schematic diagram of the gene encoding toad NK₁ receptor isoforms. Analysis of the genomic sequences of mammalian and invertebrate tachykinin receptors (12, 14, 19, 20, 33) indicates that all tachykinin receptor proteins are encoded by a 5-exon gene structure (exon 1–exon 5) interrupted by 4 introns (intron A–intron D). The truncation of bNK₁-B occurs at the position where intron D is inserted, implying that during pre-mRNA splicing, an intron sequence may be retained, which results in the insertion of a premature termination codon. The cDNA encoding bNK₁-C is created by a 192-bp nucleotide deletion of the bNK₁-B cDNA within the exon 5 region, causing a frame shift. The transmembrane domains (TM I to TM VII) are shown by solid dark box; numbers indicate amino acid position at which splicing sites insert. The codes for translation initiation (ATG) and termination (TGA) are also indicated.
18), which are potent in mammals but ineffective in the toad (3, 22). Thus during evolution, the sequences of tachykinin receptors in modern amphibians and mammals have diverged from that of the ancestral tachykinin receptor, and conservation of sequences such as those involved in mammalian nonpeptide antagonist binding has not conferred survival value.

All three isoforms had broadly similar distribution patterns, with quantitative differences. The high level of expression in toad small intestine matches our earlier binding and functional data showing high-potency NK₁ receptors responding to bufokinin (22). Because all three isoforms are densely expressed in the small intestine, our earlier data probably represent interactions at the three isoforms, if not affinity states. As in mammals (2) and other vertebrates (8), there was very high expression in brain and especially spinal cord. The endogenous ligand for these toad receptor(s) is presumably bufokinin (mammalian SP is absent), although the origin of the peptide, whether neuronal or endocrine, is not clear.Bufokinin might be released from nerve varicosities in these organs, since we have previously reported the distribution of immunoreactive bufokinin in nerves in toad intestine, bladder, around blood vessels, and in endocrine cells in the intestinal mucosa (21). The presence of all three isoforms in the lung was somewhat unexpected, given our previous study showing lack of immunoreactive bufokinin in this organ in the toad (21). Furthermore, high levels of expression in the skeletal muscle, particularly of bNK₁-A, are surprising, and further studies would be required to demonstrate the histological location of the receptor protein. It is possible that the receptor(s) is located on vascular endothelial cells as shown in previous autoradiographic studies of mesenteric vessels (21), because both skeletal muscle and lung are well endowed with capillaries. The role that NK₁ receptor might play in the testis is less clear, although tachykinins have been shown to modulate the functions of several cell types in the mammalian testis (7). The development of oligonucleotide probes and antibodies specific for each isoform would be important tools to ascertain their functional significance in different tissues and locations.

All isoforms expressed in COS-7 cells showed high affinity for [125I]BH-bufokinin and displayed similar high affinity for the endogenous bufokinin, although bNK₁-A lacks any COOH-terminal sequence. This suggests that interaction of bufokinin with the toad NK₁ receptor does not involve the COOH-terminal region(s). However, the binding profiles of SP and NKA were very different at the three isoforms, with particularly low affinity at bNK₁-A. Because these isoforms vary only at the intracellular tail region, this COOH-terminal divergence must underlie the quantitative differences in binding affinity for SP and NKA. The shallow competition curves and the strikingly dissimilar binding profiles for each isoform in our cell line binding studies may reflect the occurrence of various affinity states caused by coupling to different G proteins (16) or even the same G protein(s) in different ways. Alternatively, it is now accepted that different ligands can induce various conformations of tachykinin NK₁ and NK₂ receptors (27).

Although bufokinin bound with equal affinity for all three isoforms, these were not equally active in the Xenopus oocyte expression system. Thus the short isoform, bNK₁-A, was inactive, as shown for mammalian truncated NK₁ receptors expressed in heterologous systems (9, 30), whereas bNK₁-B and bNK₁-C produced increases in chloride current in response to tachykinin stimulation. For bNK₁-B, there was an excellent correlation between functional and binding data, whereas for bNK₁-C there was a discrepancy between potencies of SP and particularly NKA. High-affinity agonist binding does not necessarily correlate with the ability of the receptor to promote agonist-induced functional responses, particularly in heterologous expression systems. In this respect, signal transduction systems may be important. Further studies to determine the signal transduction pathways utilized by these isoforms will be of considerable interest. Little is known about G proteins in amphibia or the regions of the intracellular domains of GPCRs with which they interact.

In Xenopus oocytes, stimulation of bNK₁-B and bNK₁-C was followed by rapid desensitization to subsequent applications of tachykinins. This suggests that bNK₁ receptors couple through G proteins to the calcium-dependent chloride channel, and this was confirmed by our studies with niflumic acid (Fig. 5C). Similar biphasic chloride current responses have been observed for stimulation of dopamine D₁ receptors expressed in Xenopus oocytes and have been attributed to receptor coupling to stimulation of cAMP production and release of calcium from calcium stores, both of which may lead to activation of the calcium-dependent chloride channel (28). The mechanism of desensitization in mammalian systems involves agonist-induced phosphorylation of Ser/Thr residues at the COOH terminus by a receptor-specific kinase, allowing β-arrestin to bind and cause receptor internalization (23, 26, 39). Because these residues are found in the appropriate cytoplasmic domains of bNK₁-B and bNK₁-C receptors (Fig. 1), desensitization mechanisms in the toad NK₁ receptor appear similar to those described in mammals (30).

The role of the short isoform bNK₁-A is unclear. As in the toad, there is widespread expression of both long and truncated forms of NK₁ receptor in the human brain and peripheral tissues (4). The lack of ability to produce a functional response in the Xenopus oocyte system could be due to the truncated COOH terminus inducing a differently folded protein tertiary structure, thus causing abnormal trafficking, whereas receptor protein folding might occur normally in native Bufo systems. Alternatively, bNK₁-A might require a specific G protein, which does not exist in Xenopus oocytes. Insights into the role of bNK₁-A may be obtained from studies with truncated splice variants of other GPCRs and ion channel receptors. In many cases, these truncated protein molecules appear to act as binding, nonsignaling receptors on their own and exert functions only when forming heterodimeric complexes with other variants. The truncated toad NK₁ receptor may be a nonfunctional receptor itself but heterodimerize with the full-length isoform to regulate receptor activation.

In summary, this study is the first evidence for the existence of a naturally occurring truncated form (bNK₁-A) of NK₁-like receptor in nonmammalian species and is also the first identification of a unique third tachykinin receptor isoform (bNK₁-C) in any species. Thus bNK₁-A and bNK₁-B are the counterparts of the mammalian truncated and long form of NK₁ receptor, whereas the mammalian equivalent of bNK₁-C is unknown, and it may be redundant or have undergone mutation in other vertebrates. Our study suggests that the alternative splicing of NK₁ receptor has been conserved under the selection of evolutionary pressure. Receptors found in...
lower animals undoubtedly have counterparts with important functions in humans. The identification of these new receptor isoforms and their specific pharmacological properties may provide novel insights into the modulation of tachykinin receptor activities and provide important clues for a better understanding of the phylogenetic origin of the tachykinin family.

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GRANTS

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