

International Union of Pharmacology. LVI. Ghrelin Receptor Nomenclature, Distribution, and Function

ANTHONY P. DAVENPORT, TOM I. BONNER,¹ STEVEN M. FOORD, ANTHONY J. HARMAR, RICHARD R. NEUBIG, JEAN-PHILIPPE PIN, MICHAEL SPEDDING, MASAYASU KOJIMA, AND KENJI KANGAWA

Clinical Pharmacology Unit, University of Cambridge, Cambridge, United Kingdom (A.P.D.); Laboratory of Genetics, National Institute of Mental Health, Bethesda, Maryland (T.I.B.); GlaxoSmithKline Research and Development, Stevenage, Hertfordshire, United Kingdom (S.M.F.); Division of Neuroscience and Centre for Neuroscience Research, University of Edinburgh, Edinburgh, United Kingdom (A.J.H.); Department of Pharmacology, University of Michigan, Ann Arbor, Michigan (R.R.N.); Centre National de la Recherche Scientifique, Montpellier, France (J.-P.P.); Institut de Recherches Internationales Servier (I.R.I.S.), Neuilly-sur-Seine, France (M.S.); and National Cardiovascular Center Research Institute, Suita, Osaka, Japan (M.K., K.K.)

Abstract	541
I. Introduction.....	542
II. Growth hormone secretagogue receptor 1a designated as the ghrelin receptor.....	542
III. Distribution of receptor and mRNA encoding the receptor.....	543
IV. Radiolabeled ligands	543
V. Agonists	544
VI. Antagonists	544
VII. Physiological role	544
VIII. Pathophysiological role	544
IX. Genetically modified animals	545
A. Ghrelin receptor.....	545
B. Peptide.....	545
Acknowledgments.....	545
References	545

Abstract—Ghrelin is a 28-amino acid peptide originally isolated from rat stomach and is cleaved from a 117-amino acid precursor. The sequence of the mature peptide from rats and mice differs by two amino acids from that of human ghrelin. Alternative splicing of the ghrelin gene transcript can result in the translation of a second biologically active peptide, des-Gln¹⁴-ghrelin. Both peptides have a unique post-translational modification, octanoylation of Ser³, which is essential for the binding to receptors in hypothalamus and pituitary and stimulating the release of growth hormone from the pituitary. The growth hormone secretagogue receptor (GHS-R1a, Swiss-Prot code Q92847, LocusLink ID 2693), a rhodopsin-like seven transmembrane spanning G pro-

tein-coupled receptors belonging to Family A, was cloned in 1996 from the pituitary and hypothalamus and shown to be the target of growth hormone secretagogues (GHS), a class of synthetic peptide and non-peptide compounds causing growth hormone release from the anterior pituitary. In 1999, ghrelin was identified as the endogenous cognate ligand for this receptor. The purpose of this review is to propose an official International Union of Pharmacology Committee on Receptor Nomenclature and Drug Classification (NC-IUPHAR) nomenclature designating GHS-R1a as the ghrelin receptor to follow the convention of naming receptors after the endogenous agonist, abbreviated where necessary to GRLN.

Address correspondence to: Dr. Anthony Davenport, NC-IUPHAR Emerging Pharmacology Group, Clinical Pharmacology Unit, University of Cambridge, Addenbrooke's Hospital, Cambridge, CB2 2QQ, U.K. E-mail: apd10@medschl.cam.ac.uk

¹ This article was written in a personal capacity and does not represent the opinions of the National Institutes of Health, Department of Health and Human Services, or the Federal Government.

Article, publication date, and citation information can be found at <http://pharmrev.aspetjournals.org>.

doi:10.1124/pr.57.4.1.

TABLE 1
Amino acid sequences of human, rat, and mouse ghrelin

Formatted Alignments

rat-mouse ghrelin
human ghrelin

10

G	S	S	F	L	S	P	E	H	Q	K	A
G	S	S	F	L	S	P	E	H	Q	R	V

20

Q	Q	R	K	E	S	K	K	P	P	A	K	L	Q	P	R
Q	Q	R	K	E	S	K	K	P	P	A	K	L	Q	P	R

I. Introduction

Growth hormone secretagogue receptor (GHS-R²), previously designated as an orphan receptor, was paired in 1999 with ghrelin, using Chinese hamster ovary cells expressing the rat *GHS-R* gene and proposed as the cognate endogenous ligand (Kojima et al., 1999). Ghrelin is a 28-amino acid peptide originally isolated from rat stomach and is cleaved from a 117-amino acid precursor. The human ghrelin cDNA encodes a prepropeptide with 83% sequence identity to rat preproghrelin. The sequence of the mature rat ghrelin peptide differs by two amino acids from that of the human sequence (Table 1; Kojima et al., 1999). Tomasetto et al. (2000) isolated a gene from mouse predicted to encode a 117-amino acid prepropeptide that is now thought to be homologous to rat and human ghrelin. The authors called the predicted mature sequence “motilin-related peptide”. However, the structure of this peptide modified by post-translational acylation (see below) could not be identified from the predicted amino acid sequence.

Alternative splicing of the ghrelin gene transcript can result in the translation of a second biologically active peptide, des-Gln¹⁴-ghrelin (Hosoda et al., 2000). Both peptides have a unique post-translational modification, octanoylation of Ser³, which is essential for the binding to receptors in hypothalamus and pituitary and stimulating the release of growth hormone from the pituitary. However, there is evidence that this modification may not be essential for some of the peripheral effects of ghrelin. For example, des-octanoyl ghrelin may have cardiovascular effects (Baldanzi et al., 2002). Antiproliferative actions of ghrelin and growth hormone secretagogues have been observed in breast carcinoma cells not expressing GHS-R mRNA (Cassoni et al., 2001). Ghrelin is thought to be predominantly secreted from X/A-like cells within the gastric mucosa (Kojima et al., 1999) and may be the source of the majority of circulating plasma ghrelin (Ariyasu et al., 2001), although minor sources of ghrelin-like immunoreactivity have been detected in neurones from human pituitary and hypothalamic nu-

clei (Korbonits et al., 2001), rat and human placenta (Gualillo et al., 2001), and islet cells in human neonatal pancreas (Wierup et al., 2002).

This review proposes an official nomenclature and briefly highlights the significance of ghrelin and its receptor. For more detailed information on function, see recent reviews including Kojima et al. (2001); Nagaya and Kangawa (2003a,b); Korbonits et al. (2004); and van der Lely et al. (2004). A curated catalog of all gene sequences encoding structures in the human genome similar to G protein-coupled receptors (excluding sensory receptors and pseudogenes) has been produced including orphan receptors recently paired with their cognate ligands (Foord et al., 2005).

II. Growth Hormone Secretagogue Receptor 1a Designated as the Ghrelin Receptor

Howard et al. (1996) cloned a G protein-coupled receptor of the pituitary and hypothalamus of humans and swine and showed it to be the target of growth hormone secretagogues, a class of peptide and nonpeptide compounds leading to growth hormone (GH) release from the anterior pituitary. Nucleotide sequence analysis revealed two types of cDNAs apparently derived from the same gene, which the authors referred to as Ia and Ib. The human full-length type Ia cDNA encodes the predicted polypeptide of 366 amino acids with seven transmembrane domains and is the subject of this classification. Type Ib is predicted to encode a truncated polypeptide of 289 amino acids with only five transmembrane (1–5) domains. The function, if any, is not yet known. The GHS-R1a receptor belongs to Family A, i.e., the rhodopsin-like family of G protein-coupled receptors and signals via a G_{q/11} α-subunit that results in the release of inositol triphosphate and Ca²⁺.

Following the International Union of Pharmacology convention of naming receptors after the endogenous agonist, the GHS-R1a is designated as the ghrelin receptor abbreviated where necessary to GRLN receptor. This abbreviation was chosen because the single letter G is likely to be confused with G proteins and the next logical abbreviation GH (and GHR) are already in use for the growth hormone receptor. There are two isoforms of the GH receptor, and the abbreviation GHRL has been used for the full-length receptor to distinguish between the short isoform (GHSR).

²Abbreviations: GHS-R, growth hormone secretagogue receptor; GH, growth hormone; GRLN, ghrelin; CNS, central nervous system; MK-0677, *N*-[1(*R*)[1,2-dihydro-1-methylsulfonylspiro(3*H*-indole-3,4'-piperidin)-1'-yl]carbonyl-2-(phenylmethoxy)ethyl]-2-amino-2-methylpropanamide; EP-80317, (2*S*,5*S*)-5-amino-1,2,3,4,6,7-hexahydro-azepino(3,2,1-*hi*)indol-4-one-2-carboxylic acid-*D*-2Me-Trp-*D*-Lys-Trp-*D*-Phe-Lys-NH₂; GHRP, growth hormone-releasing peptide; GHRH, GHR hormone.

TABLE 2
Classification of ghrelin receptor

Receptor	Ghrelin, GRLN
Receptor code	2.1:GHS:1:GHS1:HUMAN:00
Previous names	GHS-R, GHS-R1a (approved human gene symbol)
Structural information	7TM Human: 366aa (SwissProt Q92847), chr. 3q26.31 (LocusLink 2693) Rat: 364aa (SwissProt O08725), chr. 2Q24 (LocusLink 84022) Mouse: 364aa (SwissProt Q99P50), chr. 3A3 (LocusLink 208188)
Functional assays	In vitro pharmacology using human isolated vessels (Wiley and Davenport, 2002) In vitro pharmacology using isolated guinea pig papillary muscle (Bedendi et al., 2003)
Endogenous agonists	Ghrelin ($IC_{50} = 8.1 \text{ nM}/EC_{50} = 1.5 \text{ nM}$) = des-Gln ¹⁴ -ghrelin ($IC_{50} = 7.4 \text{ nM}/EC_{50} = 1.5 \text{ nM}$) (Matsumoto et al., 2001; Bedendi et al., 2003)
Selective agonists	GHRP-2 ($IC_{50} = 0.4 \text{ nM}$) > MK-0677 ($IC_{50} = 0.8 \text{ nM}$) > GHRP-6 ($IC_{50} = 1.5 \text{ nM}$) (cloned rat receptor; McKee et al., 1997)
Antagonists	[D-Lys ³]-GHRP-6, EP-80317
Antagonist potencies	
Radioligand assays	Human hypothalamus, human cardiovascular tissue
Radioligands	[¹²⁵ I-His ⁹]-ghrelin ($K_d = 0.22\text{--}0.57 \text{ nM}$) (Katugampola et al., 2001) [¹²⁵ I-Tyr ⁴]-ghrelin ($K_d = 0.44 \text{ nM}$) (Muccioli et al., 2001) [¹²⁵ I-Tyr ⁴]-ghrelin ($K_d = 0.51 \text{ nM}$) (Bedendi et al., 2003)
Transduction	
Mechanism	Coupled to G- α -11 proteins
Receptor distribution	Humans, specific [¹²⁵ I-His ⁹]-ghrelin binding was localized to the human vasculature including aorta, coronary arteries, pulmonary arteries, arcuate arteries (in the kidney), and saphenous veins; rats: binding sites were also localized to the vasculature in peripheral tissues as well as the granular layer of the cerebellum in the CNS (Katugampola et al., 2001)
Tissue function	Stimulates release of growth hormone from the anterior pituitary, gastric acid secretion, and motility; may alter appetite and energy balance; vasodilatation

aa, amino acid; chr., chromosome.

The GRLN receptor has 73% amino acid sequence identity with the orphan receptor GPR38. Of the receptors with identified ligands, it is most closely related to the neurotensin receptor-1 (35% overall protein identity). Bednarek et al. (2000) found that short peptides encompassing the first four or five residues of ghrelin functionally activate human GRLN receptor about as efficiently as the full-length ghrelin. The Gly-Ser-Ser(*n*-octanoyl)-Phe segment appears to constitute the “active core” required for agonist potency at the receptor.

III. Distribution of Receptor and mRNA Encoding the Receptor

In the rat brain, mRNA encoding the receptor was detected in multiple hypothalamic nuclei (a major target for regulation of food intake and energy balance), pituitary gland, and dentate gyrus of the hippocampal formation. In other brain areas, discrete signals were detected in the CA2 and CA3 regions of the hippocampus, the substantia nigra, ventral tegmental area, and dorsal and median raphe nuclei. In human tissues, mRNA was detected in normal anterior pituitary, pituitary adenomas, hypothalamus (consistent with its role in regulating growth hormone release), and hippocampus. In human peripheral tissue, mRNA was detected in adrenal cortex, testes, pancreas, heart, and lung (McKee et al., 1997; Yokote et al., 1998).

In human tissue, specific [¹²⁵I-His⁹]-ghrelin binding was localized to the vasculature including aorta, coro-

nary arteries, pulmonary arteries, arcuate arteries (in the kidney), and saphenous veins. [¹²⁵I-His⁹]-ghrelin binding was significantly up-regulated (3- to 4-fold) in both atherosclerotic coronary arteries and saphenous vein grafts with advanced intimal thickening compared with normal vessels (Katugampola et al., 2001). In rats, binding sites were also localized to the vasculature in peripheral tissues as well as the granular layer of the cerebellum in the CNS (Katugampola et al., 2001). Antisera generated to the receptor have been used to map immunoreactivity in the hypothalamus, pituitary, and stomach of this species (Shuto et al., 2001).

IV. Radiolabeled Ligands

Two radiolabeled analogs of ghrelin have been synthesized (Table 2). [¹²⁵I-His⁹]-Ghrelin has been extensively characterized in human and rat tissues, where the ligand bound with a single affinity. In human heart, binding was saturable, specific, and reversible with an association rate constant (k_{obs}) of $0.16 \pm 0.004 \text{ min}^{-1}$, a dissociation rate constant of $0.068 \pm 0.0005 \text{ min}^{-1}$ (giving a kinetically derived K_D of 0.1 nM), and by saturation binding assay, a K_D of $0.43 \pm 0.08 \text{ nM}$ and B_{max} of $7.8 \pm 0.9 \text{ fmol mg}^{-1} \text{ protein}$. Half-time for dissociation was 11 min. Optimum binding was over pH range 6.75 to 7.25 (Katugampola et al., 2001). [¹²⁵I-His⁹]-Ghrelin binding was significantly up-regulated (3- to 4-fold) in both atherosclerotic coronary arteries and saphenous vein grafts with advanced intimal thickening compared

with normal vessels, suggesting a role in the development of atherosclerosis and may therefore represent a novel therapeutic target in the treatment of cardiovascular disease (Katugampola et al., 2001).

In human CNS tissue, [^{125}I -Tyr 4]-ghrelin bound with K_D values of 0.44 nM in hypothalamus and 0.41 nM in pituitary. Binding was inhibited by ghrelin, hexarelin, MK-0677, and the growth hormone secretagogue antagonist EP-80317 (Muccioli et al., 2001). Bedendi et al. (2003) characterized [^{125}I -Tyr 4]-ghrelin in guinea pig ventricle ($K_d = 0.51 \pm 0.06$ nM, $B_{\text{max}} = 10.9 \pm 1.8$ fmol mg^{-1} protein). In competition binding assays using this radioligand, IC_{50} values for unlabeled competing ligands, all expressed as nanomolar concentrations, were 8.1 ± 0.9 for ghrelin, 7.4 ± 0.4 for des-Gln 14 -ghrelin, 12.5 ± 1.7 for des-octanoyl ghrelin, and 20.8 ± 2.3 for hexarelin.

V. Agonists

The rank order of potency for endogenous agonists is as follows: ghrelin ($\text{IC}_{50} = 8.1$ nM, $\text{EC}_{50} = 1.5$ nM) = des-Gln 14 -ghrelin ($\text{IC}_{50} = 7.4$ nM, $\text{EC}_{50} = 1.5$ nM) (Matsumoto et al., 2001; Bedendi et al., 2003). Other growth hormone-releasing peptides (GHRP) such as GHRP-6 (His-D-Trp-Ala-Trp-D-Phe-Lys-NH $_2$) as well as synthetic low molecular weight peptides such as hexarelin ($\text{IC}_{50} = 24$ nM) also compete for the binding of [^{125}I -Tyr 4]-ghrelin in human hypothalamus with a comparable affinity to the unlabeled peptide, although nonpeptide (MK-0677) secretagogues developed using GHRP-6 as a template were less potent in this assay ($\text{IC}_{50} = 330$ nM; Muccioli et al., 2001).

For artificially expressed receptors, McKee et al. (1997) reported [^{35}S]MK-0677 bound to the rat receptor sequence transfected into COS-7 cells with a $K_D = 0.7$ nM. The rank order of competition for peptide and nonpeptide secretagogues was GHRP-2 ($\text{IC}_{50} = 0.4$ nM) > MK-0677 ($\text{IC}_{50} = 0.8$ nM) > GHRP-6 ($\text{IC}_{50} = 1.3$ nM). Synthesis of these peptide and nonpeptide growth hormone secretagogues led to the cloning of the growth hormone secretagogue receptor in 1996 (Howard et al., 1996), prior to the discovery of ghrelin as the endogenous ligand in 1999 (Kojima et al., 1999).

VI. Antagonists

Selective ghrelin antagonists that have been characterized in detail are not yet available. Some growth hormone secretagogue receptor antagonists such as EP-80317 are reported to compete for the binding of [^{125}I -Tyr 4]-ghrelin in human hypothalamus with $\text{IC}_{50} = 14$ nM comparable with unlabeled ghrelin in this preparation (Muccioli et al., 2001).

VII. Physiological Role

Early studies in humans and rats showed that ghrelin potently stimulates release of growth hormone from the

anterior pituitary. Ghrelin is thought to act on GRLN receptors present on pituitary somatotrophs, and ghrelin binds to GRLN receptors on growth hormone-releasing hormone (GHRH) positive cells in the hypothalamus triggering GHRH liberation. Ghrelin therefore is believed to be involved in the regulation of GH secretion together with the GH liberator GHRH and the GH inhibitor somatostatin.

Ghrelin stimulates gastric acid secretion and motility. Central and peripheral administration of ghrelin to animals increases food intake leading to weight gain and reduced fat utilization suggesting that the peptide (with several other peptides) may have significant effects on appetite and energy balance (Asakawa et al., 2003; Bagdasarian et al., 2003; Cowley et al., 2003). In a number of species including humans, circulating ghrelin levels significantly increase during fasting and decrease as a response to food intake (Sugino et al., 2002). This regulatory mechanism of ghrelin secretion is believed to be mediated via cholinergic afferences from the gastrointestinal tract (Date et al., 2000; Sugino et al., 2003). At the same time, ghrelin levels are low in obese and high in lean individuals, suggesting that ghrelin is not only important for the acute regulation of food intake but also plays an important role in the regulation of long-term energy homeostasis. These functions are consistent with the major source of ghrelin in endocrine cells in the upper gastrointestinal tract (Hosoda et al., 2000; Inui, 2001).

Ghrelin has a number of actions in the cardiovascular system, consistent with the localization of receptors to cardiovascular tissue. In humans, the peptide is a potent vasodilator in vivo (Okumura et al., 2002) and in vitro (Wiley and Davenport, 2002). Ghrelin elicits these actions independent of the endothelium, indicating a direct effect on the vascular smooth muscle (Wiley and Davenport, 2002). In agreement, the ghrelin-induced vasodilatation in vivo is not altered by coadministration of the nitric-oxide synthase inhibitor N^G -monomethyl-L-arginine. Immunoreactive ghrelin has been detected in endothelial cells throughout the human vasculature, suggesting that the peptide may function as a ubiquitous endothelium-derived vasoactive peptide (Kleinz and Davenport, 2003; <http://www.wpa2online.org/20031022P>).

VIII. Pathophysiological Role

Ghrelin functions as a vasodilator in humans. Receptors are significantly up-regulated in human atherosclerosis suggesting a role in compensating for the increased vasoconstriction in this condition (Katugampola et al., 2001; Wiley and Davenport, 2002). The precise pathophysiological role of ghrelin has not been established. In a rat model of chronic heart failure and in human chronic heart failure patients, ghrelin caused a fall in mean arterial blood pressure and had beneficial effects

on stroke volume and cardiac output (Nagaya et al., 2001a,b,c); however, whether the observed effects of ghrelin are completely or partially mediated via central GH release remains unclear.

Ghrelin circulates at high levels in the plasma in humans. Levels are reduced in obese humans compared with lean control subjects, but whether this is cause or effect is not clear. Patients with anorexia nervosa have higher than normal plasma ghrelin levels that decrease if weight gain occurs (Tanaka et al., 2003).

Prader-Willi syndrome is a genetic disorder characterized by mild mental retardation, short stature, abnormal body composition, muscular hypotonia, and distinctive behavioral features. Excessive eating causes progressive obesity with increased cardiovascular morbidity and mortality. It is a complex disease and is likely to have many defects, one of which may be ghrelin. In patients, circulating oxytocin levels were abnormally low and ghrelin levels abnormally high. Thus, oxytocin and ghrelin might be involved in the hyperphagia (Haqq et al., 2003).

Low ghrelin concentration may be a risk factor for type 2 diabetes and hypertension. Poykko et al. (2003) characterized the effect of the ghrelin Arg51Gln (which changes the carboxy terminus of the mature peptide) and Leu72Met mutations on ghrelin concentrations in the population-based hypertensive and control cohorts. Ghrelin concentrations were negatively associated with fasting insulin, systolic and diastolic blood pressure, and the prevalence of type 2 diabetes and insulin resistance. In the control cohort, low ghrelin was associated with hypertension (blood pressure >140/90 mm Hg). Subjects with the ghrelin 51Gln allele had lower ghrelin concentrations than the Arg51Arg homozygotes and may have a role in the etiology of type 2 diabetes and the regulation of blood pressure.

IX. Genetically Modified Animals

A. Ghrelin Receptor

Deletion of the gene-encoding GRLN receptor in mice produced the expected phenotype. Homozygous mice did not show growth hormone release or increased food intake as a result of ghrelin treatment (Sun et al., 2004).

B. Peptide

Mice with deletion of the gene-encoding ghrelin did not display any phenotypic changes compared with controls; neither growth nor appetite was changed (Sun et al., 2003).

Acknowledgments. This work was supported by the British Heart Foundation (A.P.D.).

REFERENCES

Ariyasu H, Takaya K, Tagami T, Ogawa Y, Hosoda K, Akamizu T, Suda M, Koh T, Natsui K, Toyooka S, et al. (2001) Stomach is a major source of circulating ghrelin and feeding state determines plasma ghrelin-like immunoreactivity levels in humans. *J Clin Endocrinol Metab* **86**:4753–4758.

- Asakawa A, Inui A, Kaga T, Katsuura G, Fujimiya M, Fujino MA, and Kasuga M (2003) Antagonism of ghrelin receptor reduces food intake and body weight gain in mice. *Gut* **52**:947–952.
- Bagnasco M, Tulipano G, Melis MR, Argiolas A, Cocchi D, and Muller EE (2003) Endogenous ghrelin is an orexigenic peptide acting in the arcuate nucleus in response to fasting. *Regul Pept* **111**:161–167.
- Baldanzi G, Filigheddu N, Cutrupi S, Catapano F, Bonissoni S, Fubini A, Malan D, Baj G, Granata R, Broglio F, et al. (2002) Ghrelin and des-acyl ghrelin inhibit cell death in cardiomyocytes and endothelial cells through ERK1/2 and PI 3-kinase/AKT. *J Cell Biol* **159**:1029–1037.
- Bedendi I, Alloati G, Marcantoni A, Malan D, Catapano F, Ghe C, Deghenghi R, Ghigo E, and Muccioli G (2003) Cardiac effects of ghrelin and its endogenous derivatives des-octanoyl ghrelin and des-Gln14-ghrelin. *Eur J Pharmacol* **476**:87–95.
- Bednarek MA, Feighner SD, Pong SS, McKee KK, Hreniuk DL, Silva MV, Warren VA, Howard AD, Van Der Ploeg LH, and Heck JV (2000) Structure-function studies on the new growth hormone-releasing peptide ghrelin: minimal sequence of ghrelin necessary for activation of growth hormone secretagogue receptor 1a. *J Med Chem* **43**:4370–4376.
- Cassoni P, Papotti M, Ghe C, Catapano F, Sapino A, Graziani A, Deghenghi R, Reissmann T, Ghigo E, and Muccioli G (2001) Identification, characterization and biological activity of specific receptors for natural (ghrelin) and synthetic growth hormone secretagogues and analogs in human breast carcinomas and cell lines. *J Clin Endocrinol Metab* **86**:1738–1745.
- Cowley MA, Smith RG, Diano S, Tschöp M, Pronchuk N, Grove KL, Strasburger CJ, Bidlingmaier M, Esterman M, Heiman ML, et al. (2003) The distribution and mechanism of action of ghrelin in the CNS demonstrates a novel hypothalamic circuit regulating energy homeostasis. *Neuron* **37**:649–661.
- Date Y, Kojima M, Hosoda H, Sawaguchi A, Mondal MS, Suganuma T, Matsukura S, Kangawa K, and Nakazato M (2000) Ghrelin, a novel growth hormone-releasing acylated peptide, is synthesized in a distinct endocrine cell type in the gastrointestinal tracts of rats and humans. *Endocrinology* **141**:4255–4261.
- Foord SM, Bonner TI, Neubig RR, Rosser EM, Pin J-P, Davenport AP, Spedding M, and Harmar AJ (2005) International Union of Pharmacology. XLVI. G-protein coupled receptor list. *Pharmacol Rev* **57**:279–288.
- Gualillo O, Caminos J, Blanco M, Garcia-Caballero T, Kojima M, Kangawa K, Dieguez C, and Casanueva F (2001) Ghrelin, a novel placental-derived hormone. *Endocrinology* **142**:788–794.
- Haqq AM, Stadler DD, Rosenfeld RG, Pratt KL, Weigle DS, Frayo RS, LaFranchi SH, Cummings DE, and Purnell JQ (2003) Circulating ghrelin levels are suppressed by meals and octreotide therapy in children with Prader-Willi syndrome. *J Clin Endocrinol Metab* **88**:3573–3576.
- Hosoda H, Kojima M, Matsuo H, and Kangawa K (2000) Ghrelin and des-acyl ghrelin: two major forms of rat ghrelin peptide in gastrointestinal tissue. *Biochem Biophys Res Commun* **279**:909–913.
- Howard AD, Feighner SD, Cully DF, Arena JP, Liberato PA, Rosenblum CI, Hamelin M, Hreniuk DL, Palyha OC, Anderson J, et al. (1996) A receptor in pituitary and hypothalamus that functions in growth hormone release. *Science (Wash DC)* **273**:974–977.
- Inui A (2001) Ghrelin: an orexigenic and somatotrophic signal from the stomach. *Nat Rev Neurosci* **2**:551–560.
- Katugampola SD, Pallikaros Z, and Davenport AP (2001) [¹²⁵I-His(9)]-ghrelin, a novel radioligand for localizing GHS orphan receptors in human and rat tissue: up-regulation of receptors with atherosclerosis. *Br J Pharmacol* **134**:143–149.
- Kleinz M and Davenport AP (2003) Endothelial ghrelin: a compensatory dilator peptide in atherosclerosis. *Atherosclerosis* **170**:S9–S10.
- Kojima M, Hosoda H, Date Y, Nakazato M, Matsuo H, and Kangawa K (1999) Ghrelin is a growth-hormone-releasing acylated peptide from stomach. *Nature (Lond)* **402**:656–660.
- Kojima M, Hosoda H, Matsuo H, and Kangawa K (2001) Ghrelin: discovery of a natural endogenous ligand for the growth hormone secretagogue receptor. *Trends Endocrinol Metab* **12**:118–122.
- Korbonits M, Bustin SA, Kojima M, Jordan S, Adams EF, Lowe DG, Kangawa K, and Grossman AB (2001) The expression of the growth hormone secretagogue receptor ligand ghrelin in normal and abnormal human pituitary and other neuroendocrine tumors. *J Clin Endocrinol Metab* **86**:881–887.
- Korbonits M, Goldstone AP, Gueorguiev M, and Grossman AB (2004) Ghrelin—a hormone with multiple functions. *Front Neuroendocrinol* **25**:27–68.
- Matsumoto M, Hosoda H, Kitajima Y, Morozumi N, Minamitake Y, Tanaka S, Matsuo H, Kojima M, Hayashi Y, and Kangawa K (2001) Structure-activity relationship of ghrelin: pharmacological study of ghrelin peptides. *Biochem Biophys Res Commun* **287**:142–146.
- McKee KK, Palyha OC, Feighner SD, Hreniuk DL, Tan CP, Phillips MS, Smith RG, der Ploeg LHT, and Howard AD (1997) Molecular analysis of rat pituitary and hypothalamic growth hormone secretagogue receptors. *Mol Endocrinol* **11**:415–423.
- Muccioli G, Papotti M, Locatelli V, Ghigo MC, and Deghenghi R (2001) Binding of [¹²⁵I]-labelled ghrelin to membranes from human hypothalamus and pituitary gland. *J Endocrinol Invest* **24**:RC7–RC9.
- Nagaya N and Kangawa K (2003a) Ghrelin, a novel growth hormone-releasing peptide, in the treatment of chronic heart failure. *Regul Pept* **114**:71–77.
- Nagaya N and Kangawa K (2003b) Ghrelin improves left ventricular dysfunction and cardiac cachexia in heart failure. *Curr Opin Pharmacol* **3**:146–151.
- Nagaya N, Kojima M, Uematsu M, Yamagishi M, Hosoda H, Oya H, Hayashi Y, and Kangawa K (2001a) Hemodynamic and hormonal effects of human ghrelin in healthy volunteers. *Am J Physiol Regul Integr Comp Physiol* **280**:R1483–R1487.
- Nagaya N, Miyatake K, Uematsu M, Oya H, Shimizu W, Hosoda H, Kojima M, Nakanishi N, Mori H, and Kangawa K (2001b) Hemodynamic, renal and hormonal effects of ghrelin infusion in patients with chronic heart failure. *J Clin Endocrinol Metab* **86**:5854–5859.
- Nagaya N, Uematsu M, Kojima M, Ikeda Y, Yoshihara F, Shimizu W, Hosoda H,

- Hirota Y, Ishida H, Mori H, and Kangawa K (2001c) Chronic administration of ghrelin improves left ventricular dysfunction and attenuates development of cardiac cachexia in rats with heart failure. *Circulation* **104**:1430–1435.
- Okumura H, Nagaya N, Enomoto M, Nakagawa E, Oya H, and Kangawa K (2002) Vasodilatory effect of ghrelin, an endogenous peptide from the stomach. *J Cardiovasc Pharmacol* **39**:779–783.
- Poykko SM, Kellokoski E, Horkko S, Kauma H, Kesaniemi YA, and Ukkola O (2003) Low plasma ghrelin is associated with insulin resistance, hypertension and the prevalence of type 2 diabetes. *Diabetes* **52**:546–553.
- Shuto Y, Shibasaki T, Wada K, Parhar I, Kamegai J, Sugihara H, Oikawa S, and Wakabayashi I (2001) Generation of polyclonal antiserum against the growth hormone secretagogue receptor (GHS-R): evidence that the GHS-R exists in the hypothalamus, pituitary and stomach of rats. *Life Sci* **68**:991–996.
- Sugino T, Hasegawa Y, Kikkawa Y, Yamaura J, Yamagishi M, Kurose Y, Kojima M, Kangawa K, and Terashima YA (2002) Transient ghrelin surge occurs just before feeding in a scheduled meal-fed sheep. *Biochem Biophys Res Commun* **295**:255–260.
- Sun Y, Ahmed S, and Smith RG (2003) Deletion of ghrelin impairs neither growth nor appetite. *Mol Cell Biol* **23**:7973–7981.
- Sun Y, Wang P, Zheng H, and Smith RG (2004) Ghrelin stimulation of growth hormone release and appetite is mediated through the growth hormone secretagogue receptor. *Proc Natl Acad Sci USA* **101**:4679–4684.
- Tanaka M, Naruo T, Yasuhara D, Tatebe Y, Nagai N, Shiiya T, Nakazato M, Matsukura S, and Nozoe S (2003) Fasting plasma ghrelin levels in subtypes of anorexia nervosa. *Psychoneuroendocrinology* **28**:829–835.
- Tomasetto C, Karam SM, Ribieras S, Masson R, Lefebvre O, Staub A, Alexander G, Chenard MP, and Rio MC (2000) Identification and characterization of a novel gastric peptide hormone: the motilin-related peptide. *Gastroenterology* **119**:395–405.
- van der Lely AJ, Tschop M, Heiman ML, and Ghigo E (2004) Biological, physiological, pathophysiological and pharmacological aspects of ghrelin. *Endocr Rev* **25**:426–457.
- Wierup N, Svensson H, Mulder H, and Sundler F (2002) The ghrelin cell: a novel developmentally regulated islet cell in the human pancreas. *Regul Pept* **107**:63–69.
- Wiley KE and Davenport AP (2002) Comparison of vasodilators in human internal mammary artery: ghrelin is a potent physiological antagonist of endothelin-1. *Br J Pharmacol* **136**:1146–1152.
- Yokote R, Sato M, Matsubara S, Ohye H, Niimi M, Murao K, and Takahara J (1998) Molecular cloning and gene expression of growth hormone-releasing peptide receptor in rat tissues. *Peptides* **19**:15–20.