Targeting Neuropeptide Receptors for Cancer Imaging and Therapy: Perspectives with Bombesin, Neurotensin, and Neuropeptide-Y Receptors

Clément Morgat1–3, Anil Kumar Mishra2–4, Raunak Varshney4, Michèle Allard1,2,5, Philippe Fernandez1–3, and Elif Hindi6,7

1CHU de Bordeaux, Service de Médecine Nucléaire, Bordeaux, France; 2University of Bordeaux, INCIA, UMR 5287, Talence, France; 3CNRS, INCIA, UMR 5287, Talence, France; 4Division of Cyclotron and Radiopharmaceutical Sciences, Institute of Nuclear Medicine and Allied Sciences, DRDO, New Delhi, India; and 5EPHE, Bordeaux, France

Learning Objectives: On successful completion of this activity, participants should be able to list and discuss (1) the presence of bombesin receptors, neurotensin receptors, or neuropeptide-Y receptors in some major tumors; (2) the perspectives offered by radiolabeled peptides targeting these receptors for imaging and therapy; and (3) the choice between agonists and antagonists for tumor targeting and the relevance of various PET radionuclides for molecular imaging.

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Receptors for some regulatory peptides are highly expressed in tumors. Selective radiolabeled peptides can bind with high affinity and specificity to these receptors and exhibit favorable pharmacologic and pharmacokinetic properties, making them suitable agents for imaging or targeted therapy. The success encountered with radiolabeled somatostatin analogs is probably the first of a long list, as multiple peptide receptors are now recognized as potential targets. This review focuses on 3 neuropeptide receptor systems (bombesin, neurotensin, and neuropeptide-Y) that offer high potential in the field of nuclear oncology. The underlying biology of these peptide/receptor systems, their physiologic and pathologic roles, and their differential distribution in normal and tumoral tissues are described with emphasis on breast, prostate, and lung cancers. Radiolabeled analogs that selectively target these receptors are highlighted.

Key Words: cancer; molecular imaging; peptide/neuropeptide; PET; radiopharmaceutical; receptor; bombesin; neurotensin; neuropeptide Y

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Molecular imaging with PET or SPECT can visualize biochemical processes and their dysfunction using specific probes. These nuclear medicine techniques are helpful in fundamental research and clinical routine to characterize mechanisms involved in a pathologic process; to assist clinicians in diagnosis, staging, and patient management; to select patients who are expected to benefit from a specific treatment; and to monitor its efficacy. In oncology, molecular imaging is strongly dependent on the availability of a specific target on tumor cells or within the tumor stroma or vasculature and the suitability of the designed radiolabeled vector, which depends on its biodistribution, metabolism, affinity, and specificity for the target. One of the most promising avenues in PET nuclear oncology is the imaging of neuropeptide (regulatory peptide) receptors.

Targeting somatostatin receptors has been widely used for imaging neuroendocrine tumors (NETs) using diethyleneetriaminepentaacetic acid (DTPA)-octreotide labeled with 111In and for peptide receptor radionuclide therapy of metastatic NETs using somatostatin analogs labeled with 90Y or 177Lu (1). Recently, some high-affinity somatostatin analogs holding a DOTA-chelate (DOTATOC, DOTATATE, DOTANOC), and radiolabeled with 68Ga (I, 2) or 64Cu (3) for PET/CT imaging, showed excellent results in gastroenteropancreatic NETs supraventional 111In-DTPA-octreotide imaging (Fig. 1A). These new analogs also provided encouraging results in pheochromocytomas and paragangliomas (Fig. 1B) (4). Also of importance in NETs is the incretin receptor family. Insulinoles have high expression of glucagon-like peptide-1 receptor, and glucagon-like peptide 1 radiolabeled analogs have been shown to offer excellent sensitivity (Fig. 2) (5). Another member of this family, the receptor for glucose-dependent insulinotropic polypeptide, has recently been found to be expressed in most pancreatic, ileal, and bronchial NETs, including those that are somatostatin receptor–negative (6), as well as in medullary thyroid cancer (7), and radiolabeled glucose-dependent insulinotropic polypeptide analogs are promising (8). Other targets in NETs are the cholecystokinin B receptor and the recently described neuropeptide S receptor 1 (9).

The success encountered in NETs is probably only the first of a long list. This review focuses on 3 neuropeptide receptor systems whose significance in the field of oncology is growing (bombesin, neurotensin, and neuropeptide-Y [NPY] receptors). The underlying
biology, distribution, and physiologic role of these peptide/receptor systems are described. We then discuss their presence in tumors, with a focus on breast, prostate, and lung cancers. Promising radiolabeled peptides that specifically target these receptors are highlighted.

THE BOMBESIN, NEUROTENSIN, AND NPY RECEPTORS

The bombesin, neurotensin, and NPY receptors are present in the central nervous system and in peripheral tissues. Physiologic distribution in the central nervous system is outside the scope of the present topic and, because of the blood–brain barrier, is of little relevance for imaging after systemic administration. Neuropeptides are synthesized in the gastrointestinal tract and other peripheral organs by a restricted number of specialized cells. They can act as autocrine, paracrine, or endocrine molecules and bind with high affinities to their receptors, which in most of cases are G protein–coupled receptors (GPCRs) (10). GPCRs, also known as 7-transmembrane receptors, transduce signals through their interactions with extracellular small-molecule ligands and intracellular G proteins to initiate signaling cascades (Fig. 3).

Bombesin System

Bombesin was originally derived from the skin of the frog Bombina bombina. Two related peptides, gastrin-releasing peptide (GRP) and neuromedin-B, are present in humans (11). GRP elicits...
gastrin release and regulates gastric acid secretion and enteric motor function. Receptors of the bombesin family are GPCRs (11, 12).

There are 3 receptors: GRP receptor (GRPR) (also known as bombesin receptor 2 [BB2]); neuromedin-B receptor (BB1); and orphan receptor (BRS3, or BB3). GRP has higher affinity for GRPR than for neuromedin-B receptor. GRPR is promising for cancer targeting (11). GRPR is expressed in the pancreas and at lower levels in the colon, breast, prostate, and skin (11).

Neurotensin System

Neurotensin is a 13-amino-acid peptide that functions as a neurotransmitter and hormone. In the gastrointestinal tract, neurotensin is released from the enteroendocrine N cells in response to lipid ingestion and is involved in the stimulation of pancreatic, biliary, and gastric acid secretions; the facilitation of fatty acid absorption; and the regulation of small-bowel motility. The C-terminal region neurotensin(8–13) is responsible for the activation of neurotensin receptor (13). Neurotensin effects are mediated through 3 receptor subtypes: neurotensin receptor 1 (NTSR1) and NTSR2 (high- and low-affinity receptors, respectively) are GPCRs (12), whereas NTSR3 (sortilin) has a single-transmembrane domain. NTSR1 is promising for cancer targeting. In peripheral tissues, NTSR1 is located mainly in the colon and lung (14).

NPY System

The NPY family comprises 3 peptides: NPY, polypeptide-Y, and pancreatic polypeptide. Major emphasis is given to NPY in oncology. NPY plays integrative functions in peripheral organs such as vasocostriction or induction of food intake. In humans, NPY exerts its effects through 4 GPCRs: Y1, Y2, Y4, and Y5 (12). Y1, Y2, and Y5 can be associated with different aspects of oncogenesis and angiogenesis. In peripheral organs, NPY receptors can be found in colon, kidney, adrenal gland, reproductive organs, testis, and breast (15).

PRESENCE OF BOMBESIN, NEUROTENSIN, OR NPY RECEPTORS IN SELECTED TUMORS

We focus on breast, prostate, and lung cancer, but the presence of these receptors is also signaled in other tumors. Neuropeptide receptors not only can be present in tumors but also can influence the oncopathologic process and be expressed at specific stages of carcinogenesis or tumor progression and in selective subtypes of a tumor.

Quantitative receptor autoradiography and semiquantitative immunochemistry–immunohistochemistry are considered relevant methods to compare levels of receptor expression between normal and tumoral tissues. Although less straightforward, data on receptor messenger RNA levels or neuropeptide levels in tumors have also been considered.

Breast Cancer

Neurotensin Receptors. One team showed that 91% of invasive ductal breast carcinomas were positive for NTSR1 (16). Also, the level of expression of NTSR1 was positively correlated with tumor size, Scarff-Bloom-Richardson grade, number of metastatic lymph nodes, recurrence, and survival (17). The neurotensin receptor is not present in normal epithelial breast cells (18).

Bombesin Receptors. Using receptor autoradiography, Gugger and Reubi reported the presence of GRPR in 62% of invasive breast
carcinomas, often with high density and heterogeneous distribution (19). Lymph node metastases from patients with GRPR-positive primary tumors were also GRPR-positive. Gugger and Reubi also found a ubiquitous GRPR expression in non-neoplastic human breast tissue (19). In a preliminary report, GRPR messenger RNA has been found to be correlated with estrogen receptor expression (20).

NPY Receptors. With receptor autoradiography, NPY receptors have been identified in 85% of breast carcinomas. Lymph node metastases from receptor-positive primary tumors were also positive. Y$_1$ was the dominant receptor in tumors, whereas non-neoplastic breast tissue expressed Y$_2$ preferentially (21). Reubi et al. suggested that neoplastic transformation might switch the NPY receptor from Y$_2$ to Y$_1$ subtype (21). Recent in vitro studies have incriminated Y$_3$ in breast cancer growth and angiogenesis (22).

Preliminary Conclusions. NTSR$_1$ is an attractive target associated with clinical and pathologic factors for poor prognosis (17). GRPR and NPY receptors should also be of interest for targeting breast cancer metastases when the primary tumor is positive, but comparison between these receptors is needed. Importantly, no study has investigated the distribution of these neuropeptide receptors according to tumor phenotype (based on the status of estrogen receptor, progesterin receptor, and human epidermal growth factor receptor 2) or molecular classification of breast cancers (23). Identification of targetable receptors in specific subtypes of breast cancer would be of major importance—notably so in triple-negative breast cancer, which currently has limited systemic treatment options other than chemotherapy.

Prostate Cancer

Bombesin Receptors. Using receptor autoradiography, Markwalder and Reubi reported that GRPR is present, often in high density, in invasive carcinoma as well as in prostatic intraepithelial neoplasia, whereas GRPR density in non-neoplastic prostate hyperplasia was low (24). Well-differentiated carcinomas had a higher receptor density than poorly differentiated ones. One study found GRPR to be expressed in 86% of lymph node metastases but only 53% of bone metastases (25). Beer et al. studied prostate samples from 530 patients using immunohistochemistry (26). Normal prostate tissues were mostly GRPR-negative, whereas GRPR was overexpressed in prostate cancer. However, more aggressive prostate cancer had lower GRPR expression levels than lower-grade tumors, with significant inverse correlation between GRPR expression and increasing Gleason score, prostate-specific antigen value, and tumor size. Moreover, GRPR expression was positively correlated with androgen receptor expression (26). Kömer et al. found a progressive increase in GRPR density over atypical glands from normal prostate gland to high-grade prostatic intraepithelial neoplasia but no further increase to invasive carcinoma (27). These findings are of importance when interpreting GRP imaging studies.

Neurotensin Receptors. Early studies noted that neurotensin and neurotensin receptors are recruited in advanced prostate cancer as an alternative growth pathway in the absence of androgens (28). NTSR$_1$ is expressed in prostate cancer cells but not in normal prostate epithelial cells (29). In cell cultures, NTSR$_1$ expression increases with the tumorigenic potential of cancer cells (30). NTSR$_1$ was also reported to be involved in resistance to radiotherapy (29).

NPY Receptors. Recent studies uncovered the expression of Y$_1$-R gene and protein in prostate cancer cells and a role of NPY in regulating tumor growth (31,32). Data on the expression of NPY-R in tissues from patients with prostate cancer of different stages are therefore urgently needed.

Preliminary Conclusions. The natural history of prostate cancer extends from an indolent localized process to biochemical relapse after radical treatment with curative intent to lethal castrate-resistant metastatic disease. There is a need to improve diagnostic imaging in many clinical circumstances, and molecular imaging is expected to play an important role (33). In addition to $^{18}$F-FDG and $^{18}$F-choline, several other PET tracers are in development (33).

Neuropeptide imaging in prostate cancer has been focused mostly on GRPR targeting, with exciting first results with some novel radiolabeled analogs. No doubt, other neuropeptide receptors such as NTSR$_1$ and NPY receptors will enlarge the field of investigation. GRPR and NTSR$_1$ have divergent expression as regards androgen status and, thus, may have complementary roles in prostate cancer. GRPR expression is positively correlated with androgen receptor expression, and GRPR imaging might be most sensitive in the early stage of disease or in patients with biochemical-relapse “prostate-specific antigen rise” who are not on androgen-deprivation therapy. Contrarily, the NTSR$_1$ pathway appears to be activated by androgen deprivation, suggesting a role for NTSR$_1$ imaging during the switch to castration-resistant disease (28–30).

Lung Cancer

Neurotensin Receptors. Alifano et al. investigated NTSR$_1$ expression in patients with pathologic stage I lung adenocarcinoma. Immunopositivity was found in 60% of cases. NTSR$_1$ positivity was associated with lower survival rates (34). In vitro, neurotensin antagonist SR48692 inhibits proliferation (35). NTSR$_1$ is also expressed in 90% of mesotheliomas (36).

Bombesin Receptors. GRPR is expressed at similar rates in non–small cell lung cancer (62%) and small cell lung cancer (53%), with subsets of patients showing distinctly strong expression (37). Early studies have shown that GRP stimulates the clonal growth of human small cell lung cancer cell lines and that bombesinlike peptides can function as autocrine growth factors (38). Recently, it was found that a subset of cells that persist after chemotherapy, “cancer stem-like cells,” have increased expression of receptors for GRP and arginine vasopressin (39).

Preliminary Conclusions. Improvements in diagnosis and treatment and identification of new targets in lung cancer are urgently needed (40). The identification of NTSR$_1$ as a marker of poor prognosis in resected stage I lung adenocarcinoma may help decisions on adjuvant treatment (34). NTSR$_1$ expression also opens important perspectives for imaging and targeting. NTSR$_1$ and GRPR are strongly expressed in subsets of lung adenocarcinomas (34,37). It will be important to determine the molecular profile of these tumors and whether they are associated with driver mutations or gene rearrangements (e.g., epidermal growth factor receptor and EML4-ALK) involved in tumor progression.

Other Tumors

The role of these neuropeptide receptors extends to other tumors. Pilot studies drew attention to the role of neurotensin in pancreatic adenocarcinoma (41,42). In xenografts of human pancreatic carcinoma Mia PaCa-2, neurotensin significantly increased the size, weight, and DNA and protein content, and these effects were inhibited by SR48692 (41). With receptor autoradiography, 75% of ductal pancreatic adenocarcinomas were neurotensin receptor–positive, whereas no neurotensin receptors were found in endocrine pancreatic cancers, in chronic pancreatitis, or in normal pancreatic tissues (42). This high expression in ductal pancreatic adenocarcinomas offers the molecular basis for neurotensin
hormone ligands. However, GRPR, NTSR 1, and NPY receptors prepared a somatostatin antagonist (177Lu-DOTA-JR11) with the agonist 177Lu-DOTATATE in the same patients found higher tumor physiologic effects, an antagonist is preferred, especially when non-specific uptake and higher tumor-to-kidney and tumor–to–bone marrow ratios. Both radionuclides have somewhat less optimal physical properties than 18F. The high positron energy of 68Ga (maximum $\beta^+$, 1.9 MeV) might slightly affect resolution on PET imaging (Table 1). As for 64Cu, the longer half-life, low positron branching (17.8%), and the presence of $\beta^+$ emission (38.5%) would increase radiation dose. However, because many peptides have fast urinary clearance, patients’ absorbed doses remain in the range of those with 18F examinations. Distinct advantages of these radioisotopes over 18F are chemical properties excellent for peptide labeling through appropriate chelators, and the ability to predict dosimetry and better plan radiopeptide therapy with 177Lu, 90Y, or 64Cu-labeled radiopharmaceuticals.

**Radiolabeled GRP Analogs**

A proof of concept for in vivo GRPR targeting was provided by Van de Wiele et al., who used 99mTc-labeled N3S-Gly-5-Ava-BN (7-14) (RP527), a selective agonist. In breast cancer patients, specific uptake was noted in the primary tumor in 8 of 9 patients and in involved axillary lymph nodes. Tumor uptake matched GRPR expression at immunohistochemistry (52). No uptake was seen in tamoxifen-resistant patients with bone metastases.

Among antagonists, 68Ga-RM2, also known as BAY 86-7548 (68Ga-DOTA-4-amino-1-carboxymethyl-piperidine-d-Phe-Gln-Trp-Ala-Val-Gly-His-Sta-Leu-NH2), has been assessed in 14 patients with prostate cancer (11 untreated, 2 with biochemical recurrence, and 1 whose cancer was hormone-refractory) (53). This pilot study had encouraging results as related to the detection of primary prostate cancer and metastatic lymph nodes (Fig. 4), as well as in detection of local recurrence in the prostate bed and nodal relapse. However, 68Ga-BAY 86-7548 failed to show multiple bone metastases in the hormone-refractory patient. These findings are consistent with levels of GRPR expression in tissues according to tumor status (hormone-sensitive vs. castration-resistant) (25).

Another GRPR antagonist, 64Cu-CB-TE2A-AR-06 (CB-TE2A-PEG3, b-Phe-Gln-Trp-Ala-Val-Gly-His-Sta-Leu-NH2), has recently been investigated in 4 patients with newly diagnosed prostate cancer (Gleason 6–7). It was found to be metabolically stable for receptor scintigraphy for early tumor diagnosis, as well as a rationale for treatment strategies with neurotensin receptor antagonists and radiolabeled neurotensin analogs (42). In head and neck squamous cell carcinomas, high messenger RNA expression levels of neurotensin and NTSR1 are associated with a poor metastasis-free survival rate (43). In vitro, neurotensin agonists have been shown to promote cellular invasion, migration, and induction of interleukin 8 and matrix metalloproteinase 1 transcripts (43). NTSR1 is also overexpressed in colorectal carcinoma (44). GRPR and NTSR1 are both expressed in gastrointestinal stromal tumors. Melanocortin-1 receptor in melanomas is targetable with peptide receptor radionuclide therapy (64), 67Cu, and 161Tb).

68Ga and 64Cu are experiencing wide development. Some of their physical properties are shown in Table 1. 68Ga is attractive because of in-house production with a 68Ge/68Ga generator and its short half-life, allowing rapid examination (51). On the other hand, the longer half-life of 64Cu allows industrial shipping and can be favored when delayed imaging improves tumor-to-background ratios. Both radionuclides have somewhat less optimal physical properties than 18F. The high positron energy of 68Ga (maximum $\beta^+$, 1.9 MeV) might slightly affect resolution on PET imaging (Table 1). As for 64Cu, the longer half-life, low positron branching (17.8%), and the presence of $\beta^+$ emission (38.5%) would increase radiation dose. However, because many peptides have fast urinary clearance, patients’ absorbed doses remain in the range of those with 18F examinations. Distinct advantages of these radioisotopes over 18F are chemical properties excellent for peptide labeling through appropriate chelators, and the ability to predict dosimetry and better plan radiopeptide therapy with 177Lu, 90Y, or 64Cu-labeled radiopharmaceuticals.

### Radiolabeled Analogs Targeting Bombesin, Neurotensin, or NPY Receptors

Ideal radioligands should have fast clearance from circulation, low in vivo metabolism, high affinity, specific uptake, and high tumor-to-nontumor ratios. Because of their lower molecular weight, peptide probes can more easily meet these criteria than antibodies.

Classically, peptide receptor targeting used only analogs that were agonists. More recently, however, the use of antagonists has been a subject of major interest (49,50). Although not internalized into tumor cells after binding to the receptors, some antagonists offer excellent targeting (49). A recent clinical study that compared a somatostatin antagonist ($^{177}$Lu-DOTA-JR11) with the agonist $^{177}$Lu-DOTATATE in the same patients found higher tumor uptake and higher tumor-to-kidney and tumor–to–bone marrow ratios with the radiolabeled antagonist (50). However, the exact mechanisms (number of binding sites, dissociation rate, metabolic stability) by which some antagonists behave better than agonists in vivo are still unclear and will need further investigation. When the peptide has tumor-stimulating properties or undesirable physiologic effects, an antagonist is preferred, especially when non-negligible amounts have to be administered, such as for peptide receptor radionuclide therapy (49).

Macrocyclic chelators, such as DOTA, NODAGA, or CB-TE2A (4,11-bis(carboxymethyl)-1,4,8,11-tetraazabicyclo[6.6.2]hexadecane), can form stable complexes with various radiometals relevant for PET ($^{68}$Ga, $^{64}$Cu) or SPECT ($^{111}$In) imaging or $\beta$ therapy ($^{90}$Y, $^{177}$Lu, $^{67}$Cu, $^{161}$Tb).

### Table 1

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Half-life</th>
<th>Production</th>
<th>Positron-branching</th>
<th>Mean/max $\beta^+$ energy (MeV) (63)</th>
<th>Positron range in water (mm) (Rms/Rmax) (63)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}$F</td>
<td>109.8 min</td>
<td>Cyclotron</td>
<td>96.7%</td>
<td>0.250/0.64</td>
<td>0.2/2.3</td>
</tr>
<tr>
<td>$^{68}$Ga</td>
<td>67.6 min</td>
<td>$^{68}$Ge/$^{68}$Ga generator</td>
<td>89.1%</td>
<td>0.836/1.9</td>
<td>1.2/9.0</td>
</tr>
<tr>
<td>$^{64}$Cu</td>
<td>12.7 h</td>
<td>Cyclotron</td>
<td>17.4%</td>
<td>0.278/0.58</td>
<td>0.2/2.0</td>
</tr>
</tbody>
</table>

Rms/Rmax = root-mean square positron range/maximum extrapolated range.
and showed high focal uptake in 3 of 4 patients (Fig. 5). The fourth patient had less than 5% tumor cells, resulting in modest focal uptake (54). GRPR imaging showed high physiologic uptake in the pancreas (Fig. 5).

Radiolabeled Neurotensin Analogs

The first generation of radiolabeled analogs was somewhat disappointing. Buchegger et al. used 99mTc-NT-XI in 4 patients with ductal pancreatic adenocarcinomas: only a single patient had tumor uptake (this tumor showed high expression of NT receptors in vitro (55). Nontumoral uptake was high in several organs.

Recently, better stabilized analogs aiming for NTSR 1 have been synthesized, such as 99mTc-NT-XIX (99mTc-(NH3)Ac-Arg-(N-CH3)-Arg-Pro-Dmt-Tle-Leu), [188Re]-NT-XIX, [111In]-DOTA-NT-20.4 ([111In-Ac-Lys(DOTA)-Pro-Arg-Me-Arg-Pro-Tyr-Tle-Leu-OH), 68Ga-DOTA-NT-20.3 (68Ga-Ac-Lys(DOTA)-Pro-Arg-Me-Arg-Pro-Tyr-Tle-Leu-OH), 177Lu-NT127 (177Lu-NLys-Lys-Pro-Tyr-Tle-Leu), and [18F]-DEG-NS-NT (18F-(2-(2-fluoroethoxy)ethoxy)ethylsulfonyl) ethene-neurotensin) (56–59). Figure 6 shows PET imaging with [18F]-DEG-VS-NT in mice bearing NTSR 1-positive tumor xenografts. These encouraging results pave the way for clinical trials.

Radiolabeled NPY Analogs

Y1 receptor ligands with high affinity were recently developed, and a proof of concept was provided by the use of 99mTc(CO)3-NaHis-Ac-[Phe7,Pro34]-NPY in women with breast cancer (60).

Multiple Targeting

Because various neuropeptide receptors can be overexpressed in some tumors, multitargeting can be a way to enhance targeting and counteract heterogeneity of expression within tumors. Heterodimeric ligands were developed for dual targeting of GRPR and NPY receptors in breast cancer (61). Arg-Gly-Asp-bombesin hybrid peptides were also developed for dual targeting of GRPR and integrin αvβ3-aiming receptors on tumor cells and vasculature (62). We think that it would also be helpful to consider dual targeting of GRPR and NTSR1 in prostate cancer. A heterodimeric peptide may capture the whole spectrum of the disease (androgen-dependent and castration-resistant prostate cancer).
CONCLUDING REMARKS

The overexpression of bombesin, neurotensin, or NPY receptors on tumors offers wide perspectives for new applications in imaging and peptide-targeted therapy in oncology.

Preliminary clinical results with the newly synthesized 68Ga- or 64Cu-radiolabeled bombesin analogs are promising, and we are witnessing a rapidly growing interest in GRPR targeting in prostate cancer and other GRPR-expressing tumors.

Substantial efforts have recently led to the synthesis of excellent neurotensin analogs. There is no doubt that the impact will be great, given the accumulating evidence on the role of NTSR1 in breast cancer, prostate cancer, lung cancer, pancreatic adenocarcinoma, and many other tumors. The new radiolabeled NPY analogs are also promising.

In the coming years, the important challenges for successful clinical application will be to better define, within specific subtypes of tumors, which neuropeptide receptors are overexpressed and at which stage of carcinogenesis and cancer progression they are overexpressed. In this context, new classifications based on immunohistochemistry and molecular analysis must be integrated into the rational development of new neuropeptide analogs.

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