Glucagon-like peptide-1 receptor overexpression in cancer and its impact on clinical applications

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INTRODUCTION

G protein-coupled peptide hormone receptors play an increasing role as tumor targets in cancer medicine (Reubi, 2003). The underlying molecular basis is primarily an overexpression of a specific peptide receptor on tumor cells, irrespective of receptor functions. This overexpression allows a receptor-targeted scintigraphic imaging and radiotherapy of tumors with adequate radiolabeled peptide analogs (Reubi, 2003). Somatostatin receptors were the first receptors identified for these purposes (Reubi, 2003). Historically, the somatostatin peptide analogs high overexpress GLP-1 receptors (GLP-1R). Targeting GLP-1R with the stable GLP-1 analogs 111In-DOTA/DPTA-exendin-4 offers a new approach to successfully localize these small tumors. This non-invasive technique has the potential to replace the invasive localization of insulinomas by selective arterial stimulation and venous sampling. Malignant insulinomas, in contrast to their benign counterparts, express GLP-1R in only one-third of the cases, while they more often express the somatostatin type 2 receptors. Importantly, one of the two receptors appears to be always expressed in malignant insulinomas. The GLP-1R overexpression in selected cancers is worth to be kept in mind with regard to the increasing use of GLP-1 analogs for diabetes therapy. While the functional role of GLP-1R in neoplasia is not known yet, it may be safe to monitor patients undergoing GLP-1 therapy carefully.

Keywords: glucagon-like peptide-1, glucagon-like peptide-1 receptor, insulinoma, 111In-DOTA/DPTA-exendin-4
targeting of tumors is a high receptor expression in tumors, but a low receptor expression in normal background tissues. Further activities included the development of adequate radiolabeled GLP-1 analogs, testing of such analogs in in vivo animal models and application of selected suitable candidate analogs to tumor patients in preliminary clinical studies. This review summarizes the knowledge on the in vitro and in vivo basis of GLP-1 receptor targeting of tumors accumulated in the last decade.

**GLP-1R in Tumors**

The GLP-1R expression has been systematically assessed in a broad spectrum of original human tumor tissues using in vitro receptor autoradiography (Reubi and Wasers, 2003; Körner et al., 2007). The GLP-1R was thus identified in specific and application of selected suitable candidate analogs to tumor activities included the development of adequate radiolabeled GLP-1 analogs, testing of such analogs in animal models, and with suitable candidate analogs to tumor receptors. Consequently, OctreoScan® is not a reliable tool to detect these tumors (Plückinger et al., 2004). Third, the exact intraoperative localization of insulinsomas is critical in order to minimize the surgical intervention (Rostambeigi and Thompson, 2009). This is, however, difficult due to the small size of benign insulinsomas (usually 10–20 mm). Conventional radiological procedures (endosonography, MR-, and CT-imaging) are not always

| Tumor type                      | GLP-1R incidence | GLP-1R density* |
|---------------------------------|------------------|-----------------|
| **Endocrine tumors**            |                  |                 |
| Benign insulinomas              | 25/27 (93%)      | 8,133           |
| Malignant insulinomas           | 4/1 (6%)         | 8,508           |
| Gastrinomas                     | 10/10 (100%)     | 2,461           |
| Glucagonomas                    | 2/4 (50%)        | 910             |
| VIPomas                         | 1/4 (25%)        | 3,028           |
| Ileal carcinoids                | 8/27 (30%)       | 1,027           |
| Bronchial carcinoid tumors      | 11/29 (38%)      | 2,456           |
| Pheochromocytomas               | 12/20 (60%)      | 3,970           |
| Paragangliomas                  | 5/18 (28%)       | 1,353           |
| Medullary thyroid carcinomas     | 5/18 (28%)       | 1,326           |
| **Embryonal tumors**            |                  |                 |
| Medulloloblastomas              | 3/12 (25%)       | 1,246           |
| Nephroblastomas                 | 2/9 (22%)        | 421             |
| Neuroblastomas                  | 2/16 (13%)       | 932             |
| **Brain tumors**                |                  |                 |
| Meningiomas                     | 7/20 (35%)       | 989             |
| Astrocytomas                    | 4/16 (25%)       | 1,069           |
| Glioblastomas                   | 2/21 (9%)        | 790             |
| Ependymomas                     | 1/6 (16%)        | 1,075           |
| **Carcinomas**                  |                  |                 |
| Ovarian adenocarcinomas         | 2/12 (16%)       | 688             |
| Prostate adenocarcinomas         | 1/20 (5%)        | 1,283           |

*Mean value of two tumors tested with in vitro GLP-1R autoradiography.

In contrast to most other gastroenteropancreatic neuroendocrine tumors, show relatively low expression levels of somatostatin receptors. Consequently, OctreoScan® is not a reliable tool to detect these tumors (Plückinger et al., 2004). Third, the exact intraoperative localization of insulinsomas is critical in order to minimize the surgical intervention (Rostambeigi and Thompson, 2009). This is, however, difficult due to the small size of benign insulinsomas (usually 10–20 mm). Conventional radiological procedures (endosonography, MR-, and CT-imaging) are not always
FIGURE 1 | Hormone and receptor determinations in vitro in a benign insulinoma. (A) Immunohistochemistry for insulin showing strongly labeled tumor cells. Bar = 0.01 mm. (B–D) In vitro GLP-1R autoradiography on consecutive insulinoma tissue sections. (B) Hematoxylin & eosin (H&E) staining showing the tumor tissue. Bar = 1 mm. (C) Autoradiogram showing total binding of 125I-GLP-1(7-36)amide. The entire tumor is strongly positive. (D) Autoradiogram showing non-specific binding of 125I-GLP-1(7-36) amide in the presence of 100 nM cold GLP1(7-36) amide. Reprinted from Christ et al. (2010), with permission from Elsevier.

successful in localizing insulinomas (Chatziioannou et al., 2001). Moreover, [18F]FDOPA PET shows at present controversial results, with sensitivities ranging between 17 and 90% (Kauhanen et al., 2007; Tessonnier et al., 2010). Although selective arterial stimulation and venous sampling is a reliable intraoperative tool to detect insulinomas in experienced institutions (Wiesli et al., 2004), it is an invasive procedure with the associated risks. Moreover, this procedure identifies only the region of the pancreas – depending on the vasculature – where the insulinoma should be located and not the tumor itself (Wiesli et al., 2004).

GLP-1R IN NON-NEOPLASTIC TISSUES

The GLP-1R expression was similarly characterized in human normal tissues. It has been found in the pancreatic islets and acini, stomach, duodenal Brunner’s gland, small and large intestinal myenteric plexus, lung and kidney vasculature, breast parenchyma, heart, brainstem, hypothalamus, neurohypophysis, and meninges (Wei and Mojsov, 1995; Körner et al., 2007). In vitro receptor autoradiography revealed that GLP-1R levels were highest in the neurohypophysis, followed by Brunner’s glands, meninges, and pancreatic islets (Körner et al., 2007). Of practical importance, with the exception of Brunner’s glands, the different tissues in the pancreatic area (i.e., pancreas islets and acini, intestines, and kidney) exhibit far lower GLP-1R density levels than insulinomas. This results in a high tumor-to-background ratio in GLP-1R density levels for insulinomas, which is an important prerequisite for a GLP-1R-targeted scintigraphic imaging of insulinomas. Prominent species differences in the physiological GLP-1R expression between humans and rodents are noteworthy. Indeed, autoradiography experiments indicate that GLP-1R density levels are considerably higher in the lungs of rats and mice than of humans (Körner et al., 2007). This has to be considered when interpreting results of in vivo testing of GLP-1R targeting in rodent models. Likewise, the GLP-1R expression in the thyroid gland is substantial in rodents, but virtually absent in humans (Körner et al., 2007). In rodent thyroids, GLP-1Rs are located in the medullary C-cells. Of interest, treatment with GLP-1 analogs in rats is known to occasionally lead to thyroid C-cell hyperplasia and medullary thyroid carcinoma, whereas in humans there is so far no evidence of such complications. It can be speculated whether the species differences in the GLP-1R density expression in the precursor cells of these tumors, the medullary C-cells, contribute to these controversial findings (Waser et al., 2011).

RADIOLABELLED GLP-1 ANALOGS

In general, radioactively labeled peptide analogs represent pharmaceuticals with favorable characteristics. Due to their small size, they show fast diffusion and rapid blood clearance and lack
radiopeptides have not yet been tested in insulinoma patients. However, since peptides are physiologically degraded within minutes in the human blood by potent peptidases such as dipeptidyl-peptidase-4 (DPP-4; Baggio and Drucker, 2007), stable peptide analogs have to be used instead in clinical applications. As for GLP-1, a naturally occurring stable analog exists, namely exendin-4, which is a component of the Gila monster venom. It shares 53% homology with GLP-1 and similarly binds to GLP-1Rs, but is resistant to DPP-4 cleavage (Nauck, 2009). Exendin-4 is, therefore, a good candidate for the development of radiolabeled GLP-1R ligands.

The first radiopeptides tested in vivo GLP-1R targeting were 125I-labeled GLP-1 and the 1-analog exendin-3 (Gotthardt et al., 2002). However, the low peptide stability of GLP-1 and the low efficiency of radio-iodination of exendin-3 limited their clinical use. Further testing resulted in the development of 111In-labeled exendin-4 (Wild et al., 2006): exendin-4 was coupled via the Lys side chain to a chelator (DOTA, diethylenetriaminepentaacetic acid) using a spacer (Abs, aminohexanoic acid) and then labeled with 111In. This radiopptide was subsequently extensively tested in vitro and in vivo in insulinoma models and applied to insulinoma patients (see below). Lately, several studies have been published that describe GLP-1R ligands suitable for PET/CT imaging, such as 68Ga, 124I, or 18F-labeled exendin-4, or for SPECT/CT imaging like 99mTc-labeled exendin-4 (Brom et al., 2008; Wild et al., 2010; Wu et al., 2011; Kiesewetter et al., 2012). These novel radiopptides have not yet been tested in insulinoma patients.

GLP-1R TARGETING IN ANIMAL MODELS

Initially, GLP-1R targeting was performed in the rat insulinoma cell line RINm5F and in a rat insulinoma animal model (NEOH rats) using 125I-labeled GLP-1 and exendin-3 (Gotthardt et al., 2002). Specific uptake was detected in the cell and animal models. This provided the proof of principle for GLP-1R targeting of insulinoma (Gotthardt et al., 2002).

Follow-up experiments were carried out in the Rip1tag2 mouse model with 111In-DTPA-exendin-4. These transgenic mice develop tumors of the pancreatic β-cells in a reproducible multi-stage fashion (Hanahan, 1985) and, therefore, represent an ideal model to study GLP-1R targeting in vivo and in vitro. Using GLP-1R multiprobe SPECT/MRI and SPECT/CT, in vivo GLP-1R imaging was performed in these animals following administration of 111In-DTPA-exendin-4 (Wild et al., 2006). In parallel, GLP-1R autoradiography of the tumors was carried out in vitro. Finally, biodistribution and pharmacokinetics as well as internalization and cellular retention of 111In-DTPA-exendin-4 were measured in vivo (Wild et al., 2006).

This preclinical study showed the following main findings:

First, the GLP-1R density in the tumors was extremely high, resulting in a remarkably high uptake of 111In-DTPA-exendin-4 (287 ± 62% IA/g tissue) already 4 h after injection. Second, excellent visualization of tumors as small as 1 mm by pinhole SPECT/MRI and SPECT/CT was demonstrated. Third, the tumor-to-background ratio was very high (between 13.6 and 299), substantiating the high potential of this radiopptide to specifically localize GLP-1R positive lesions within the pancreas. Lastly, in vitro studies in the cells derived from the tumor model demonstrated a specific internalization of 111In-DTPA-exendin-4, and biochemical investigations confirmed the high metabolic stability of the radiopptide in the tumor cells as well as in the serum.

The same Rip1tag2 mouse model also provided preliminary data on GLP-1R-targeted therapy of insulinoma. Mice were injected with different doses of 111In-DTPA-exendin-4 (1.1, 5.6, and 28 MBq) and sacrificed 7 days after injection. Most impressively, a single injection lead to a reduction in tumor volume of up to 94% in a dose-dependent manner without significant acute organ toxicity. Histological examination revealed that the decrease in tumor mass was mainly due to an increase in tumor cell apoptosis and decreased proliferation (Wicki et al., 2007).

GLP-1R TARGETING IN HUMANS

The first patient who underwent GLP-1R scintigraphy suffered from severe endogenous hyperinsulinemic hypoglycemia with non-convulsive seizures. MRI, CT scan, and endosonography did not detect any suspicious lesion. However, GLP-1R scintigraphy revealed an increased extrahepatic uptake in the mesentery supplied by the anterior mesentery artery. Selective arterial stimulation and venous sampling correctly indicated the vascular territory, but since this patient had an ectopic insulinoma, the results of the invasive investigation without GLP-1R imaging would have been misleading for the surgical strategy (Wild et al., 2008).

In a proof of principle study, 111In-DOTA-exendin-4 was prospectively administered to a total of six patients (Christ et al., 2009). All of them presented with neuroglycopenic symptoms lasting for 4–26 months. Biochemical evaluation during a fasting test revealed endogenous hyperinsulinemic hypoglycemia in all patients.

Conventional imaging (CT or MRI) reliably detected the insulinoma in only two patients, whereas endosonography identified a possible lesion in four patients, in keeping with data in the literature (McAuley et al., 2005). In three patients, selective arterial stimulation and venous sampling was performed, with accurate localization in all (Christ et al., 2009). Remarkably, GLP1-R scintigraphy correctly detected the insulinoma in all six consecutive patients (Figure 2, Christ et al., 2009). Four patients underwent an enucleation of the insulinoma. In two patients, a Whipple procedure had to be performed due to the localization of the insulinoma. In all patients, a benign insulinoma was confirmed by histology. In vivo autoradiography studies showed GLP-1R densities in the range as previously described (between 2,800 to >10,000 dpm/mg tissue; Reubi and Wasser, 2003), but low levels of somatostatin receptor type 1 in 2 patients only (Christ et al., 2009). Importantly, within a time frame of 2–14 days after injection of 111In-DOTA-exendin-4, intraoperative utilization of a gamma probe was highly beneficial for the in situ localization of the insulinoma in all patients, resulting in a successful enucleation where possible (Christ et al., 2009).

Fortunately, background uptake over the whole body was low with the exceptions of the kidneys, which were strongly labeled due to renal excretion of the radioligand (Figure 2). In two
FIGURE 2 | 111In-DOTA-exendin-4 whole-body planar images (A–C) and 111In-DOTA-exendin-4 SPECT/CT images (D,E) from the same patient. Whole-body scans were carried out 20 min (A), 4 h (B), and 3 days (C), and SPECT/CT scans were performed 4 h (D) and 3 days (E) after injection of 57 MBq 111In-DOTA-exendin-4. Four hours after injection, there was already a focal 111In-DOTA-exendin-4 uptake visible in the head of the pancreas (arrow on whole-body (B) and SPECT/CT (D) scan. The tumor-to-pancreas-uptake ratio was 1.9 at 4 h after injection (D) and 3.2 at 3 days after injection of the radioligand. The longest residence times of 111In-DOTA-exendin-4 were observed in the tumor (arrow) and kidneys (E). Reproduced from Christ et al. (2009), with permission from The Endocrine Society.

Conventional imaging (MRI, CT, endosonography) was positive in 17 patients. 111In-DTPA-DOTA-exendin-4 SPECT/CT detected 23 true positive benign insulinomas and five additional positive lesions (one malignant insulinoma; two islet cell hyperplasias; two uncharacterized lesions). True negative tests were detected in two patients (one malignant insulinoma; one islet cell hyperplasia). Malignant insulinomas were diagnosed based on the histological finding of a positive lymph node, not detected on conventional imaging preoperatively. There was no false negative result. Sensitivity was 100% and the positive predictive value was 82% (Christ et al., 2012). These findings are encouraging and suggest that in vivo GLP-1R imaging defines a new non-invasive diagnostic approach to successfully localize small benign insulinomas.

About 90% of insulinomas are benign and only 10% of patients present with malignant disease usually characterized by liver metastasis (Plockinger et al., 2004). Anecdotal evidence suggests that malignant insulinomas exhibit more often somatostatin receptor type 2 than benign ones and can, therefore, be visualized by OctreoScan® (Plockinger et al., 2004). A more extensive study with data from 10 patients with malignant insulinoma showed that somatostatin receptor type 2 were expressed in seven patients, whereas GLP-1R were present in four patients, and both receptors in only one patient (Wild et al., 2011). Importantly, one of the two imaging methods appears always to be positive in a malignant type of insulinoma (Wild et al., 2011). The consequences of the respective receptor expression in an insulinoma with regard to biological behavior (malignant or benign course) remains to be established.
SIDE EFFECTS AND LIMITATIONS
In humans, the injection of 111In-DOTA-exendin-4 and 111In-DPTA-exendin-4 was well tolerated. Due to the small amount of exendin-4, the decrease in plasma glucose concentrations was only 1.4 ± 0.7 mmol/L after 40 min (Christ et al., 2009). By regularly monitoring glucose levels, no severe hypoglycemic episode occurred. One patient experienced a short episode of vomiting only with 111In-DOTA-exendin-4. Otherwise, no further side effects were observed (Christ et al., 2009).

In two patients, there was focal 111In-DOTA-exendin-4 uptake in the proximal duodenum. This may be related to the presence of Brunner’s glands of the duodenum which, as previously mentioned, are known to contain GLP-1Rs in a significant density (Korner et al., 2007), as observed in particular in patients with chronic pancreatitis (Stolte et al., 1981). Such hyperplastic glands may possibly be detected by GLP-1R imaging.

A differential diagnosis of endogenous hyperinsulinemic hypoglycemia includes nesidioblastosis, also known as “non-insulinoma pancreatogenous hypoglycemia syndrome” in a clinical setting (Thompson et al., 2000). Histopathologically, this entity is defined as a diffuse hyperplasia of β-cells occurring usually in children (Takovac et al., 1971). Recent evidence suggests that this pathology can also be demonstrated in adults, in particular after bypass surgery for morbid obesity (Service et al., 2009). In the previously mentioned series of patients (Christ et al., 2012), islet cell hyperplasia was diagnosed in three patients, two were positive on GLP-1R imaging and one was negative. Based on these preliminary data GLP-1R imaging does not appear to be an appropriate tool to diagnose or exclude islet cell hyperplasia. These findings are further supported by the recent evidence that the in vivo density of GLP-1R in pancreatic tissues of patients with nesidioblastosis after bypass surgery for morbid obesity is much lower than in benign insulinomas (Reubi et al., 2010).

Recently, 18F-DOPA-PET has successfully been used to detect nesidioblastosis and benign insulinoma (Kauhanen et al., 2007). Although, 18F-DOPA-PET may be helpful to diagnose nesidioblastosis, in benign insulinomas the tumor-to-background ratios are higher for 111In-DOTA-exendin-4 SPECT than for 18F-DOPA-PET (3.3 vs. 1.4), suggesting an increased sensitivity of targeting GLP-1Rs (Kauhanen et al., 2007; Christ et al., 2009) in benign insulinomas.

SUMMARY AND CONCLUSION
Because of the massive GLP-1R overexpression in selected gastrointestinal tumors, GLP-1 and GLP-1R play an increasing role in endocrine gastrointestinal tumor management. Targeting GLP-1R with 111In-DOTA-exendin-4 or 111In-DPTA-exendin-4 offers a new approach that permits the successful localization of small benign insulinomas pre- and intraoperatively. Since virtually all benign insulinomas express GLP-1Rs and the preliminary clinical data are very encouraging, it is likely that this approach will affect the algorithm of pre- and intraoperative localization of suspected insulinomas.

In contrast to benign insulinomas, where the exact localization of the tumor is the main goal, the clinical challenge in malignant, metastasizing insulinomas is to define the extension of the disease and—if possible—an offer to targeted therapy (peptide receptor radionuclide therapy, PRRT). Contrary to benign insulinomas, malignant insulinomas more often express somatostatin receptors than GLP-1R. Importantly, one of the two receptors seems to be always positive. With regard to the increasing and successful use of GLP-1 analogs for diabetes therapy, it is worth keeping in mind that selected cancers can overexpress GLP-1R. While the functional role of these receptors in these tumors is not known yet, it may be safe to monitor patients with such tumors carefully during their GLP-1-analog-based diabetes therapy.

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