CLINICAL STUDY

Immunohistochemical identification of the PTHR1 parathyroid hormone receptor in normal and neoplastic human tissues

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Abstract

Background: Parathyroid hormone (PTH) is a crucial regulator of calcium homoeostasis in humans. Although it is well known that PTH acts primarily on kidney and bone, the precise cellular and subcellular sites of PTH action have not been visualised in human tissues.

Method: We developed and characterised a novel anti-peptide antibody to the carboxy-terminal region of the human PTH receptor type 1 (PTHR1). Specificity of the antiserum was demonstrated by i) detection of a broad band migrating at $M_r$ 85 000–95 000 in western blots of membranes from human kidney and PTHR1-transfected cells; ii) cell surface staining of PTHR1-transfected cells; iii) translocation of PTHR1 receptor immunostaining after agonist exposure; and iv) abolition of tissue immunostaining by preadsorption of the antibody with its immunising peptide. The distribution of PTHR1 receptors was investigated in 320 human tumours and their tissues of origin.

Results: In the kidney, PTHR1 receptors were predominantly detected at the basolateral plasma membrane of epithelial cells in the proximal and distal tubules but not in the thin limbs of Henle, collecting ducts or glomeruli. In bone, PTHR1 receptors were detected as discrete plasma membrane staining of osteocytes and osteoblasts, whereas osteoclasts remained unstained. In addition, PTHR1 was found in the gut and in a number of neoplastic tissues including colorectal carcinoma, prostate cancer, renal cell carcinoma and osteosarcoma.

Conclusion: This is the first localisation of PTHR1 receptors in human tissues at the cellular level. The overexpression of PTHR1 receptors may provide a molecular basis for efficient targeting of human tumours with radiolabelled PTH analogues.

Introduction

Parathyroid hormone (PTH) is an 84-amino acid peptide that is involved in the control of calcium homoeostasis in mammals (1). PTH is almost exclusively synthesised in the parathyroid gland, but to some extent also in the thymus and hypothalamus. Synthesis and secretion of PTH are reciprocally regulated by the extracellular calcium concentration, which is monitored by the calcium-sensing receptor in the parathyroid gland. PTH acts primarily on the kidney and bone, mediating its effects by binding to PTH receptor type 1 (PTHR1). In the kidney, PTH stimulates the reabsorption of calcium in the distal convoluted tubule. It also leads to an enhancement of 1α-hydroxylase activity in the kidney, thus causing an increase in calcium absorption from the intestine via an elevation of 1,25-dihydroxycholecalciferol. In bone, PTH induces calcium release by acting indirectly on osteoclasts. The direct stimulatory effect on osteoblasts leads to an increase in bone mass. In addition to calcium homoeostasis, PTH also regulates blood phosphate concentration by the inhibition of the tubular phosphate reabsorption in the kidney (1, 2).

PTH-related peptide (PTHrP) was originally discovered as a tumour product causing hypercalcaemia. In addition, there is compelling evidence from both in vitro and in vivo observations that PTHrP promotes tumour cell growth, aggressiveness and metastasis (3–13). However, PTHrP is not only produced in tumours but also in a wide variety of non-malignant tissues, where it can act in an endocrine, paracrine or autocrine manner. In the foetus, PTHrP is present in many tissues such as skin, mammary glands, lung, gut, bone and teeth, and is thought to regulate cell proliferation and differentiation during organogenesis (4, 14–18). PTHrP exhibits N-terminal homology with PTH. PTH and
PThRp bind with equal affinity and efficacy to PTHR1 (19), and their effects on calcium and phosphate homeostasis are largely indistinguishable. In fact, the amino-terminal 34 amino acids of both PTH and PThRp are sufficient for the activation of the PTHR1 receptor.

In addition to PTHR1, a second G protein-coupled PTH receptor, PTHR2, has been identified (20). The PTHR2 receptor responds to PTH, but does not interact with PThRp. PTHR2 is expressed only in a few tissues, e.g. brain, pancreas, kidney and testis, and its physiological function is still unknown (1). In contrast, PTHR1 has been found in the classical target tissues of PTH action including kidney and bone. In parallel to the occurrence of PThRp, PTHR1 also seems to be present in other non-malignant and malignant tissues and is thought to mediate PThRp-dependent effects on cell proliferation and differentiation. Most previous studies have detected the PTHR1 receptor on the mRNA level or via ligand-binding assays (7–9, 21–24). Consequently, only limited information is currently available concerning the cellular and subcellular localisation of the PTHR1 receptor in human tissues. These reports comprise investigations on giant cell tumours (25), chondrosarcoma (8), ameloblastoma (26), medulloblastoma (27), prostate cancer (13), breast cancer (28, 29) and gastric cancer (30). To the best of our knowledge there are currently no more extensive studies involving other human tumour species and investigating different types of tumours in parallel.

Thus, the aim of the present study was to evaluate the prevalence and cellular localisation of PTHR1 in a total of 320 samples from 18 different human tumour entities by means of immunohistochemistry. For this purpose, we have generated and characterised a novel antibody directed to the carboxy-terminal sequence of the PTHR1 receptor. We have also developed an immunohistochemical protocol that allows an efficient detection of this receptor in formalin-fixed, paraffin-embedded human tissues.

Materials and methods

Tissue specimens

A total of 320 tumour specimens were obtained from the Departments of Pathology of the Otto-von-Guericke University, Magdeburg and the Charité, Berlin, Germany. All tissue specimens had been fixed in formalin and embedded in paraffin. The following tumour species were investigated: renal cell carcinoma (n = 44, classified as clear cell carcinoma (n = 25), papillary type (n = 12) or chromophobic type (n = 7)), osteosarcoma (n = 4), gastric adenocarcinoma (n = 12), colorectal adenocarcinoma (n = 11), ductal pancreatic adenocarcinoma (n = 18), breast carcinoma (n = 41), ovarian carcinoma (n = 44), adenocarcinoma of the corpus uteri (n = 4), squamous cell carcinoma of the cervix uteri (n = 13), endometriosis (n = 6), prostate adenocarcinoma (n = 16), carcinoïd (n = 15), pancreatic insulinoma (n = 4), pituitary adenoma (n = 20), pheochromocytoma (n = 22), glioblastoma (n = 23), astrocytoma (n = 15) and melanoma (n = 8). Several of the tumour specimens contained adjacent normal tissue, which was also analysed. In addition, fresh samples from kidney tissue and from different parts of the gut were obtained from the Department of Urology, Friedrich-Schiller-University, Jena, Germany and from the Department of Pathology, Ernst-Moritz-Arndt-University, Greifswald, Germany respectively. Samples were immediately frozen in liquid nitrogen and were stored at −80 °C until western blot analysis.

Generation and purification of the PTHR1 antibody

Polyclonal antisera were generated against the carboxy-terminal tail of the human PTHR1 receptor. The identity of the peptide used for the immunisation of the rabbits was EEASGPERPPALLQEEWETVM. The peptide was custom synthesised by Gramsch Laboratories (Schwabhausen, Germany), purified by HPLC and coupled to keyhole limpet haemocyanin as described previously (31, 32). The conjugate was mixed 1:1 with Freund’s adjuvant and injected into three rabbits (1781–1783) for PTHR1 antisera production. Animals were injected at 4-week intervals, and serum was obtained 2 weeks after immunisations beginning with the second injection. The specificity of the antisera was initially tested using immuno-dot blot analysis as described (31, 32). For subsequent analysis, antibodies were affinity purified against their immunising peptide using the Pierce SulfoLink Immobilization Kit for Peptides (Thermo Scientific, Rockford, IL, USA) according to the instructions of the manufacturer. In initial dot blot analyses and preliminary immunohistochemical investigations, the antiserum (1781) displayed high affinity along with strong and specific immunostaining. This antiserum was therefore used throughout the study.

Immunocytochemistry

Chinese hamster ovary (CHO) cells were stably transfected with a plasmid encoding for the human hemagglutinin (HA)-tagged PTHR1 receptor (HA-PTHR1) (33). Cells were grown on coverslips overnight either with or without subsequent 30-min exposure to human PTH (1–34) (Bachem, Weil am Rhein, Germany). Cells were then fixed and incubated with 1 μg/ml anti-PTHR1 (1781) antibody or 1 μg/ml anti-HA (HA.11) antibody (Covance, Princeton, NJ, USA) followed by Cy2-conjugated secondary antibodies (Dianova, Hamburg, Germany). Specimens were mounted as described previously and examined using a Leica TCS SP5 laser scanning confocal microscope (Leica, Wetzlar, Germany) (31).
**Western blot analysis**

Lysates were prepared from stably transfected CHO cells as well as from fresh human kidney or gut tissue as described (31). Samples were then subjected to 8% SDS-PAGE and immunoblotted onto nitrocellulose. Blots were incubated with 0.1 μg/ml anti-PTHR1 (1781) antibody or 1 μg/ml anti-HA (HA.11) antibody followed by a peroxidase-conjugated secondary antibody incubation and ECL detection (Amersham). For adsorption controls, the antiserum was preincubated with 10 μg/ml of the peptide used for immunisation of the rabbits for 2 h at room temperature.

**Immunohistochemistry**

Five-micrometer sections were prepared from the paraffin blocks and floated onto positively charged slides. Immunostaining was performed by an indirect peroxidase labelling method as described previously (34). Briefly, sections were dewaxed, microwaved in 10 mM citric acid (pH 6.0) for 16 min at 600 W and then incubated with 0.1 μg/ml anti-PTHR1 (1781) antibody overnight at 4°C. Detection of the primary antibody was performed using a biotinylated anti-rabbit IgG followed by an incubation with peroxidase-conjugated streptavidin (BioGenex, San Ramon, CA, USA). Sections were developed by incubation in 3-amino-9-ethylcarbazole (AEC) in acetate buffer (BioGenex). The sections were then rinsed, counterstained with Mayer’s haematoxylin and mounted in glycerol. For immunohistochemical controls, the primary antibody was either omitted, replaced by preimmune serum or adsorbed for 2 h at room temperature with 10 μg/ml of the peptide used for immunisations. To assign the immunostaining to the different tubular segments of the kidneys, additional double-labelling experiments were performed. For this purpose, kidney sections were incubated overnight at 4°C with 0.1 μg/ml anti-PTHR1 (1781) antibody together with one of the following antibodies: polyclonal goat anti-human thiazide-sensitive sodium/chloride cotransporter (NCC; Santa Cruz Biotechnology, Santa Cruz, CA, USA; dilution: 1:500) as a marker for initial distal convoluted tubules (35); monoclonal mouse anti-human sodium/calcium exchanger 1 (NCX1; Acris Antibodies GmbH, Hiddenhausen, Germany; dilution: 1:1000) for distal convoluted tubules and connecting ducts (35); monoclonal mouse anti-human Tamm–Horsfall protein (THP; Biozol, Eching, Germany; dilution: 1:1000) for thick ascending limbs of loops of Henle (distal straight tubules) (36); monoclonal mouse anti-human aquaporin 1 (AQP1; clone 1/A5F6; AbD Serotec, Morphosys UK Ltd, Oxford, UK; dilution: 1:500) for proximal tubules and the thin descending limbs of loops of Henle (37). Detection of the anti-PTH1R (1781) antibody was performed using an Alexa Fluor 488-coupled anti-rabbit IgG (Invitrogen), and the other antibodies were visualised using Cy3-conjugated secondary anti-goat or anti-mouse antibodies (Dianova) respectively. Specimens were mounted and examined using a Leica TCS SP5 laser scanning confocal microscope.

**Evaluation of the staining patterns**

Two independent investigators evaluated all immunohistochemical stainings. The presence or absence of staining and the intensity of the colour were noted as well as the number of cells showing a positive staining and whether or not the immunoreactivity was localised to the plasma membrane. Tumours were only categorised as positive if the majority of tumour cells displayed a moderate to strong staining of the plasma membrane and/or the cytoplasm.

**Results**

**Characterisation of the PTHR1 antibody**

The specificity of the PTHR1 (1781) antiserum was monitored using western blot analysis. When membrane preparations from CHO cells stably transfected with HA-PTHR1 were electrophoretically separated and blotted onto nitrocellulose, the anti-HA antibody as well as the anti-PTHR1 (1781) antiserum revealed a broad band migrating at Mr 85 000–95 000. In contrast, no respective band was detected with either antiserum in membrane preparations from non-transfected wild-type CHO cells (Fig. 1A). The antiserum was also tested for possible cross-reactivity with other proteins present in human tissues. When membrane preparations from normal kidney tissue were electrophoretically separated and blotted onto nitrocellulose, the anti-PTHR1 (1781) antiserum detected a broad band migrating at Mr 85 000–95 000 (Fig. 1B). This immunoreactive band was completely abolished by preadsorption of the antiserum with 10 μg/ml of the immunising peptide (Fig. 1B). The evaluation of a series of tissue specimens of the gut revealed a similar immunoreactive band in the colon but not in the duodenum or ileum (data not shown). In addition to western blot analysis, the antiserum was characterised by immunocytochemical staining of transfected cells. When CHO cells stably expressing HA-PTHR1 were stained either with anti-HA (HA.11) or anti-PTHR1 (1781) antiserum, a distinct immunofluorescence localised at the level of the plasma membrane was detected (Fig. 1C). After incubation with human PTH (1–34), the HA immunoreactivity as well as the PTHR1 immunoreactivity was translocated from the plasma membrane into the cytosol, indicating that the receptors underwent rapid agonist-dependent endocytosis (Fig. 1C).
Immunohistochemical localisation of PTHR1 in human tumours and in their tissues of origin

The anti-PTHR1 antibody was employed for immunohistochemical staining of a variety of human tumours. Many of the tumour specimens contained adjacent non-malignant tissue, which enabled us to analyse the distribution of PTHR1 in normal tissues as well. A set of positively stained tissues was also incubated with antibodies preadsorbed with the immunising peptide, which in each case led to a complete abolition of immunostaining (Fig. 2B, insert in Fig. 2I).

A distinct immunoreactivity for PTHR1 was observed in normal kidney tissue (Fig. 2A, D, E and F). PTHR1 was present in the epithelial cells of the proximal and distal tubules, whereas the thin limbs of Henle and the collecting ducts were negative. Immunostaining was also not seen in the glomeruli with the only exception of the Goormaghtigh’s cells of the juxtaglomerular apparatus. In all tubular cells, the immunoreactivity was predominantly localised at the basolateral plasma membrane. The staining of the cytoplasm was much less intense. To exactly allocate the immunostaining for PTHR1 to the different tubular segments, additional double-labelling experiments were performed (Fig. 3). There was a complete colocalisation of PTHR1 and NCC in the initial distal convoluted tubules (Fig. 3A–C) and of PTHR1 and NCX1 in the late distal convoluted tubules and connecting ducts (Fig. 3D–F). In all cases, the glomeruli were completely devoid of staining. Both PTHR1 and THP were present in the thick ascending limbs of Henle, whereas the proximal tubules were stained positively for PTHR1 only. Neither PTHR1 nor THP was observed in collecting ducts (Fig. 3G–I). As expected, AQP1 was found in proximal tubules as well as in thin descending limbs of loops of Henle. A staining for PTHR1, however, was seen in proximal tubules only (Fig. 3J–L).

In bone, a discrete immunostaining of the plasma membrane of osteocytes as well as of osteoblasts was observed (Fig. 2G). In the duodenum, jejunum, ileum and colon ascendens, a distinct staining of isolated small groups of epithelial cells was noticed. These cells were exclusively found at the bottom of the crypts, and the immunoreactivity was clearly localised at the basolateral membrane (Fig. 2H). In the colon transversum, colon descendens, colon sigmoideum and rectum, the staining was not restricted to the bottom of the crypts, but was present in all epithelial cells. Again, the immunostaining was confined to the basolateral membrane of the cells (Fig. 2I). The acinar cells of the prostate gland were strongly positive for PTHR1 as well. Also in this case, the immunoreactivity was predominantly localised at the plasma membrane, but a slight to moderate staining was also seen in the cytoplasm. A slight to moderate staining of the cytosol was further noticed in cells of the sebaceous gland and cells of the epithelial hair sheath of normal skin as well as cell clusters within all three parts of the adrenal cortex. No immunostaining for PTHR1 was seen in the tumour-free tissue from stomach, mammary, ovary, cervix and corpus uteri or pituitary gland (not shown).
The prevalence of PTHR1 in tumours is summarised in Table 1. Expression of PTHR1 was observed in all cases of colorectal carcinoma, prostate adenocarcinoma and melanoma. Immunostaining for PTHR1 was frequently found in renal cell carcinoma (23%), especially the papillary type (42%), in ductal pancreatic adenocarcinoma (44%) and in osteosarcoma (50%). PTHR1 was also observed in some samples of corpus uteri carcinoma (25%), breast carcinoma (17%), ovarian carcinoma (14%), cervix uteri carcinoma (15%), pituitary adenoma (15%) and pheochromocytoma (9%). While the staining pattern was homogeneous in renal cell carcinoma and prostate adenocarcinoma, most other tumour samples exhibited a heterogeneous distribution of PTHR1 immunostaining. In renal cell carcinomas, colorectal carcinomas, pancreatic adenocarcinomas, prostate adenocarcinomas and carcinoids, the receptor was predominantly localised at the plasma membrane (Fig. 2C and J–L). In most other tumours, the PTHR1 immunoreactivity was mainly distributed throughout the cytosol (not shown).

Discussion

In an effort to visualise the cellular and subcellular sites of action of PTH and PTHrP in human tissues, we generated an antibody that exerts a selective specificity for human PTHR1 receptor. We showed that the carboxy-terminal tail of PTHR1 can serve as an epitope for the generation of an antiserum that effectively stains formalin-fixed, paraffin-embedded human tissues. There is evidence that the anti-PTHR1 (1781) antibody specifically detects its targeted receptor and does not crossreact. First, in western blot analyses of crude extracts from PTHR1-transfected cells, human kidney and distal human gut, the anti-PTHR1 antibody detected a broad band migrating at $M_r$ 85 000–95 000, which corresponds to the expected size of the glycosylated form of the receptor. Secondly, the immunoreactive band detected in membrane preparations from normal human kidney tissue and from samples of the distal normal human gut was completely abolished by preadsorption of the antibody with its
immunising peptide. Thirdly, the antibody revealed a distinct staining of the cell membrane of PTHR1-transfected cells. After agonist exposure, this immunostaining translocated from the cell surface to the cytosol, indicating a rapid endocytosis of the receptor. Fourthly, immunostaining of both malignant and non-malignant tissues was completely abolished by pre-adsorption of the antibody with its immunising peptide. Finally, all three novel PTHR1 antisera generated in the present study gave similar results.

As expected from the classical sites of PTH action, the most prominent immunostaining was detected in normal human kidney. We observed distinct PTHR1 immunoreactivity (as confirmed also by double-labelling experiments) at the plasma membranes of the epithelial cells of proximal tubules (where PTH causes an inhibition of tubular phosphate reabsorption) and distal tubules (thick ascending limbs of loops of Henle as well as initial and late distal convoluted tubules), where PTH stimulates the reabsorption of calcium. Other parts of the nephron, which are not responsive to PTH action (thin limbs of loops of Henle and collecting ducts), were devoid of staining. In addition, a distinct immunostaining was noticed in the Goormaghtigh’s cells of the juxtaglomerular apparatus. This finding may provide a plausible explanation for the observation that PTH can influence the glomerular ultrafiltration rate (38). Another classical site of action of PTH is bone. It is commonly thought that PTH exerts its anabolic effects on bone by suppressing osteoblast and osteocyte apoptosis and by increasing osteoblast proliferation (39). There is still some controversial discussion whether osteoclasts are targeted directly by PTH or indirectly via osteoblasts (40). The present investigation revealed a distinct immunostaining of the plasma membrane of osteocytes and osteoblasts in normal bone, whereas osteoclasts remained unstained. Similar observations have previously been made by means of in situ hybridisation (41). In the small intestine and in the colon ascendens, only isolated clusters of few epithelial cells in the bottom of the crypts were stained for PTHR1. The immunostaining was confined to the basolateral...
membrane of the cells. These cells may represent stem cells or Paneth cells. Interestingly, in other parts of the colon and rectum, the staining for PTHR1 was not only confined to cells in the bottom of the crypts, but was present in all epithelial cells indicating additional sites of PTH action in the gut. A distinct immunostaining was further seen in the epithelial cells of the prostate, where it also may be involved in processes such as cell proliferation and differentiation. Additionally, our antibody revealed a staining of some cell clusters within the adenral cortex supporting the observation that PTH administration can cause an increase in blood cortisol and aldosterone levels (42).

In parallel to the occurrence and expression of PTHrP in many malignant tissues, where it promotes tumour cell growth, aggressiveness and skeletal metastasis, the PTHR1 receptor also appears to occur in these tissues. In the present study, PTHR1 was observed in all tissue samples of colorectal carcinoma and prostate adenocarcinoma and in some cases of osteosarcoma, renal cell carcinoma, gastric cancer and breast carcinoma. Additionally, immunostaining for PTHR1 was detected in melanoma and in some cases of ductal pancreatic adenocarcinoma, corpus and cervix uteri carcinoma, ovarian carcinoma, pituitary adenoma and pheochromocytoma. In renal cell carcinomas, colorectal carcinomas, prostate adenocarcinomas and carcinoids, the receptor was mainly localised at the plasma membrane of the tumour cells, whereas in all other tumours immunoreactivity to PTHR1 was distributed throughout the cytosol. The biological significance of cytosolic PTHR1 expression in these tumours is as yet unknown.

In conclusion, we have generated and characterised a novel anti-PTHR1 antibody, which enabled us to visualise PTHR1 receptors in human formalin-fixed, paraffin-embedded tissues. PTHR1 was localised at the cellular level in some human tumours investigated in the present investigation and in their tissues of origin for the first time. Since the receptor was found in many tumour species, it may provide a valuable target for both diagnosis and therapy. Thus, immunohistochemical PTHR1 visualisation may be helpful to identify those tumours with sufficient receptor overexpression as a possible target for diagnostic and/or therapeutic intervention using radiolabelled PTH analogues.

### Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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