Identification of the Acyltransferase that Octanoylates Ghrelin, an Appetite-Stimulating Peptide Hormone

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SUMMARY

Ghrelin is a 28 amino acid, appetite-stimulating peptide hormone secreted by the food-deprived stomach. Serine-3 of ghrelin is acylated with an eight-carbon fatty acid, octanoate, which is required for its endocrine actions. Here, we identify GOAT (Ghrelin *O*-Acyltransferase), a polytopic membrane-bound enzyme that attaches octanoate to serine-3 of ghrelin. Analysis of the mouse genome revealed that GOAT belongs to a family of 16 hydrophobic membrane-bound acyltransferases that includes Porcupine, which attaches long-chain fatty acids to Wnt proteins. GOAT is the only member of this family that octanoylates ghrelin when coexpressed in cultured endocrine cell lines with prepro-ghrelin. GOAT activity requires catalytic asparagine and histidine residues that are conserved in this family. Consistent with its function, GOAT mRNA is largely restricted to stomach and intestine, the major ghrelin-secreting tissues. Identification of GOAT will facilitate the search for inhibitors that reduce appetite and diminish obesity in humans.

INTRODUCTION

The appetite-stimulating peptide hormone, ghrelin, is the only protein in animals that is known to be modified by *O*-acylation with octanoate, an eight-carbon fatty acid. Octanoylation is required for the endocrine actions of ghrelin, but the enzyme that catalyzes this modification has not yet been identified (Kojima and Kangawa, 2005).

The discovery of ghrelin was reported in 1999 by Kojima et al. (1999), who were searching for a ligand for an orphan G protein coupled receptor (GHS-R1a) that stimulates the secretion of growth hormone in the pituitary gland. The ligand was purified from rat stomach, and it was shown to stimulate the release of growth hormone from cultured pituitary cells. Kojima, et al. (1999) determined that the 28 amino acid ghrelin is derived proteolytically from a precursor of 117 amino acids. Analysis by mass spectroscopy revealed that serine-3 of ghrelin is modified by *O*-acylation with an octanoyl group, which is required for growth hormone releasing activity. Serine-3 is conserved in mammals, birds, and fish. In ghrelin of the bullfrog, serine-3 is replaced by threonine, but this residue is also octanoylated (Kojima and Kangawa, 2005). Thus, *O*-octanoylation of ghrelin has been conserved in vertebrates over millions of years of evolution. Likewise, the GHS-R1a receptor for octanoylated ghrelin has also been highly conserved in vertebrates as far back as zebrafish (NCBI database, XP_001340408).

Interest in ghrelin rose dramatically when it was demonstrated that ghrelin concentrations in human plasma rise immediately before mealtimes (Cummings et al., 2001; Cummings, 2006). How much of this ghrelin surge represents the acylated active form is unknown. Infusion of acylated ghrelin into the cerebral ventricles of rats markedly enhances food intake apparently through actions on the hypothalamus (Kamegai et al., 2001). Peripheral administration of ghrelin to humans stimulates food intake (Wren et al., 2001; Small and Bloom, 2004). Elimination of ghrelin or its receptor in mice through knockout technology caused a modest but significant reduction in obesity when the mice were presented with high fat diets (Wortley et al., 2005; Zigman et al., 2005). These findings aroused interest in ghrelin inhibitors as potential preventatives for obesity in humans.

One way to inhibit the action of ghrelin would be to block the enzyme that attaches octanoate. An inhibitor should be quite specific since no other protein is known to be octanoylated. Thus far, however, the octanoylating enzyme has escaped identification. In the current studies, we have identified the ghrelin-acylating enzyme by taking advantage of the bioinformatic work of Hofmann (2000), who delineated a family of acyltransferases that catalyze *O*-acylation reactions. The initial insight came from studies on the *Drosophila wingless* gene and its mammalian homolog, *Wnt*. Genetic studies in *Drosophila* had earlier demonstrated that Wingless activity required the action of another gene *porcupine* (Kadowaki et al., 1996). Hofmann observed that the amino acid sequence of Porcupine contains a conserved region that is found in a variety of membrane-bound hydrophobic enzymes that transfer long-chain fatty acids to membrane-associated hydroxyl acceptors. Hofmann named

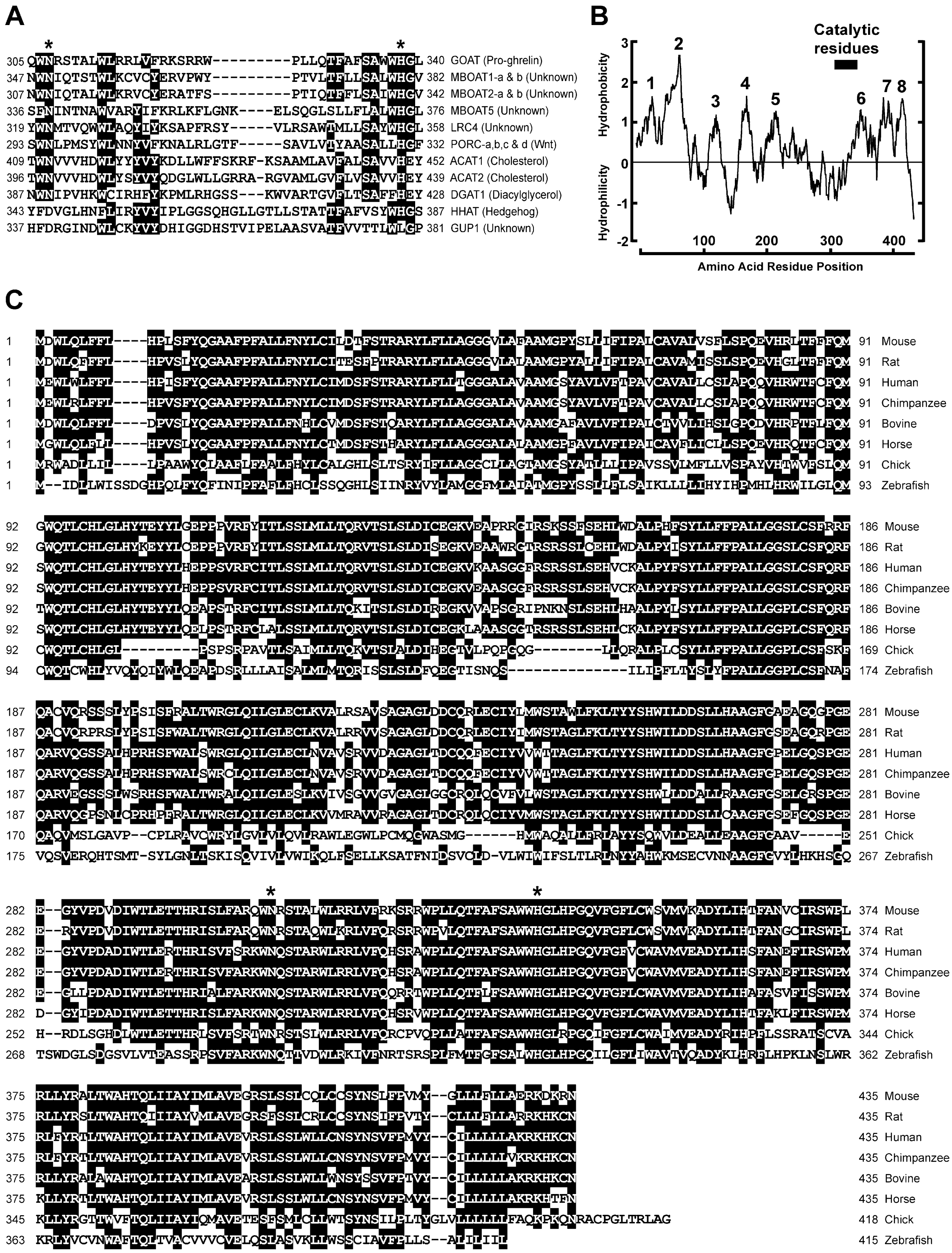

Figure 1. Amino Acid Sequence and Domain Structure of GOAT

(A) Alignment of the most highly conserved region of all 16 MBOATs in the mouse genome. Amino acid residues conserved in more than 50% of the sequences are shaded. Asterisks (*) denote the putative catalytic asparagine and histidine residues (Hofmann, 2000). In the case of MBOATs with different isoforms (MBOAT1, MBOAT2, and PORC), for simplicity the numbering refers to isoform-a. Substrates for MBOATs are shown in parentheses.

(B) Hydropathy plot of mouse GOAT. The residue-specific hydropathy index was calculated over a window of 18 residues with software from DNASTAR. The predicted 8 transmembrane helices are numbered. *Bar* denotes the region of GOAT that contains the two catalytic residues as denoted in (A).

this family MBOATs for Membrane-Bound *O*-Acyltransferases. Other examples include acyl-CoA:cholesterol acyltransferases (ACATs), which attach fatty acids to the hydroxyl group of cholesterol and diacylglycerol acyltransferase-1 (DGAT1), which acylates the hydroxyl group of diacylglycerol.

Subsequent studies showed that Porcupine is required for the attachment of long-chain fatty acids to serine and cysteine residues in Wnt (Willert et al., 2003; Takada et al., 2006). Like Porcupine, all other MBOATs are believed to transfer only long-chain fatty acids of 16–18 carbons. Here, we show that the mouse genome encodes 16 MBOATs produced by 11 genes and demonstrate that one of these MBOATs catalyzes the octanoylation of ghrelin when it is expressed together with prepro-ghrelin in cultured endocrine cell lines. We name this enzyme GOAT for Ghrelin *O*-Acyltransferase.

RESULTS

16 Membrane-Bound *O*-Acyltransferases in the Mouse Genome

Figure 1A shows the conserved sequences in the putative catalytic domains of mammalian proteins that belong to the MBOAT family. These 11 catalytic domains are found in 16 MBOAT proteins since two of the encoding genes give rise to two isoforms and one gives rise to four isoforms as a result of alternative splicing. We identified these sequences through a search of genomic databases (see Experimental Procedures). The criteria for inclusion were based on the original work of Hofmann (2000), who identified this family. The asparagine and histidine residues that are thought to participate in catalysis are indicated by asterisks. All of these enzymes are postulated to transfer fatty acyl groups to hydroxyl or sulfhydryl groups, forming ester or thioester bonds. Among the known substrates are lipids such as cholesterol and diacylglycerol. At least one protein, Wnt, is thought to be a substrate by virtue of a serine that is acylated (Takada et al., 2006). As described below, MBOAT4 is now shown to mediate the octanoylation of ghrelin, and hence it is designated GOAT. The substrates for seven of the putative MBOATs (MBOAT1-a/b, MBOAT2-a/b, MBOAT5, LRC4, and GUP1) remain unknown.

Figure 1B shows a hydropathy plot of mouse GOAT. The sequence suggests eight transmembrane segments, a finding in keeping with the sequences of other MBOATs, all of which have multiple membrane-spanning helices. The GOAT sequence is highly conserved in mammalian and avian species, and a close relative is found in zebrafish (Figure 1C). The putative catalytic asparagine and histidine residues are conserved throughout.

Proteolytic Processing of Prepro-Ghrelin in INS-1 Cells

As a first step in identifying the enzyme that octanoylates ghrelin, we sought to identify cultured cells that process pro-ghrelin to ghrelin. For this purpose we produced prepro-ghrelin in a variety of cultured cell lines through cDNA transfection. As shown in Figure 2A, prepro-ghrelin contains 117 amino acids (Kojima and Kangawa, 2005). Cleavage of the 23 amino acid signal sequence yields pro-ghrelin, which has glycine as its N-terminal residue, hereafter designated residue 1. The C terminus of mature ghrelin is generated by prohormone convertase 1/3, which cleaves after arginine-28 of pro-ghrelin, generating the mature 28 amino acid peptide (Zhu et al., 2006).

After transfection, cell extracts were subjected to SDS-PAGE and immunoblotted with a polyclonal antibody that we raised against mouse ghrelin. All of the transfected cells produced an immunoreactive peptide with an apparent molecular mass of 12 kDa that corresponds to pro-ghrelin with the signal sequence removed (Figure 2B). Three endocrine cell lines—mouse pituitary AtT-20 cells, rat insulinoma INS-1 cells, and mouse insulinoma MIN-6 cells—all produced a smaller peptide with an apparent molecular mass of 3 kDa that corresponds to ghrelin (Figure 2B, lanes 2–7). Two nonendocrine cell lines—human kidney HEK293 cells and Chinese hamster ovary (CHO-7) cells—failed to produce mature ghrelin (lanes 8–11).

To confirm that the mature ghrelin band resulted from cleavage at arginine-28 of pro-ghrelin, we prepared cDNAs encoding mutant forms of prepro-ghrelin with amino acid substitutions at or near arginine-28. The cDNAs were transfected into INS-1 cells, and mature ghrelin was identified by SDS-PAGE and immunoblotting (Figure 2C). Replacement of arginine-28 with either lysine or leucine abolished cleavage (lanes 5 and 6), whereas replacement of residue 26 or 27 with an arginine reduced cleavage but did not abolish it (Figure 2C, lanes 3 and 4).

To further confirm the sites of cleavage that generate ghrelin, we prepared a cDNA encoding prepro-ghrelin with a Flag-tag at the C terminus. We introduced this cDNA into INS-1 cells and isolated the Flag-tagged peptides by adherence to an immunoaffinity gel. SDS-PAGE was used to separate the Flag-tagged pro-ghrelin and the Flag-tagged C-terminal peptide that was generated after cleavage at arginine-28 of ghrelin. The separated peptides were then transferred to PVDF membranes and processed for Edman degradation (Figure 2D). The N-terminal sequence of pro-ghrelin was GSSFL, which is consistent with cleavage of the signal sequence at the position indicated in Figure 2A. The N-terminal sequence of the smaller fragment, ALEG, is consistent with cleavage after arginine-28 of ghrelin. Considered together, the data of Figures 2C and 2D indicate that the INS-1 cells process prepro-ghrelin at the correct sites to produce authentic mature ghrelin.

Expression Cloning of Ghrelin *O*-Acyltransferase

We next developed a reverse-phase chromatographic procedure to separate octanoylated ghrelin from desacyl-ghrelin (Figure 2E). For use as standards, we purchased synthetic octanoylated and desacyl-ghrelin (see Experimental Procedures). The peptides were applied to a C18 reverse-phase cartridge and eluted with a step-gradient of 20%, 40%, and 80%-CH_3CN in 0.1% TFA. The eluted peptides were subjected to SDS-PAGE and immunoblotted with anti-ghrelin. As shown in the upper panel of Figure 2E, desacyl-ghrelin was eluted in the 20%-CH_3CN fraction,

(C) Alignment of amino acid sequences of GOAT orthologs in eight vertebrate species. Amino acid residues conserved in 50% or more of the sequences are shaded. The putative catalytic asparagine and histidine residues are denoted by asterisks (*).

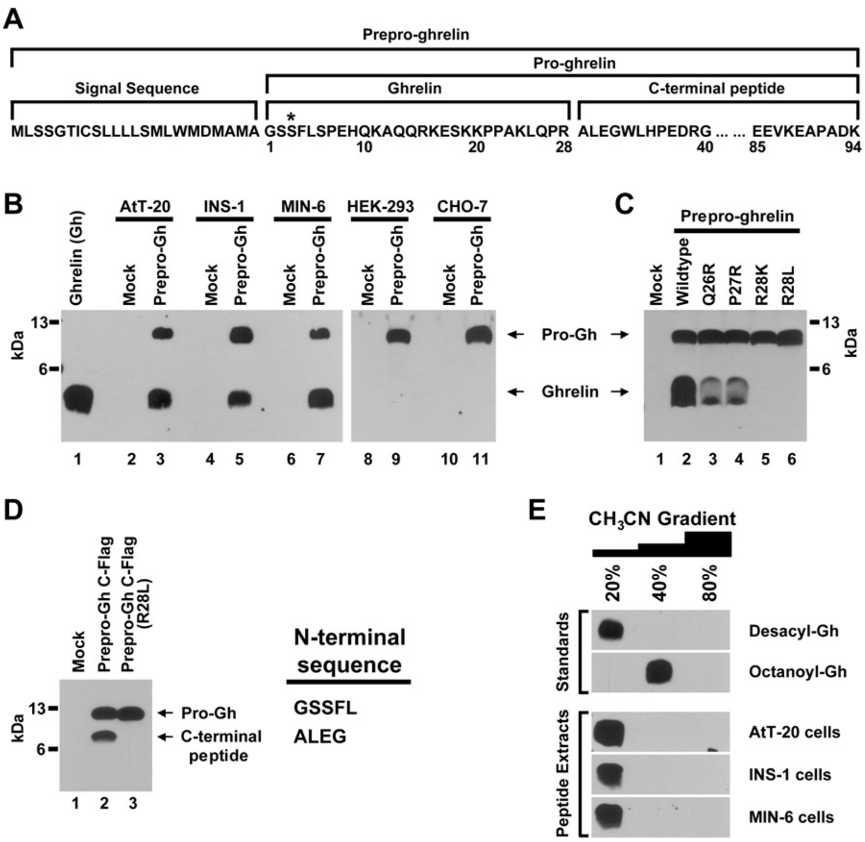

Figure 2. Processing of Prepro-Ghrelin in Cultured Cells

(A) Amino acid sequence of mouse prepro-ghrelin. As it enters the ER, prepro-ghrelin is processed to pro-ghrelin by cleavage between alanine and glycine, which removes the signal sequence. Pro-ghrelin is further processed to ghrelin by prohormone convertase 1/3, which cleaves between arginine and alanine (Zhu et al., 2006). Asterisk (*) denotes serine-3 of ghrelin, which is octanoylated.

(B) Processing of mouse pro-ghrelin (pro-Gh) in different cell lines. The indicated cells were set up for experiments on day 0 as described in Experimental Procedures. On day 2, one dish of each cell line was transfected with 5 μg of mouse prepro-ghrelin cDNA, and a second dish was subjected to mock transfection with pcDNA3.1. On day 4, cells were harvested, and peptides were extracted for SDS-PAGE and immunoblot analysis with rabbit anti-ghrelin antibody. Lane 1 contains synthetic octanoyl-ghrelin.

(C) Effect of cleavage-site mutations on the processing of pro-ghrelin. INS-1 cells were set up as described in (B) and transfected on day 2 with 6 μg of a cDNA encoding the indicated wild-type or mutant versions of prepro-ghrelin. On day 4, cells were harvested for SDS-PAGE and immunoblot as in (B).

(D) N-terminal sequencing of pro-ghrelin and C-terminal peptide containing a C-terminal Flag-tag. On day 0, 30 dishes of INS-1 cells were set up for experiments. On day 2, the cells were transfected with 5 μg of a cDNA encoding mouse prepro-ghrelin with a C-terminal Flag-tag. On day 4, the cells were solubilized in Triton X-100, and a small aliquot of the resulting 100,000 × g supernatant (~1% of sample) was subjected to SDS-PAGE and immunoblotted with anti-Flag M2 monoclonal antibody (left panel, lanes 1–3) as described in Experimental Procedures. The remainder of the 100,000 × g supernatant was treated with anti-Flag affinity gel, after which the eluted proteins were subjected to SDS-PAGE and transferred to a PVDF membrane. The separated peptides corresponding to pro-ghrelin and its C-terminal peptide (identified by amido black staining) were then processed for Edman degradation as described in Experimental Procedures. The N-terminal sequences are shown in the right panel.

(E) Production of desacyl-ghrelin but not octanoylated ghrelin in three endocrine cell lines. The indicated cells were set up for experiments on day 0. On day 2, each dish of cells was cotransfected with 3 μg mouse prepro-ghrelin cDNA and 2 μg pcDNA3.1 mock vector. On day 3, each dish of cells received a direct addition of 100 μM octanoate-albumin (final concentration). On day 4, four dishes of cells from each cell line were harvested and pooled, and the extracted peptides were fractionated by reverse-phase chromatography as described in Experimental Procedures. The three eluted fractions (25% of each sample) were subjected to SDS-PAGE and immunoblot analysis with rabbit anti-ghrelin antibody. The band corresponding in molecular mass to ghrelin is shown. Synthetic desacyl-ghrelin and octanoyl-ghrelin were studied as standards.

and octanoyl ghrelin was eluted in the 40%-CH_3CN fraction. To determine whether any of the endocrine cell lines could produce octanoylated ghrelin, we transfected the cells with a cDNA encoding prepro-ghrelin and subjected the extracted peptides to reverse-phase chromatography. All of the ghrelin peptides were eluted in the 20%-CH_3CN fraction, indicating that none of them was octanoylated (lower panel of Figure 2E).

Figure 3 shows a series of experiments designed to determine whether any of 16 MBOATs were capable of producing octanoylated ghrelin when expressed with prepro-ghrelin in INS-1 cells. We first prepared cDNAs encoding each of the MBOATs with a C-terminal Flag-tag. When transfected into INS-1 cells, all of these cDNAs produced MBOAT protein that could be detected by SDS-PAGE and immunoblotting with anti-Flag (Figure 3A). These cDNAs were then transfected into INS-1 cells together with a cDNA encoding prepro-ghrelin. The ghrelin peptides were extracted and subjected to reverse-phase chromatography. GOAT was the only MBOAT that produced acylated ghrelin, which was detected as a 3-kDa band that emerged in the 40%-CH_3CN fraction (Figure 3B). To confirm the acylating activity of GOAT, we repeated the cotransfection experiment (Figure 3C). When the prepro-ghrelin cDNA was transfected together with a control cDNA (pcDNA3.1), ghrelin emerged in the 20%-CH_3CN fraction, indicating a lack of acylation. We noted that pro-ghrelin emerged in the 40% and 80%-CH_3CN fractions even though it was presumably not acylated. We attribute this to the known tendency of longer peptides to adhere strongly to reverse-phase resins even without acylation. When the GOAT cDNA was transfected, approximately half of the ghrelin emerged in the 40%-CH_3CN fraction, indicating acylation. The elution pattern of pro-ghrelin was the same as in the control cells transfected with pcDNA3.1.

The activity of GOAT was not restricted to INS-1 cells. As shown in Figure 3D, expression of GOAT led to acylation of

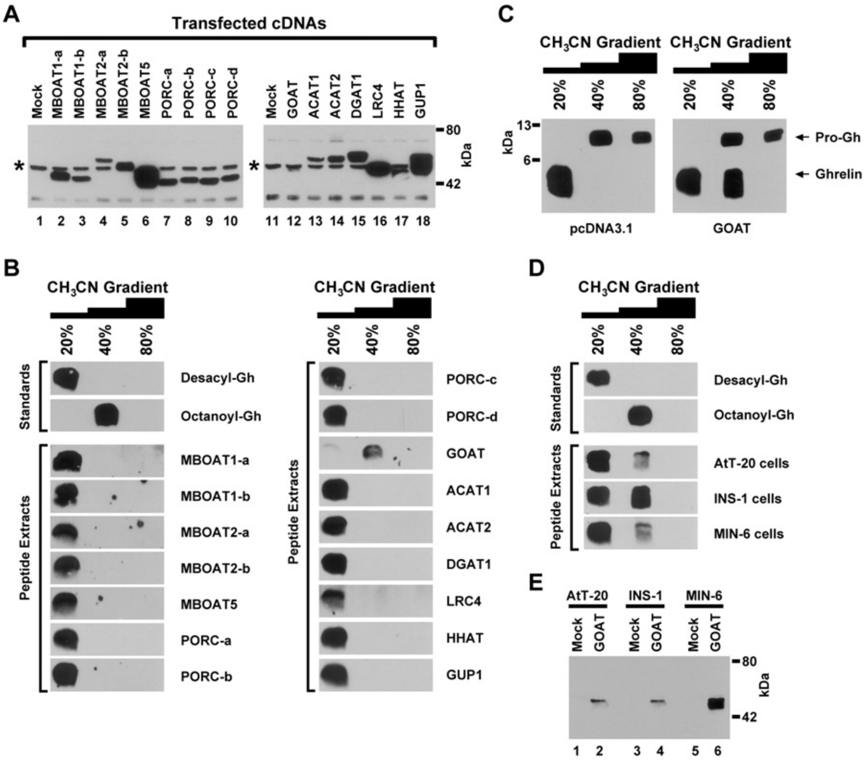

Figure 3. Identification of GOAT by Expression Testing of 16 MBOAT cDNAs

INS-1 cells were set up for experiments on day 0.

(A) Expression of 16 MBOATs by cDNA transfection in INS-1 cells. On day 2, cells were transfected with 5 μg of cDNA encoding the indicated mouse MBOAT with a C-terminal Flag-tag. On day 4, cells from two dishes were harvested and pooled, and the 20,000 × g membrane fraction (representing 20% of one dish of cells; membranes prepared as described by Nohturfft, et al. [2000]) was subjected to 10% SDS-PAGE and immunoblot analysis with anti-Flag M2 monoclonal antibody. Asterisk (*) denotes an irrelevant cross-reacting band present in the membrane fraction of INS-1 cells.

(B) GOAT is the only MBOAT that acylates ghrelin. On day 2, cells were cotransfected with 3 μg of a cDNA encoding mouse prepro-ghrelin and 2 μg of a cDNA encoding the indicated MBOAT. On day 3, each dish received a direct addition of 100 μM octanoate-albumin (final concentration). On day 4, four dishes of cells from each transfection were harvested and pooled, after which peptide extracts were processed for reverse-phase chromatography as described in Figure 2E.

(C) Acylation of ghrelin by GOAT. On day 2, cells were cotransfected with 5 μg of a cDNA encoding mouse prepro-ghrelin and 0.2 μg of a cDNA encoding mock vector pcDNA3.1 or GOAT. Cells were then processed exactly as described in (B) except the bands corresponding to both pro-ghrelin and ghrelin are shown.

(D) GOAT acylates ghrelin when expressed in three endocrine cell lines. The indicated cells were cultured, transfected, and processed as described in (C).

(E) Expression of GOAT by cDNA transfection in three endocrine cell lines. The indicated cells were cultured, transfected, and processed as described in (A) except that on day 2 the cells were transfected with 6 μg of a cDNA encoding GOAT with a C-terminal HA-tag, and on day 4 the membrane fraction (representing 40% of one dish of cells) was immunoblotted with 0.5 μg/ml anti-HA monoclonal antibody.

ghrelin in each of the three endocrine cell lines that were capable of processing pro-ghrelin to ghrelin. Figure 3E confirms that the GOAT protein was expressed in the three transfected cell lines.

Molecular Characterization of the Octanoylating Activity of GOAT

To confirm that ghrelin was acylated by GOAT, we tested the lability of the modification to hydroxylamine treatment, which is known to release ester-bound fatty acids from proteins at alkaline pH (Bizzozero, 1995). As shown in the upper panel of Figure 4A, when synthetic octanoylated ghrelin was treated with 1 M hydroxylamine (pH 8.0), the peptide no longer eluted from the reverse-phase cartridge in the 40%-CH_3CN fraction. Treatment with 1 M Tris-chloride (pH 8.0) had no such effect. The lower panel of Figure 4A shows the results of hydroxylamine treatment of peptide extracts obtained from INS-1 cells transfected with cDNAs encoding prepro-ghrelin and GOAT. When treated with 1M Tris-chloride, ghrelin eluted from the reverse-phase cartridge in the 40%-CH_3CN fraction, but when treated with 1 M hydroxylamine it reverted to the 20%-CH_3CN fraction, indicating that it had been deacylated.

Octanoylation of ghrelin in vivo is known to occur at serine-3 of the peptide. Mutation of serine-3 to alanine prevented acylation by GOAT, indicating that GOAT acylates the physiologic serine residue (Figure 4B). Replacement of serine-3 with threonine preserved acylation, a finding consistent with the observation that this position is occupied by an octanoylated threonine in bullfrog ghrelin (Kojima and Kangawa, 2005). Substitution of alanine for other serines in ghrelin (residues 2, 6, and 18) did not affect acylation (Figure 4B).

As shown in Figure 1, the predicted catalytic residues in mouse GOAT are asparagine-307 and histidine-338. Figure 5A shows that both of these residues are required in order for GOAT to modify ghrelin. Substitution of either of these residues with alanine abolished the ability of GOAT to acylate ghrelin. Another mutation (cysteine-181 to alanine) had no effect. Figure 5B shows that all of the GOAT cDNAs were expressed at similar levels in the transfected cells.

To confirm that GOAT modifies ghrelin with octanoate, we transfected INS-1 cells with cDNAs encoding prepro-ghrelin, and wild-type or mutant version of GOAT (Figure 6). The cells were incubated with [^{3}H]octanoate, and the extracted peptides were subjected to reverse-phase chromatography. Each 40%-CH_3CN fraction was subjected in duplicate to SDS-PAGE, after which the radiolabeled peptides were transferred to duplicate PVDF membranes. One membrane was subjected to immunoblot analysis with anti-ghrelin (Figure 6A), demonstrating that pro-ghrelin was present in all lanes (1–6) while acylated ghrelin was detected only in lane 2. The other membrane was subjected to autoradiography to visualize the labeled proteins (Figure 6B). For quantification, each lane of the membrane was cut into 9 slices, which were then subjected to scintillation counting

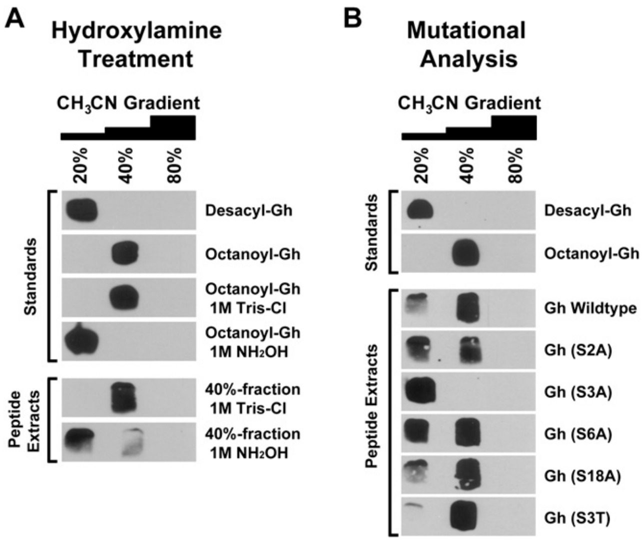

Figure 4. Modification of Ghrelin by GOAT through *O*-linked Acylation at Serine-3

INS-1 cells were set up for experiments on day 0.

(A) Hydroxylamine treatment. On day 2, cells were cotransfected with 5 μg of a cDNA encoding mouse prepro-ghrelin and 0.2 μg of a cDNA encoding GOAT. On day 4, each dish of cells received a direct addition of 50 μM octanoate-albumin (final concentration). On day 5, 10 dishes of cells were harvested and pooled, after which peptide extracts were processed for reverse-phase chromatography. The 40%-CH_3CN fraction and a synthetic octanoyl ghrelin standard were subjected to treatment with either 1 M Tris-chloride (pH 8.0) or 1 M NH_2OH (pH 8.0) (Bizzozero, 1995), followed by reverse-phase chromatography, SDS-PAGE, and immunoblot with rabbit anti-ghrelin antibody.

(B) Mutational analysis. On day 2, each dish of cells was cotransfected with 1 μg of a cDNA encoding GOAT cDNA and 4 μg of a cDNA encoding the indicated wild-type or mutant versions of mouse prepro-ghrelin. On day 3, each dish received 50 μM octanoate-albumin (final concentration). On day 4, four dishes of cells were processed for reverse-phase chromatography as described in Figure 2E.

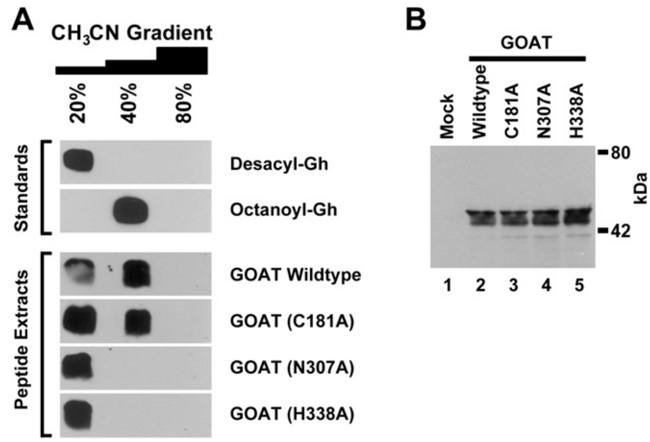

Figure 5. Identification of Residues in GOAT Required for Catalysis

INS-1 cells were set up for experiments on day 0.

(A) On day 2, each dish of cells was cotransfected with 4 μg of a cDNA encoding mouse prepro-ghrelin and 1 μg of a cDNA encoding the indicated wild-type or mutant versions of GOAT. On day 3, cells were treated with 50 μM octanoate-albumin (final concentration). On day 4, four dishes of cells were processed for reverse-phase chromatography as described in Figure 2E.

(B) On day 2, each dish of cells was transfected with 6 μg of a cDNA encoding the indicated wild-type or mutant versions of GOAT with a C-terminal HA-tag. On day 4, the membrane fraction (representing 40% of one dish of cells) was processed for immunoblot analysis with anti-HA monoclonal antibody as described in Figure 3E.

(Figure 6C). When the cells were transfected with the GOAT cDNA, labeled peptides were observed in the position of pro-ghrelin (dark upper band in lane 2 of Figure 6B) and ghrelin (diffuse lower band in lane 2). As expected, no radioactivity was incorporated into the S3A mutant of ghrelin (lane 3). Lane 4 shows the result when prepro-ghrelin contained leucine in place of arginine at the residue corresponding to position 28 of ghrelin. This substitution prevents the cleavage of pro-ghrelin to ghrelin (see Figure 1C). In this case, we observed radiolabeling of the pro-ghrelin band, but there was no ghrelin band (lane 4). We observed no labeled band when the cells were transfected with a cDNA encoding a catalytically inactive mutant of GOAT (H338A) (lane 5). As a further control, we found that transfection of a cDNA encoding another MBOAT (MBOAT1-a) failed to produce a radiolabeled band (lane 6).

To verify that the cells had incorporated [^{3}H]octanoate without changing its length, we removed the labeled fatty acid from the protein by methanolysis and subjected the methyl ester to thin-layer chromatography (TLC) in a system that separates fatty acid methyl esters according to chain length. Scintillation counting of the TLC plate confirmed that the material attached to pro-ghrelin and ghrelin was the eight-carbon [^{3}H]octanoate (Figure 6D).

Relative Distribution of GOAT and Prepro-Ghrelin mRNAs in Mouse Tissues

Finally, we used semiquantitative PCR to compare the levels of GOAT and prepro-ghrelin mRNAs in various tissues of the mouse (Figure 7). As previously reported (Kojima et al., 1999), prepro-ghrelin mRNA was expressed most highly in the stomach followed by the intestine. There was very little expression in other tissues. Likewise, GOAT mRNA was highest in stomach, and detectable in the small intestine and colon. Among other organs, only the testis had detectable amounts of GOAT mRNA. In stomach, we noted that the amount of GOAT mRNA appeared to be much lower than the amount of prepro-ghrelin mRNA. Even after 35 cycles of PCR, the intensity of the amplified GOAT product was less than that observed with prepro-ghrelin after only 30 cycles. This relative difference of ~200-fold was confirmed in experiments using quantitative real-time RT-PCR (data not shown).

DISCUSSION

In the current paper, we identify the enzyme that attaches octanoate to ghrelin, a modification that is essential for the biologic activity of the peptide. The enzyme, which we name GOAT, belongs to the MBOAT family of acyltransferases that attach fatty acids to lipids and proteins (Hofmann, 2000). All of the previously studied enzymes in this family transfer long-chain fatty acids of at least 16 carbons. GOAT is unique because it is the first family member that transfers a medium-chain fatty acid such as octanoate. Inasmuch as ghrelin is the only known octanoylated protein in animals, it seems likely that ghrelin is the sole substrate for GOAT.

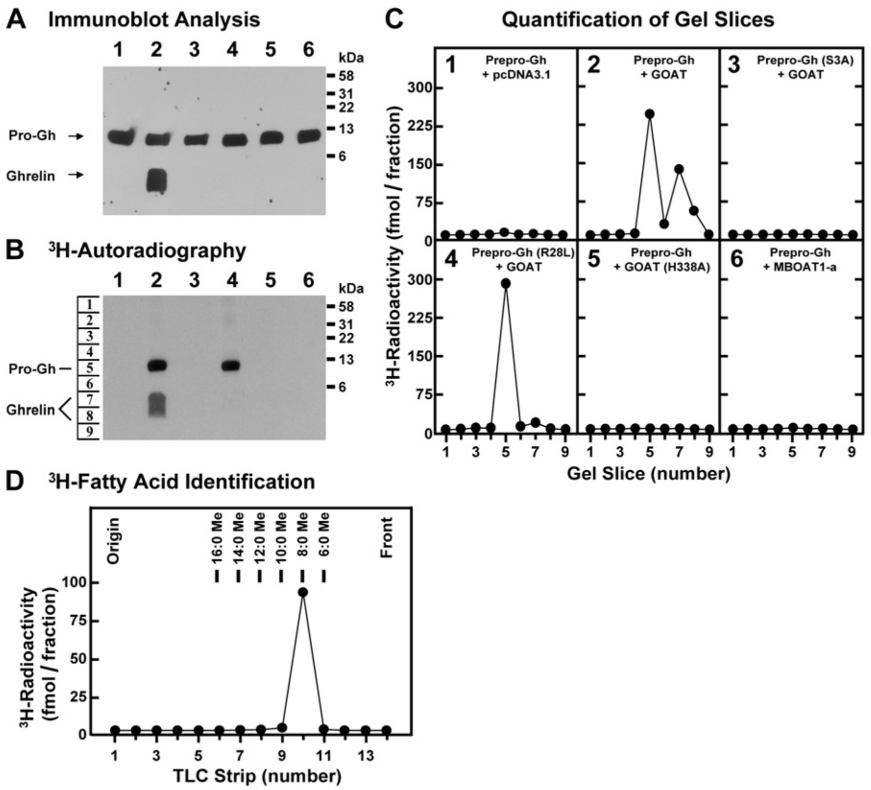

Figure 6. GOAT-Mediated Incorporation of [^{3}H]Octanoate into Pro-Ghrelin and Ghrelin

(A–C) Two dishes of INS-1 cells were set up for experiments on day 0. On day 2, cells were cotransfected with 5 μg of prepro-ghrelin (wild-type or mutant) and 0.2 μg of either GOAT (wild-type or mutant) or MBOAT1-a as indicated in Panels 1–6 in (C). On day 3, cells were switched to medium B containing 10% delipidated FCS rather than FCS. On day 4, cells were radiolabeled by incubation in 8 ml medium B containing no serum and supplemented with 1% (v/v) Insulin, Transferrin & Selenium Solution (ITS; Mediatech, Inc.), 0.1 mg/ml BSA, and 0.1 μM [^{3}H]octanoate (132 dpm/fmol). After incubation for 24 hr at 37°C, cells were harvested, pooled, and fractionated by reverse-phase chromatography. Each 40%-CH_3CN fraction (representing two dishes of cells) was divided into two equal aliquots, each of which was subjected to 16% Tricine SDS-PAGE. After electrophoresis, the separated proteins in each gel were transferred to a PVDF membrane, after which one membrane was processed for immunoblotting and the other for ^{3}H-autoradiography. (A) Immunoblot analysis with rabbit anti-ghrelin antibody. (B) ^{3}H-Autoradiography. After autoradiography, each lane was cut into nine consecutive slices (numbered 1–9), followed by liquid scintillation counting as described in Experimental Procedures. (C) Quantification of ^{3}H-radioactivity. The amount of ^{3}H-radioactivity contained in each of the nine slices is plotted.

(D) Identification of ^{3}H-labeled fatty acid on pro-ghrelin and ghrelin. Two dishes of INS-1 cells were set up, cotransfected with 5 μg mouse prepro-ghrelin cDNA and 0.2 μg GOAT cDNA, and radiolabeled with [^{3}H]octanoate as above. The identity of the ^{3}H-fatty acid covalently attached to pro-ghrelin and ghrelin was identified by fatty acid methyl ester (FAME) analysis as described in Experimental Procedures. The positions of migration of the FAME standards on reverse-phase TLC (C6:0 to C16:0 methyl esters) are shown at the top.

The only other MBOATs that are known to acylate proteins are Hedgehog acyltransferase (HHAT) and Porcupine, both of which transfer long-chain fatty acids. HHAT palmitoylates a cysteine residue in Sonic Hedgehog (Chen et al., 2004), whereas Porcupine is believed to acylate both a cysteine and a serine in Wnt (Willert et al., 2003; Takada et al., 2006). Neither HHAT nor Porcupine transfers octanoate to ghrelin (Figure 3B). It is noteworthy that GOAT, Porcupine, and HHAT acylate proteins that reside in luminal compartments in the secretory pathway. It will be interesting to determine whether some of the unassigned MBOATs act on luminal protein substrates.

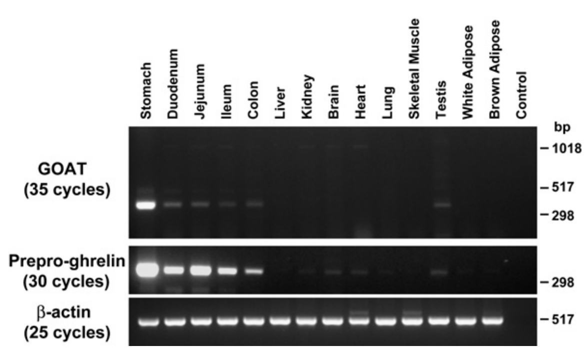

Figure 7. Expression of GOAT mRNA in Different Mouse Tissues

GOAT and prepro-ghrelin mRNAs were detected by one-step RT-PCR from total RNA of 14 mouse tissues as described in Experimental Procedures. RT-PCR of β-actin mRNA was used as an RNA quality control.

The [^{3}H]octanoate-labeling data of Figure 6 indicate that pro-ghrelin is octanoylated before it is transported to the Golgi where it is cleaved by prohormone convertase 1/3 (PC 1/3) to form mature ghrelin. This observation is consistent with the finding that pro-ghrelin isolated from PC 1/3 knockout mice was acylated (Zhu et al., 2006). These data suggest that GOAT is located in the endoplasmic reticulum (ER). The presumed donor for octanoylation is octanoyl-CoA, but how octanoyl-CoA gets into the ER lumen is unclear. One function of GOAT may be to transfer the octanoyl-CoA from the cytosolic side of the ER membrane to the luminal side. The hydrophobic nature of GOAT may assist in this translocation. GOAT appears to be specific for medium chain fatty acids like octanoate. In data not shown, when transfected INS-1 cells were radiolabeled with [^{3}H]palmitate exactly as described for [^{3}H]octanoate in Figure 6, we did not detect any [^{3}H]palmitate incorporation into ghrelin.

Ghrelin is the N-terminal fragment that is generated by cleavage of pro-ghrelin. The C-terminal fragment has been called "obestatin." A recent claim that obestatin binds to a G protein coupled receptor and acts as a ghrelin antagonist (Zhang et al., 2005) has been refuted (Chartrel et al., 2007; Gourcerol et al., 2007; Nogueiras et al., 2007). At present, there is no clear evidence for a function for the C-terminal peptide. Whether the C-terminal peptide of pro-ghrelin plays any role in octanoylation of ghrelin is not known. This question should be answerable now that GOAT has been identified.

The relative tissue distribution of GOAT mRNA matches that of ghrelin (Figure 7). It is highest in stomach. In the intestine, the two mRNAs decline with increasing distance from the pylorus. Semiquantitative PCR experiments suggest that GOAT mRNA is much less abundant than ghrelin mRNA, which would be consistent with the relationship between an enzyme and its substrate. In the stomach, ghrelin has been localized to a minor population of specialized cells that have been called "ghrelin cells." (Date et al., 2000; Kojima and Kangawa, 2005). It will be important to determine whether GOAT is also restricted to these cells.

In the current experiments with INS-1 cells, we supplied octanoate in the culture medium. In the stomach one source of octanoate is the diet (Nishi et al., 2005). Mammalian cells are not known to synthesize medium-chain fatty acids, but a specialized synthetic pathway for generating these fatty acids in ghrelin cells cannot be ruled out.

A major unanswered question relates to the reason why ghrelin, among all other proteins, is the only one that is octanoylated. This unique modification has been conserved in birds, reptiles, amphibians, and fish (Kojima and Kangawa, 2005; Kaiya et al., 2004). The octanoyl group is crucial for ghrelin's ability to bind to and activate its receptor, but is this the only reason for the modification? Does octanoylation provide a mechanism to control ghrelin activity or tissue distribution? These questions should be addressable now that GOAT has been identified.

The discovery of GOAT opens the way to a search for chemical inhibitors that may be useful in controlling appetite. Peripheral and central ghrelin administration is well documented to increase food intake in rodents and humans, presumably through actions in the hypothalamus (Cummings, 2006; Zigman and Elmquist, 2006). Available data suggest that a reduction in ghrelin or its receptor can reduce food intake and partially ameliorate obesity in fat-fed mice (Zorrilla et al., 2006; Zigman et al., 2005; Wortley et al., 2005). Whether such a reduction would reduce weight in humans is unknown, but development of a GOAT inhibitor should allow testing of this hypothesis.

EXPERIMENTAL PROCEDURES

Materials and General Methods

Synthetic desacyl-ghrelin and octanoyl-ghrelin were obtained from AnaSpec (San Jose, CA). Anti-Flag M2 monoclonal antibody, anti-Flag M2 Affinity Gel, anti-HA monoclonal antibody, bovine serum albumin (essentially fatty-acid free), all solvents, and other chemicals were obtained from Sigma unless otherwise specified. Octanoic acid was bound to albumin at a final concentration of 10 mM fatty acid and 10% (w/v) bovine serum albumin in 0.15 M sodium chloride as previously described (Hannah et al., 2001). [^{3}H-2,2′,3,3′]octanoate (60 Ci/mmol) was obtained from American Radiolabeled Chemicals. Delipidated fetal calf serum (FCS) was prepared by solvent extraction with *n*-butanol and isopropyl ether as previously described (Hannah et al., 2001). Standard methods of molecular biology (Sambrook and Russell, 2001) were used unless otherwise specified.

Bioinformatic Identification and cDNA Cloning of Mouse MBOATs

Sixteen members of the MBOAT family were identified in the mouse genome, using reported MBOAT sequences (Hofmann, 2000) for queries and PSI-BLAST searches (E-value cutoff 0.005, default parameters) (Altschul et al., 1997) against the nonredundant protein sequence database.

Full-length cDNAs for 15 of the 16 MBOATs were cloned by RT-PCR of total RNA. RNA was isolated from the stomach of C57BL/6J mice that had been either fasted for 16 hr or fed a chow diet ad libitum. Both sets of RNA were pooled together before RT-PCR. The cloned sequences with or without addition of sequences encoding a C-terminal Flag-tag (DYKDDDDK) or HA-tag (YPYDVPDYA) were inserted into pcDNA3 or pcDNA3.1 vectors (Invitrogen) driven by the cytomegalovirus (CMV) promoter-enhancer. Primers for RT-PCR were designed according to the coding sequences available in the National Center for Biotechnology Information (NCBI) database (Table S1 available online). For each MBOAT without isoforms, 10–20 cDNA clones were sequenced in their entirety; for the three MBOATs with multiple isoforms (MBOAT1, MBOAT2, and porcupine), 60 to 80 cDNA clones were sequenced.

For one of the 16 MBOATs, we initially failed to clone a full-length cDNA. This MBOAT was designated in the NCBI database (May 2007) as "similar to *O*-acyltransferase (membrane bound) domain containing 1" (XM_134120). Efforts to clone its cDNA failed because the NCBI annotation at the 5′ end was incorrect. As a result, the 5′ primers failed to prime PCR amplification. We therefore synthesized an artificial cDNA according to the sequence of XM_134120. After obtaining four segments of DNA corresponding to nucleotides 1-391, 398-885, 907-1254, and 1261-1581 of XM_134120 (synthesized by Integrated DNA Technologies, Coralville, IA), we pieced them together by fusion-PCR (Karreman, 1998). On June 20, 2007, the incorrect NCBI annotation of XM_134120 was replaced by two new annotations that were renamed MBOAT4, XM_001476434 and XM_001472220. These two versions of MBOAT4 differed from each other by 376 nucleotides at the 5′-end, and they differed from XM_134120 at the 5′-end in the following ways: XM_001476434 was 211 bp shorter than XM_134120 and XM_001472220 was 165 bp longer than XM_134120. To determine the correct 5′-end of the MBOAT4 mRNA, we carried out 5′ rapid amplification of cDNA ends (5′-RACE) using total RNA from mouse stomach, 3′ nested primers designed according to the sequence of the longer putative MBOAT4 transcript XM_001472220, and the FirstChoice RLM-RACE Kit (Ambion). The results showed that the correct annotation was XM_001476434. The current NCBI database (December 1, 2007) contains partial DNA sequence information on 11 ESTs corresponding to XM_001476434. Of the 11 ESTs, only one of them (IMAGE 5655946) extends to the 5′-end. This sequence corresponds to the cDNA that we subsequently showed to encode ghrelin *O*-acyltransferase (GOAT).

A full-length cDNA for mouse GOAT was generated by RT-PCR of total stomach RNA as described above. The chimpanzee ortholog (XP_519692) of mouse GOAT was identified by a "blastp" analysis of the nonredundant protein database. Orthologs of GOAT in other species (Figure 1C) were found by clustering identified genomic sequences with the SEALS command grouper (with criterion –lscut = 0.6) (Walker and Koonin, 1997). In genomic DNA from several species, the annotation of exons did not contain the N-terminus of the sequence. In these cases we used the N-terminal amino acid sequence translated from mouse cDNA as a query, which allowed us to identify complete GOAT ortholog amino acid sequences through the use of tblastn searches (http://www.ncbi.nlm.nih.gov/BLAST/). The reference numbers for the corresponding genomic DNA sequences were as follows: rat (NW_047474.1), human (NT_007995.14), bovine (NW_001494415.1), horse (NW_001799700.1), chicken (NW_001471685.1), and zebrafish (NW_001513480.1). Alignments were carried out by ClustalW.

Cell Culture and Transient Transfection

All cells were grown in monolayer at 37°C in an atmosphere of 8.8% CO_2. Mouse AtT-20 cells (obtained from American Type Culture Collection) were cultured in medium A (Dulbecco's modified Eagle's medium (4.5 g/L glucose) supplemented with 2 mM glutamine, 10% (v/v) FCS, 100 U/ml penicillin, and 100 μg/ml streptomycin). Rat INS-1 cells (Asfari et al., 1992) and mouse MIN-6 cells (Miyazaki et al., 1990) were obtained from Dr. Melanie Cobb (University of Texas Southwestern Medical Center). INS-1 cells were cultured in medium B (RPMI 1640 medium supplemented with 10% FCS, 10 mM HEPES, 50 μM β-mercaptoethanol, 100 U/ml penicillin, and 100 μg/ml streptomycin). MIN-6 cells were cultured in medium C (Dulbecco's modified Eagle's medium (4.5 g/L glucose) supplemented with 10% FCS, 10 mM HEPES, 50 μM β-mercaptoethanol, 100 U/ml penicillin, and 100 μg/ml streptomycin).

For transient transfections, AtT-20 cells were set up on day 0 at 1×10^6 per 100-mm dish; INS-1 cells and MIN-6 cells were set up at 1.5×10^6 per 100-mm dish. On day 2, cells were transfected with plasmids using FuGENE HD Transfection Reagent (Roche) at a ratio of FuGENE HD to plasmids of 3:1. On day 3 or 4, cells were subjected to various treatments as described in figure legends. On day 4 or 5, cells were harvested for experiments. The total amount of transfected DNA in each experiment was constant and adjusted to 5 or 6 μg per 100-mm dish by addition of pcDNA3.1 mock vector.

Generation of Anti-Ghrelin Antibody

DNA segments encoding mouse pro-ghrelin and ghrelin were cloned into pGEX-4T1 (GE Healthcare) to generate glutathione *S*-transferase (GST)-fusion proteins. For the GST-pro-ghrelin construct, the thrombin cleavage site within the vector sequence (LVPRGS) between GST and pro-ghrelin was changed to the Tobacco Etch Virus (TEV) protease site (ENLYFQG), and a His_8-tag was added to the C terminus of pro-ghrelin. GST-pro-ghrelin-His_8 and GST-ghrelin were expressed in *E. coli* and purified using glutathione-agarose beads. GST-pro-ghrelin-His_8 was cleaved by recombinant TEV protease (produced in *E.coli* as a GST fusion protein) to release pro-ghrelin-His_8, which was further purified by nickel-affinity chromatography (QIAGEN). For immunization, each rabbit was injected subcutaneously with 500 μg GST-ghrelin in incomplete Freund's adjuvant, followed by alternating booster injections of 250 μg GST-ghrelin or 250 μg pro-ghrelin-His_8, both given subcutaneously in incomplete Freund's adjuvant at two week intervals. The resulting rabbit anti-ghrelin antiserum recognized pro-ghrelin and ghrelin in both the desacylated and acylated forms. The antiserum did not recognize the C-terminal peptide derived from proghrelin cleavage.

Peptide Extraction from Cultured Cells

Peptides were extracted from cultured cells using the protocol described by Kojima et al. (1999). After harvesting, the cell pellet was boiled in 1-2 ml of H_2O for 10 min to inactivate proteases and then cooled on ice, after which acetic acid and HCl were added directly to achieve final concentrations of 1 M and 20 mM, respectively. The cell lysate was further disrupted by passage through a 22-gauge needle 10 times, followed by centrifugation at 20,000*g* for 10 min at 4°C. The resulting supernatant was concentrated under vacuum to ∼20% of the original volume, subjected to 67% (v/v) acetone precipitation, and centrifuged at 20,000*g* for 10 min at 4°C to remove the precipitate. The supernatant was evaporated under vacuum, and the residue was solubilized for SDS-PAGE and immunoblot analysis or reverse-phase chromatography followed by SDS-PAGE and immunoblot analysis as described below.

Immunoblot Analysis of Pro-Ghrelin and Ghrelin

The pellet containing the extracted peptides was dissolved in SDS-PAGE loading buffer (0.1 M Tris-chloride at pH 6.8, 5% (w/v) SDS, 0.1 M dithiothreitol, and 5% (v/v) glycerol), subjected to 16% Tricine SDS-PAGE, and then transferred to Immobilon-P PVDF membranes (Millipore) for immunoblot analysis. To prevent the diffusion of ghrelin during the blotting procedure, we washed each membrane three times with Phosphate-Buffered Saline (PBS) containing 0.05% Tween-20 (Sigma), after which the membrane was fixed at room temperature for 15 min in 50 mM HEPES-NaOH (pH 7.4) containing 2.5% (v/v) glutaraldehyde. The membrane was washed three times with the PBS/Tween-20 solution and then immunoblotted with either a 1:1000 dilution of anti-ghrelin antiserum or 0.5 μg/ml of anti-Flag M2 monoclonal antibody. Bound antibodies were visualized by chemiluminescence (SuperSignal West Pico Developing Kit; Pierce) using a 1:10,000 dilution of either donkey anti-rabbit IgG or donkey anti-mouse IgG conjugated to horseradish peroxidase (Jackson ImmunoResearch). All membranes were exposed to Phoenix Blue X-ray film for 5 s to 2 min at room temperature.

Separation of Desacyl-Ghrelin and Acyl-Ghrelin by Reverse-Phase Chromatography

The residue after evaporation of the acetone was dissolved in 3 ml of 2% (v/v) CH_3CN in 0.1% (v/v) trifluoroacetic acid (TFA) and loaded onto a 360 mg Sep-Pak C18-cartridge (Waters). The cartridge was washed with 3 ml of 2% CH_3CN in 0.1% TFA and eluted with a step-gradient consisting of 6 ml of solution containing 20%, 40%, and 80%-CH_3CN in 0.1% TFA. The first 3 ml of each 6 ml elution were collected and evaporated under vacuum, and the residue was dissolved in 80 μl of SDS-PAGE loading buffer, and aliquots of 20 μl were subjected to SDS-PAGE and immunoblot analysis as described above.

$[^3H]$Octanoate Autoradiography and Identification of $[^3H]$Fatty Acid

$[^3H]$Octanoate-labeled INS-1 cells were processed as described in the legend to Figure 6 and then subjected to autoradiography with a Kodak Transcreen LE Intensifying Screen and Biomax MS Film at −80°C for 5 days. Radioactivity in the PVDF membrane was quantified by cutting each lane into 9 consecutive pieces from top to bottom, followed by liquid scintillation counting in 10 ml of counting cocktail (3a70B, Research Products International Corp.).

To confirm the identity of the ^3H-labeled fatty acid linked to pro-ghrelin and ghrelin, fatty acid methyl ester (FAME) analysis was carried out. Two dishes of transfected cells were radiolabeled with $[^3H]$octanoate. After reverse-phase chromatography, proteins in the 40%-CH_3CN fraction were subjected to SDS-PAGE and transferred to a PVDF membrane. The pieces of membrane containing ^3H-labeled pro-ghrelin and ghrelin were cut out, pooled together, and treated with 0.5 ml of 0.1 M KOH in 100% methanol at room temperature for 2 hr to form FAME. After acidifying the sample with 0.5 ml of 1.0 M HCl, the aqueous phase was extracted twice with 0.1 ml hexane. An aliquot of the pooled organic phase (50 μl) was mixed with 50 μg of each FAME standard (methyl hexanoate, methyl octanoate, methyl decanoate, methyl dodecanoate, methyl myristate, and methyl palmitate) and loaded onto a C18 reverse-phase thin-layer chromatography (TLC) plate (150 μm, 10x20 cm, Analtech). The TLC plate was developed in a solvent system of acetone/methanol/water (80:20:10, v/v/v), and FAME standards were revealed by iodine vapor counter-staining. The lane of TLC was divided into strips numbered 1 to 14 from the origin to the front, with strips 6 to 11 containing FAME standards. The resin on each strip was then scraped off and subjected to liquid scintillation counting as described above.

GOAT mRNA Expression in Mouse Tissues

Six-month old male C57BL/6J mice were fed a chow diet ad libitum prior to study. At the end of the dark phase, mice were anesthetized and exsanguinated. Various tissues were collected, snap-frozen in liquid nitrogen, and stored at −80°C. The stomach, small intestine, and colon were flushed with cold PBS, after which the small intestine was divided into three equal lengths, designated duodenum (proximal), jejunum (medial), and ileum (distal). Each flushed segment of the gastrointestinal tract was cut open with a small scissors, and the mucosa was carefully scraped off and placed in a tube for RNA preparation. Total RNA was prepared from mouse tissues using an RNA STAT-60 kit from Tel-Test Inc. (Friendswood, Texas, USA). Equal amounts of RNA from four mice were pooled, treated with DNase I (TURBO DNA-free, Ambion), and analyzed for mRNA expression of GOAT, prepro-ghrelin, and β-actin using the TITANIUM One-Step RT-PCR Kit (Clontech). Each reaction contained 1 μg of DNase I-treated total RNA isolated from different mouse tissues and primers shown in Table S2. The cycling parameters were set as 94°C, 30 s; 60°C, 30 s; and 68°C, 30 s. Number of cycles for GOAT, prepro-ghrelin, and β-action was 35, 30, and 25, respectively. Aliquots (20 μl) of the 50-μl RT-PCR samples were loaded onto 1.5% agarose gel. All animal experiments were performed with the approval of the Institutional Animal Care and Research Advisory Committee at the University of Texas Southwestern Medical Center at Dallas.

Supplemental Data

Supplemental Data include Supplemental Experimental Procedures and two tables and can be found with this article online at http://www.cell.com/cgi/content/full/132/3/387/DC1/.

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