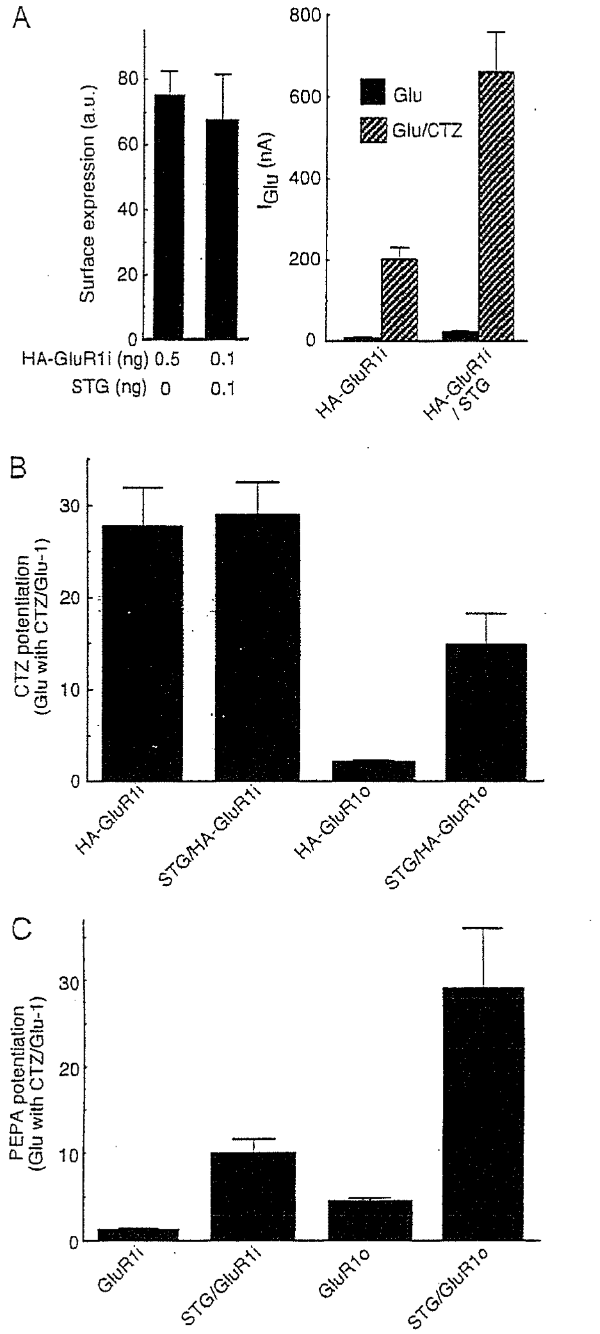

Fig. 1. Stargazin (STG) modulates the subunit specificity of AMPAR potentiators. (*A*) Surface levels of HA-tagged GluR1i (HA-GluR1i) were measured by chemiluminescence. (*Left*) Similar levels of surface GluR1 were detected from oocytes injected with 0.5 ng of GluR1i cRNA alone and with 0.1 ng of GluR1i plus 0.1 ng of stargazin. a.u., arbitrary units. (*Right*) As compared with GluR1 alone, channels containing GluR1i plus stargazin show approximately three times larger currents evoked by 10 μM glutamate, I_{Glu}, in the presence and absence of cyclothiazide (CTZ). (*B*) GluR1o receptors containing stargazin are robustly potentiated by cyclothiazide. (*C*) PEPA robustly potentiates glutamate-evoked currents in stargazin-containing channels of GluR1i or GluR1o. For PEPA experiments, oocytes were injected with 20 ng of GluR1 alone, and currents were evoked with 500 μM glutamate.

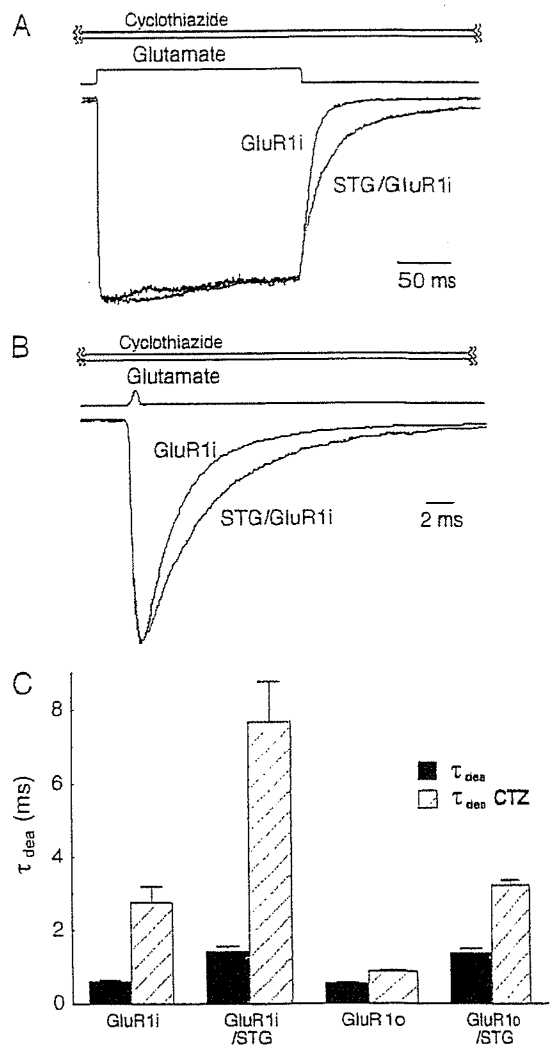

Fig. 2. Stargazin (STG) and cyclothiazide (CTZ) additively delay GluR1 deactivation. Channel kinetics in excised outside-out oocyte patches was quantitated by rapid glutamate perfusion. (*A*) Exemplary traces of responses to 200-ms applications of 10 mM glutamate show blocking of GluR1i desensitization by cyclothiazide (100 μM). (*B*) Exemplary traces of responses to 1-ms applications of 10 mM glutamate show slowing of GluR1i deactivation by stargazin. All experiments were performed with 100 μM cyclothiazide. (*C*) Both stargazin and cyclothiazide independently slow channel deactivation. Together, they additively slow deactivation of both GluR1i and GluR1o.

system. Stargazin does not affect blockade of GluR1i desensitization by cyclothiazide (Fig. 2*A*). However, GluR1i deactivation in the presence of cyclothiazide is slowed 2-fold by stargazin (τ_{off} = 6.5 for GluR1i alone; τ_{off} = 12.8 ms for GluR1i/stargazin). As was published previously (6, 7), both stargazin and cyclothiazide independently slow deactivation (Fig. 2 *B* and *C*). Interestingly, these effects are additive; the actions of stargazin and cyclothiazide slow GluR1i deactivation 12-fold (τ_{dea} = 0.6 for GluR1i alone; τ_{dea} = 7.2 ms for GluR1i/stargazin plus cyclothiazide). Cyclothiazide by itself has a smaller influence on deactivation of GluR1o channels (17). In the presence of stargazin, however, GluR1o channels show significantly slowed deactivation by cyclothiazide (Fig. 2*B*).

The data described above were based on use of a maximally efficacious dose of cyclothiazide (100 μM). Therefore, we asked whether stargazin might also change receptor affinity for this potentiator. As was published previously (14), we found that GluR1i channels are more potently potentiated by cyclothiazide than are GluR1o channels (Fig. 3). Interestingly, we found that stargazin increased the affinity of both channel isoforms for cyclothiazide (Fig. 3).

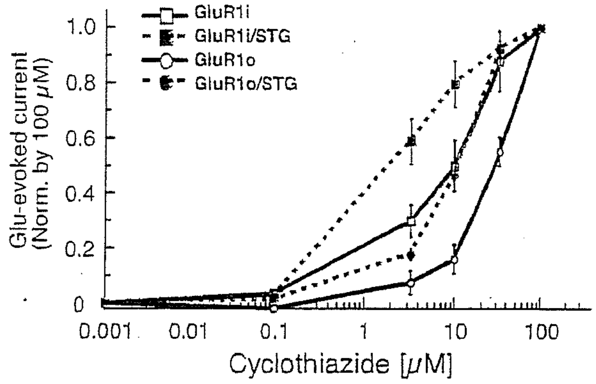

Fig. 3. Stargazin (STG) enhances GluR1 affinity for cyclothiazide. Steady-state currents evoked by glutamate (10 μM) were recorded in oocytes injected with GluR1i or GluR1o in the presence or absence of stargazin. Results are presented normalized to current with 100 μM cyclothiazide. For both GluR1i and GluR1o, stargazin shifted the EC_{50} for cyclothiazide to the left (EC_{50} for GluR1i = 10 μM, GluR1i/stargazin = 2 μM, GluR1o = 29 μM, GluR1o/stargazin = 10 μM).

Discussion

This study demonstrates that stargazin modulates the pharmacology of AMPAR potentiators. Stargazin shows additive effects with AMPAR potentiators to blunt the extent of desensitization and to slow deactivation. Furthermore, stargazin increases the affinity of AMPAR potentiators for glutamate receptor subunits. Interestingly, stargazin modulates the subunit specificity of AMPAR potentiators to make flop receptors sensitive to cyclothiazide and flip receptors sensitive to PEPA. These data provide insight into the mechanisms by which stargazin and AMPAR potentiators modulate channel activity and have implications for the development of AMPAR potentiators in the treatment of neurological diseases.

The mechanism for stargazin modulation of AMPAR kinetics is not certain. Molecular chimera analyses showed that the first extracellular loop of stargazin is essential for controlling AMPAR channel properties (6). Similarly, cyclothiazide influences channel function by interacting near the glutamate-binding pocket in the extracellular domain of the receptor (18). Because stargazin modulates the interaction and effects of AMPAR potentiators, it seems likely that the extracellular loop of stargazin may also interact near the glutamate-binding site. This model would be consistent with the increase in glutamate affinity caused by stargazin (6, 7).

Previous studies have defined at least two classes of AMPAR potentiators. Whereas two cyclothiazide molecules bind in the GluR subunit dimer interface to block desensitization (18), a single aniracetam molecule binds at the center of the dimer interface to slow channel deactivation and desensitization of AMPARs (19, 20). Future structure studies of stargazin with these different types of AMPAR potentiators should provide valuable insights.

Cyclothiazide and stargazin affect desensitization and deactivation of AMPARs independently and additively. Because cyclothiazide blocks desensitization of AMPAR flip isoforms alone and with stargazin, these results suggest that stargazin acts on the opening of AMPARs but may not modulate entry into and out of desensitized states. In support of this model, single-channel analysis revealed that stargazin modulates the gating of AMPARs (6).

The modulation of AMPAR potentiator specificity for alternatively spliced channel subunits is striking. Numerous previously published studies have established that many AMPAR potentiators affect only one of the two alternatively spliced versions of transfected AMPAR subunits. The prototypical AMPAR potentiator, cyclothiazide, specifically augments responses from flip-type channels (14). This differential effect of cyclothiazide has been used extensively to define the relative expression of flip vs. flop isoforms in neuronal populations (21, 22). Our results showing that stargazin modulates the subunit specificity of AMPAR potentiators to make flop receptors sensitive to cyclothiazide add complexity to these analyses.

This study has focused on stargazin; however, there are three additional TARPs that modulate the biophysical properties of AMPAR channels (6, 23). TARPs are differentially expressed in discrete neuronal populations throughout the brain. Notably, stargazin is enriched in cerebellum, γ-3 in cerebral cortex, γ-4 in developing brain, and γ-8 in hippocampus (23). Whether TARP isoforms differentially modulate the pharmacology of AMPARs, and whether this specificity can explain the differential responses found in various neuronal populations, will require further study.

This work has implications for the clinical pharmacology of AMPAR potentiators. Preclinical and early clinical studies have shown that AMPAR potentiators can enhance cognitive function as nootropic agents and have therapeutic potential in a variety of mental and neurodegenerative diseases, including schizophrenia, depression, and Parkinson's disease (8–11). Discovery of the TARP family of AMPAR auxiliary subunits should facilitate development of clinically useful AMPAR potentiators.

Materials and Methods

Electrophysiology Using *X. laevis* Oocytes. Two-electrode voltage-clamp recordings were performed as described in ref. 24. Briefly, GluR1i, GluR1o, and stargazin were subcloned into pGEM-HE vector. cRNAs were transcribed *in vitro* by using T7 mMessage mMachine (Ambion, Austin, TX) and injected into oocytes. Two days after injection, levels of cell surface HA-GluR1 were quantitated by chemiluminescence as described in ref. 6. Oocytes expressing similar amounts of receptor were subjected to two-electrode voltage-clamp analysis (redox holding potential, E_h = −70 mV), which was performed at room temperature in recording solution containing 90 mM NaCl, 1.0 mM KCl, 1.5 mM $CaCl_2$, and 10 mM Hepes (pH 7.4).

Outside-Out Patch Recordings. Outside-out patches from injected oocytes were obtained as described previously (25). Outside-out patch recording was carried out with an EPC-8 amplifier (HEKA Electronics, Lambrecht/Pfalz, Germany) under continuous perfusion with frog Ringer's solution (115 mM NaCl/2 mM KCl/2 mM $CaCl_2$/10 mM Hepes, adjusted to pH 7.2 with NaOH). The patch pipette was prepared from borosilicate glass capillaries (WPI Instruments, Waltham, MA) and had 4- to 7-MΩ input resistance when filled with 100 mM KCl/2 mM $MgCl_2$/10 mM EGTA/10 mM Hepes, adjusted to pH 7.2 with KOH. Responses were filtered at 10 kHz and digitized at 26 μs per point. The holding potential was at −60 mV. Fast application of glutamate was performed by using the methods described previously (25). Briefly, glutamate (10 mM) was applied by perfusion of the patch membrane with θ tubes driven by a piezo manipulator (PZ-150M; Burleigh Instruments, Fishers, NY). After recording, the patch membrane was blown off and the junction current between the control solution and 10% frog Ringer's solution was measured to monitor solution exchange without moving the patch pipette and θ tube. Responses to glutamate having a 20–80% rise time <400 μs were used for analysis. The decay phase of the response was fitted with single-exponential functions by using IGOR PRO (WaveMetrics, Lake Oswego, OR).

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MOLECULAR REPRODUCTION AND DEVELOPMENT 73:40–49 (2006)

Overexpression of Ubiquitin Carboxyl-Terminal Hydrolase L1 Arrests Spermatogenesis in Transgenic Mice

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ABSTRACT Ubiquitin carboxyl-terminal hydrolase 1 (UCH-L1) can be detected in mouse testicular germ cells, mainly spermatogonia and somatic Sertoli cells, but its physiological role is unknown. We show that transgenic (Tg) mice overexpressing *EF1α* promoter-driven UCH-L1 in the testis are sterile due to a block during spermatogenesis at an early stage (pachytene) of meiosis. Interestingly, almost all spermatogonia and Sertoli cells expressing excess UCH-L1, but little PCNA (proliferating cell nuclear antigen), showed no morphological signs of apoptosis or TUNEL-positive staining. Rather, germ cell apoptosis was mainly detected in primary spermatocytes having weak or negative UCH-L1 expression but strong PCNA expression. These data suggest that overexpression of UCH-L1 affects spermatogenesis during meiosis and, in particular, induces apoptosis in primary spermatocytes. In addition to results of caspases-3 upregulation and Bcl-2 downregulation, excess UCH-L1 influenced the distribution of PCNA, suggesting a specific role for UCH-L1 in the processes of mitotic proliferation and differentiation of spermatogonial stem cells during spermatogenesis. *Mol. Reprod. Dev. 73: 40–49, 2006.* © 2005 Wiley-Liss, Inc.

Key Words: UCH-L1; transgenic mouse; spermatogenesis; testis; apoptosis

INTRODUCTION

Mammalian spermatogenesis is a complex process of cellular differentiation. Spermatogonia serve as the self-renewing stem cells for spermatogenesis and undergo mitotic divisions that yield primary spermatocytes (Matzuk and Lamb, 2002). In addition to germ cells, somatic Sertoli cells also are a major cell population in the testis, comprising the seminiferous tubule epithelium that nurtures germ cells (Imai et al., 2004).

Components of the ubiquitin system appear to be involved in different steps and processes during spermatogenesis (Baarends et al., 2000; Sutovsky, 2003). Ubiquitin is a highly evolutionarily conserved 76-residue polypeptide that plays a critical role in many cellular processes, including the cell cycle, cell proliferation, development, apoptosis, signal transduction, and membrane protein internalization (Williams et al., 2002). Ubiquitin appears to be expressed in mammalian testes/ovaries and embryos at all developmental steps, and its level is modulated by ubiquitynating and deubiquitynating enzymes. However, the details of the involvement of these enzymes in ubiquitin-dependent proteolysis during gametogenesis and fertilization remain uncertain. Several deubiquitynating enzymes were recently reported (Wilkinson, 2000; Wing, 2003) and have been classified as either ubiquitin carboxyl-terminal hydrolases (UCHs) or ubiquitin-specific processing proteases. UCHs liberate free ubiquitin by cleaving ubiquitin-containing covalent complexes, namely ubiquitylated small ribosomal proteins (L40, S27a) or tandemly conjugated polyubiquitin (e.g., UbB, UbC) (Wilkinson, 2000). UCHs can also hydrolyze bonds between ubiquitin and small adducts or unfolded polypeptides in vitro. Thus, UCHs are thought to serve dual functions: to salvage ubiquitin that has been trapped by reactions with low-molecular weight thiols/amines and to process polyubiquitin or ubiquitylated proteins.

In mice, there are at least four closely related low-molecular weight UCH family members, UCH-L1 and UCH-L3–5 (Kurihara et al., 2001; Osawa et al., 2001). The distribution and function of UCH-L4 and UCH-L5 are not clear. UCH-L3, however, is expressed ubiquitously, whereas UCH-L1 is selectively expressed in the testis/ovary and brain. Moreover, UCH-L1 is highly

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expressed in mouse spermatogonia and somatic Sertoli cells but not in post meiotic germ cells (Kwon et al., 2004a). By contrast, UCH-L3 is detected mainly in spermatocytes and round spermatids (Kwon et al., 2004a). These two isozymes are considered to play important roles in the labeling/targeting of abnormal proteins for degradation via the ubiquitin-proteasome system (Wilkinson, 2000).

The gracile axonal dystrophy (*gad*) mouse is an autosomal recessive spontaneous mutant carrying an intragenic deletion of the gene encoding UCH-L1 (*Uchl1*). *gad* mice do not express UCH-L1 and thus are comparable to a *Uchl1* null mutant (Yamazaki et al., 1988; Saigoh et al., 1999). We recently showed that *gad* mice are resistant to the germ cell apoptosis during the first round of spermatogenesis (Kwon et al., 2005) and are also resistant to cryptorchid-induced testicular germ cell apoptosis (Kwon et al., 2004b). The expression of the apoptotic proteins p53, Bax, and caspases-3 was significantly lower in the immature testes, and the expression of both antiapoptotic and prosurvival proteins such as Bcl-2, Bcl-xL, XIAP, pCREB, and BDNF was significantly higher in *gad* mice following experimental cryptorchidism (Kwon et al., 2004b). These data prompted our hypothesis that UCH-L1 may be an important regulator of apoptosis during spermatogenesis. Experiments toward this end may provide additional evidence that UCH-L1 regulates spermatogenesis.

Our present report presents the characterization of the male sterility phenotype and the quantitation of apoptotic spermatocytes in *Uchl1* transgenic (Tg) mice. Constitutive expression of UCH-L1 in the testis results in a blockade of spermatogenesis at the pachytene stage of spermatocytes due to an increase in the number of apoptotic spermatocytes. These results indicate that excess UCH-L1 affects spermatogenesis during meiosis and, in particular, induces apoptosis in primary spermatocytes.

MATERIALS AND METHODS

Animals

We have previously described the Tg *Uchl1* mice carrying a 0.7-kb FLAG-tagged mouse *Uchl1* cDNA with the human translation elongation factor-1α (*EF-1α*) promoter (Osaka et al., 2003). Tg mice were identified by PCR analysis of tail DNA using specific primers (forward: ex6F, 5′-ATCCAGGCGGCCCATGACCTC-3′; reverse: ex9R, 5′-AGCTGCTTTGCAGAGAGCCA-3′). The *gad* mouse is an autosomal recessive mutant that was obtained by crossing CBA and RFM mice (Saigoh et al., 1999). All strains were maintained at our institute. To corroborate fertility disturbances in UCH-L1 Tg mice, a subset of the mice was continuously mated with wild-type C57BL/6J mice. The mating of two heterozygous Tg males with non-Tg females did not yield offspring until the age of 6 months despite grossly normal appearance. This was also the case for the mating of four heterozygous Tg females with non-Tg males. Their non-Tg littermates sired offspring normally. Finally, all six Tg mice were infertile, but they did not exhibit any apparent neurological phenotype during adulthood. Controls included nontransgenic (non-Tg) littermates and UCH-L1-deficient *gad* mice (Saigoh et al., 1999). Mice were sacrificed by cervical dislocation before tissue collection. Animal care and handling were in accordance with institutional regulations for animal care and were approved by the Animal Investigation Committee of the National Institute of Neuroscience, National Center of Neurology and Psychiatry of Japan.

mRNA Isolation, and Exogenous *Uchl1* Expression Measured by Quantitative Real-Time RT-PCR

Total RNA from testes was isolated using the Trizol reagent (Gibco BRL Life Technologies, Bethesda, MD) and purified following the manufacturer's instructions. Real-time quantitative RT-PCR primer pairs flanking introns were used to specifically amplify transgene products, and their sequences were: forward, 5′-ATTTCAGGTGTCGTGAGGAA-3′; and reverse, 5′-CCCACGTGGGAGACCTGATA-3′. Real-time quantitative PCR products, from 0.25–2.5 ng of reverse-transcribed cDNA samples, were detected using an ABI Prism, 7700 system (Applied Biosystems) as described previously (Aoki et al., 2002). β-Actin and GAPDH were used as endogenous controls. Results are expressed as the ratio of the mRNA level of the transgene to that of β-actin or GAPDH. As an external standard for quantitative analysis, the cDNA of the 3′-noncoding region of mouse *Uchl1* cDNA (covering the RT-PCR primers) was cloned and inserted into a pcDNA3 vector, purified, precisely quantified, and serially diluted 10-fold to 10 copies/μl. Standard curves were determined using linear regression analysis of the Ct values relative to plasmid copy numbers. In each real-time quantitative PCR assay, a 10-fold serially diluted cDNA template series was added to construct a standard curve for copy number. Each sample was analyzed in triplicate, and copy numbers were determined from each corresponding standard curve by the ratio of Tg *UCH-L1* to mouse *Uchl1*.

Histological Observations, Immunohistochemistry, and Immunofluorescence

Morphological studies were performed on six male controls and two male Tg mice (Tg21 and Tg22, both 6 months old). The two control groups consisted of three non-Tg wild-type C57BL/6J mice, 6 months old, littermates, and three *gad* mice, age 4 months. Testes were fixed in 4% paraformaldehyde for 24 hr and embedded in paraffin. Serial 5-μm sections were used for histology after hematoxylin–eosin staining as well as for immunohistochemistry and the TUNEL assay. Primary monoclonal or polyclonal antibodies against the following proteins were used at the final dilutions indicated: UCH-L1 (RA95101, Ultraclone, Lucigen, Middleton, WI, 1:2,000), FLAG (FM2, Sigma, St. Louis, MO, 1:500), PCNA (PC10, Santa Cruz Biotechnology, Santa Cruz, CA, 1:200), PCNA (Clone 24, BD Transduction

Laboratory, Lexington, KY, 1:2,000), vimentin (Zymed, 1:100), and ubiquitin (Dako, Carpenteria, CA, 1:400). For controls, the primary antibody was replaced with normal rabbit serum or was omitted (these controls always yielded negative staining). For immunofluorescence studies, secondary antibodies were anti-mouse-Cy3 or -FITC or anti-rabbit-conjugated-Cy3 or -FITC (Jackson ImmunoResearch, West Grove, PA, 1:500).

TUNEL Assay

TUNEL staining was performed according to the original protocol, with modifications (Harada et al., 2004). The number of apoptotic cells was determined by counting positively stained nuclei in 30 tubule cross-sections per testis section in each testis (Kwon et al., 2004b). For clarity and brevity, we also counted all the TUNEL-stained cells within the entire cell population of testicular tubules in each section. In addition, we also counted the apoptosis-positive tubules (i.e., tubules containing at least one apoptotic cell) in each testis.

Western Blotting

Protein lysates were prepared from mouse testes as described (Kwon et al., 2004b). Approximately 20 µg of total protein was loaded per lane on 15% SDS–PAGE gels. Primary antibodies (diluted as indicated) were used to detect the following proteins: UCH-L1 (RA95101, 1:5,000), FLAG (FM2, Sigma, 1:2,000), Bcl-2 (Cell Signaling, Beverly, MA, 1:1,000), caspase-3 (Cell Signaling, 1:400), polyubiquitin (FK2 clone, Medical & Biological Laboratory, Nagoya, Japan, 1:1,000), and monoubiquitin (U5379, Sigma, 1:1,000). Blots were further incubated with peroxidase-conjugated goat anti-mouse IgG or goat anti-rabbit IgG (1:5,000; Pierce, Rockford, IL) for 1 hr at room temperature. Immunoreactions were visualized using the SuperSignal West Dura extended duration substrate (Pierce) and analyzed with a ChemiImager (Alpha Innotech, San Leandro, CA). ChemiImager data were analyzed using AlphaEase software (Alpha Innotech) to yield the relative level of each protein.

RESULTS

Sterile Phenotype of *Uchl1* Tg Mice

We initially attempted to overexpress *Uchl1* in neurons using a Tg construct containing the *EF-1α* promoter (Mizushima and Nagata, 1990). The transgene was also strongly expressed in gonads as well as other Tg mice via the same promoter (Furuchi et al., 1996). We obtained six Tg mice having high transgene copy number, each of which most likely carried the transgene in a unique genomic location (see below). Four of these mice were females (Tg11, Tg12, Tg43, Tg81) and two were males (Tg21 and Tg22). Unexpectedly, all of these Tgs were sterile. Thus, it was not possible to maintain Tg lines during the course of these experiments. However, in addition to the sterile phenotype, the six independent Tg mice showed a similar pattern of *Uchl1* transgene expression and common pathological defects, the latter being limited to the testes or ovaries. The Tg loci were generated by random integration rather than by site-specific recombination, and thus the animals produced by our Tg procedure usually had more than one transgene integrated at each chromosomal site (Kroll and Amaya, 1996). Therefore, in each of the six Tg mice, the transgene most likely integrated into a different genomic site, raising the possibility of different position-dependent effects. Our data showed that we obtained multiple animals with similar patterns or levels of *Uchl1* transgene expression and with common pathological defects, suggesting the phenotypes reflect position-independent expression (i.e., independent of the position of transgene insertion). Thus, these Tg mice had similar infertile phenotypes that may be attributed to the overproduction of UCH-L1. Numerous gene inactivation studies have identified gene products involved in male fertility, but in most cases female reproduction was unaffected or weak damaged (Yuan et al., 2000). However, both male and female *Uchl1* Tg mice were infertile, although there were clear differences in germinal cell maturation, suggesting that UCH-L1 is required for both spermatogenesis and oogenesis. Therefore, six independent Tg founders, notably two males (Tg21 and Tg22), were analyzed in our present study.

The mating of two heterozygous Tg males with non-Tg females did not yield offspring until the age of 6 months, despite grossly normal appearance. This was also the case for the mating of four heterozygous Tg females with non-Tg males. Their non-Tg littermates sired offspring normally. At autopsy, the testes of both Tg21 and Tg22 appeared grossly smaller than those of non-Tg mice. The testes weight of Tg21 (77 mg) and Tg22 (70 mg) was only 42% and 38%, respectively, relative to non-Tg males (183 ± 16 mg), demonstrating that mice overexpressing UCH-L1 display profoundly defective testis development.

Expression Levels of the *Uchl1* Transgene

We used RT-PCR and primers specific for the *Uchl1* transgene to compare transgene expression levels in the testes or ovaries of the six Tg mice. There was some variation between animals (Fig. 1A). All the Tgs expressed a similar level of endogenous *Uchl1* mRNA (Fig. 1A); quantitation of absolute Tg *Uchl1* copy numbers using real-time quantitative RT-PCR showed that all six Tgs expressed 2.9–6.8-fold more *Uchl1* transgene mRNA compared with endogenous mRNA (4.5, 3.6, 6.2, 3.7, 2.9, and 6.8 for Tg21, Tg22, Tg11, Tg12, Tg43, and Tg81, respectively). Relative UCH-L1 protein expression was similar among four of the Tgs (76.1 ± 5.2; Fig. 1B) but was somewhat higher in Tg 21 (100) and Tg81 (106.2). The average level of endogenous UCH-L1 expression in Tg mice was ~91% relative to non-Tg mice (Fig. 1B).

Immunohistochemistry of testicular sections using an antibody against FLAG revealed that exogenous UCH-L1 localized mainly in spermatogonia and Sertoli cells (Fig. 2E), similar to the localization of endogenous UCH-L1 (Fig. 2A). Endogenous UCH-L1 localized to both the cytoplasm and nucleus of spermatogonia and Sertoli

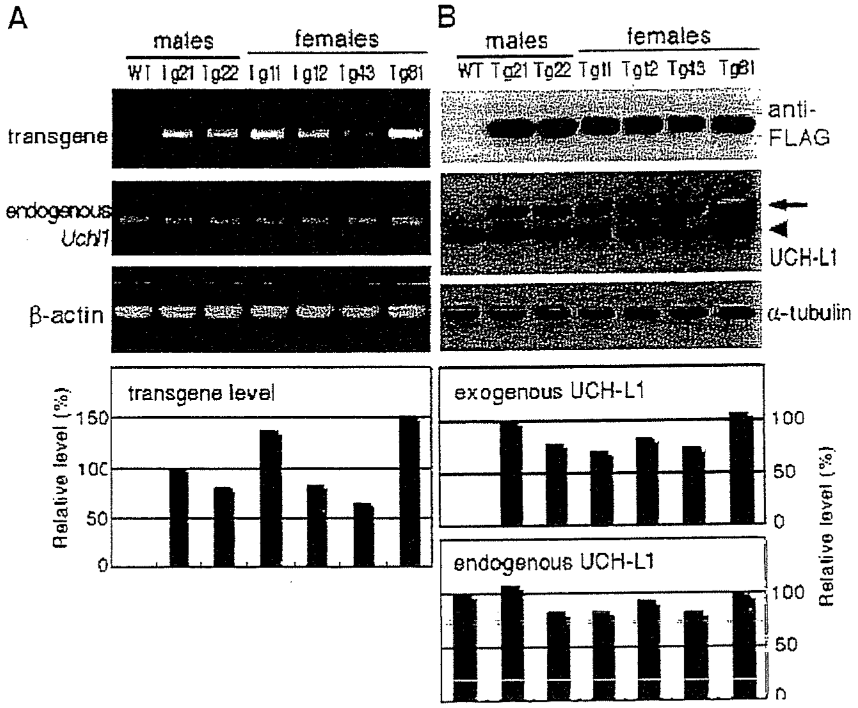

Fig. 1. Expression of transgenic ubiquitin carboxyl-terminal hydrolase 1 (UCH-L1) in the testes of Tg21 and Tg22 male mice. A: Transgenic *Uchl1* mRNA levels in the testes. RT-PCR showed high levels of *Uchl1* transgene mRNA in both Tg21 and Tg22 as well as in all ovaries from four female Tg mice. All Tg mice had a normal level of endogenous *Uchl1* mRNA. The relative expression level is indicated below each lane (as a percentage, scaled to β-actin in each lane). B: Western blot analysis of testicular or ovarian lysates. Both endogenous and exogenous UCH-L1 were detected with anti-UCH-L1, whereas exogenous UCH-L1 was specifically detected by anti-FLAG. Exogenous UCH-L1 (arrow) is slightly larger than endogenous UCH-L1 (arrowhead). WT, non-Tg wild-type.

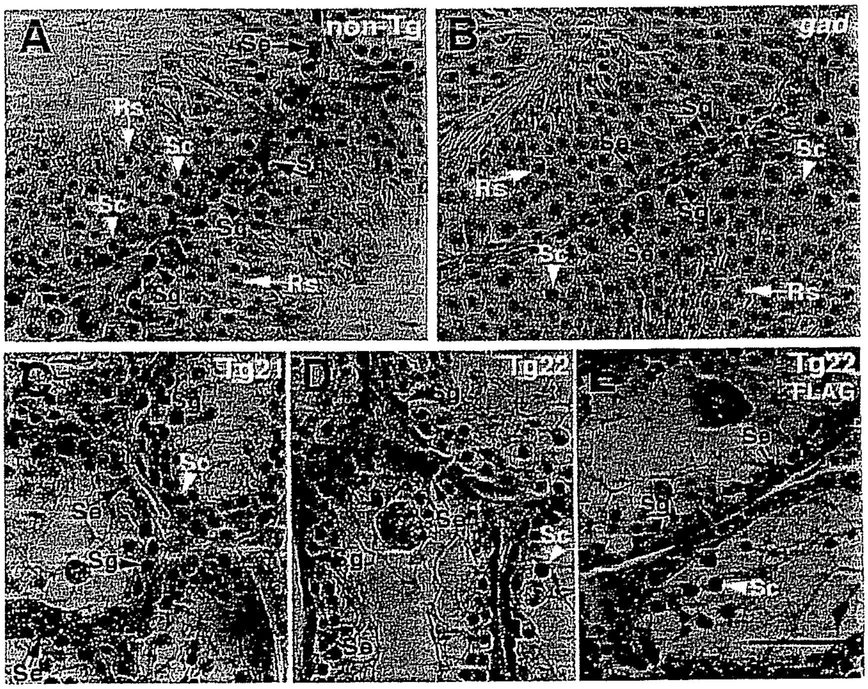

Fig. 2. Immunostaining of FLAG and UCH-L1 in *Uchl1* Tg mice shows high levels of UCH-L1 in testicular tubules. UCH-L1 immunostaining is clearly present in spermatogonia (Sg) and Sertoli cells (Se) of a non-Tg mouse (A) but not in a *gad* mouse (B). In contrast, in the testes of two Tg males, the most intense UCH-L1 immunoreactivity occurs predominantly in spermatogonia (Sg, arrowheads) and Sertoli cells (Se, arrows) but not in the primary spermatocytes (Sc, white arrowheads; C, Tg21; D, Tg22). E: Immunostaining of FLAG confirmed the transgene-derived UCH-L1 proteins in spermatogonia (Sg, arrowheads) and Sertoli cells (Se, arrows) but not in the primary spermatocytes (Sc, white arrowheads; Tg22). Magnification: ×400. Scale bar, 50 μm.

cells in the testes of non-Tg males; however, localization was not apparent around pachytene spermatocytes or round, elongated spermatids (Fig. 2A). This distribution of UCH-L1 is in good agreement with previous reports (Kon et al., 1999; Kwon et al., 2004a). Compared with non-Tg males, overexpression of UCH-L1 in seminiferous tubules of Tg males (Tg21 and Tg22) occurred predominantly in spermatogonia and Sertoli cells, and was weakly positive or negative in spermatocytes (Fig. 2C,D). These data coincided with strong induction of the *Uchl1* transgene. Tg mice expressed a higher level of total UCH-L1 (both endogenous and exogenous), suggesting a correlation between excess UCH-L1 and sterility.

Morphological Examination

Histopathological analysis of testes from 6-month-old Tg21 and Tg22 revealed terminal loss of differentiated germ cells and a large number of pachytene spermatocytes that had degenerated (with condensed nuclei and giant cells) and been sloughed off, forcing an altered structure of the seminiferous tubules such that they appeared almost empty (Fig. 3A). The deformed seminiferous tubules also contained numerous arrested spermatocytes (Fig. 3A, arrowheads) and multinucleated giant cells (arrows). In contrast, the seminiferous tubules of *gad* mice were nearly intact, as in non-Tg males (data not shown). In non-Tg males, seminiferous tubules containing elongated spermatids in the inner layer were readily detected (data not shown), whereas these tubules were scarcely detectable in Tg21 (Fig. 3A) and Tg22. On the other hand, the four female Tg mice displayed a variety of phenotypes, including an increased number of apoptotic oocytes and granulosa cells relative to non-Tg females, leading to infertility (data not shown).

In non-Tg (Fig. 3B) and *gad* mice (Fig. 3C), only a few TUNEL-positive cells were identified, located at the periphery of the tubule. However, many fewer TUNEL-positive cells were detected in the Tg males (Fig. 3D,E), and cell morphology indicated that most of these positive cells were primary spermatocytes. However, neither the TUNEL assay nor microscopy revealed evidence of apoptosis in spermatogonia or Sertoli cells. We quantitatively assessed germ cell apoptosis in Tg, non-Tg, and *gad* mice by calculating the number of apoptotic cells per tubules in each testis. This value was 25 times higher in Tg testes compared with non-Tg or *gad* testes (the averages ± SD were as follows: 553 ± 72, n = 2 in Tg testes; 22 ± 4.2, n = 3 in non-Tg; and 21 ± 5.3, n = 3 in *gad*). The percentage of apoptosis-positive tubules in Tg testes was also significantly higher than in non-Tg or *gad* mice (the averages ± SD were as follows: 95.3 ± 2.7, n = 2 in Tg testes; 7.4 ± 2.2, n = 3 in non-Tg; and 7.1 ± 1.8, n = 3 in *gad*).

A control section of caput epididymis, an androgen-dependent organ, from same Tg mice was investigated. No UCH-L1 overexpressing was detected, and no pathological symptoms could be observed in the epididymis (data not shown).

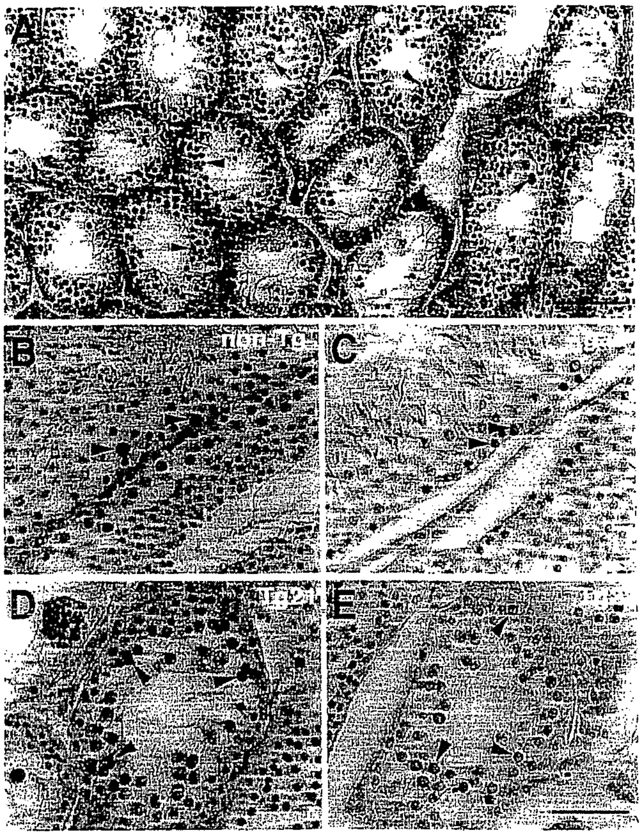

Fig. 3. Histopathology and TUNEL assay in situ. A: Hematoxylin–eosin staining of testis sections from the Tg21 male mouse shows defective spermatogenesis. Arrowheads indicate arrested spermatocytes and arrows indicate giant cells. Round spermatocytes and spermatids were rarely observed. B–E: Examples of TUNEL-positive cells characterized by the robust deposition of the reddish brown reaction product in sections of testis from non-Tg (B), *gad* (C), and Tg mice (D, Tg21; E, Tg22). Sections were counterstained with hematoxylin. A large number of TUNEL-positive cells were clearly observed at the periphery of the seminiferous tubule (arrowheads) in Tg21 (D) and Tg22 (E), whereas a lesser number of positives were apparent in non-Tg (B) or *gad* mice (C). Most of these positive cells appeared to be primary spermatocytes. Magnification: (A) ×100; (B–E) ×400. Scale bar in (A) 200 μm; (E) 50 μm.

UCH-L1 Relates to the Expression of PCNA

PCNA expression is associated with cell proliferation and DNA synthesis during S phase of the cell cycle and DNA repair in non-dividing cells (Kelman, 1997; Toschi and Bravo, 1988). Unlike UCH-L1, which is abundant in brain, PCNA is not detectable in the central nervous system (Saigoh et al., 1999; Williams et al., 2002). In the testis, PCNA is expressed in germ cells and Sertoli cells, and the nuclear localization of PCNA overlaps with that of UCH-L1 in monkey testis (Tokunaga et al., 1999). Our recent study showed that mice lacking UCH-L1 have significantly decreased numbers of PCNA-positive cells in seminiferous tubules (Kwon et al., 2003). These results led us to hypothesize that UCH-L1 may be closely associated with spermatogonial proliferation activity, possibly to maintain the primordial nature of these cells. We thus immunostained testes for PCNA and UCH-L1. In non-Tg and *gad* testes, PCNA-positive staining was confined to spermatogonia and primary spermatocytes and was not evident in Sertoli cells (Fig. 4A,D,B,E) Similarly, the percentage of PCNA-positive spermatogonia and spermatocytes in the seminiferous tubules of *gad* mice was significantly lower than that of non-Tg mice (Fig. 4A,D,B,E) as we previously observed (Kwon et al., 2003). In contrast, Tg mouse testes showed greater PCNA staining in these cells; surprisingly however, staining was observed in nearly all arrested primary spermatocytes but not in spermatogonia (Fig. 4F). These findings suggest that UCH-L1 plays a specific role in mitotic proliferation. To further clarify the effect of UCH-L1 on PCNA levels, FLAG-tagged *Uchl1* was transfected into GC-1, a germ cell line derived from type B spermatogonia (Hofmann et al., 1992). UCH-L1 (anti-FLAG, Fig. 4G,I, green) and PCNA (Fig. 4H,I, red) were then visualized using immunofluorescence microscopy. Cells transfected with *Uchl1* showed lower PCNA immunoreactivity compared with mock-transfected cells (Fig. 4G), consistent with the assertion that PCNA is downregulated by UCH-L1 in vivo. However, no change of PCNA level was observed in *Uchl3* transfected cells (data not shown),

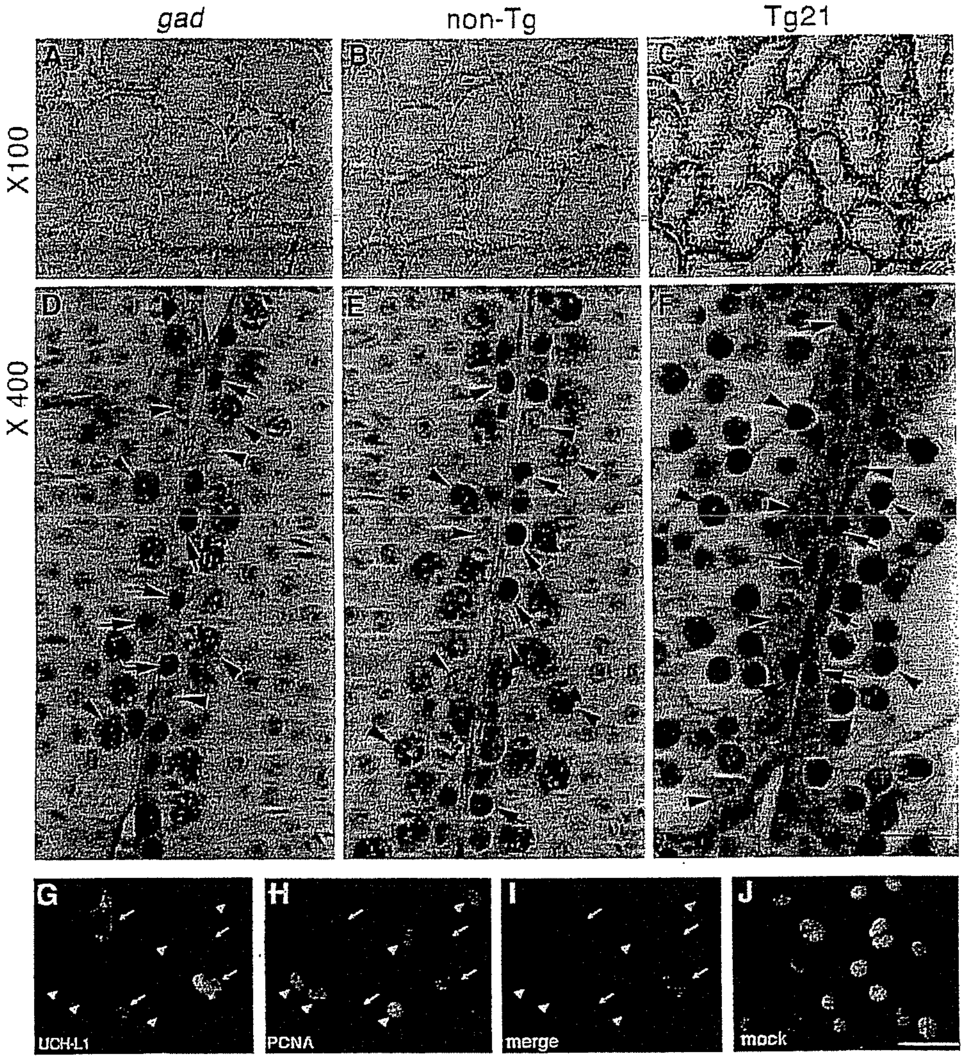

Fig. 4. PCNA immunostaining in the testes of a *gad* mouse (A, D), a non-Tg mouse (B, E), a Tg mouse (C, F; Tg21), and in the transient transfection assay with UCH-L1 using GC-1 cells (G–J). In *gad* and non-Tg testes, positive immunostaining was confined to spermatogonia (D, E; black arrows) and primary spermatocytes (D, E; red arrowheads), and staining was not seen in Sertoli cells (D, E; black arrowheads). In contrast, cell staining was more intense in the testis of Tg mice; however, this intensity was observed in almost all arrested primary spermatocytes (F; red arrowheads) but not in spermatogonia (F; black arrows). The staining of non-Tg and *gad* mice was essentially identical. However, nearly all the primary spermatocytes from Tg mice had relatively strong reactivity compared with spermatogonia that had very faint PCNA reactivity (black arrows). Plasmid pCIneo-*Uchl1* (G–I) or vector alone (J, mock) was transfected into GC-1 cells and expressed. Antibodies against FLAG (Sigma, monoclonal) and PCNA (BD Transduction Laboratory, polyclonal) were used to detect exogenously expressed UCH-L1 (G, I, green) and endogenous PCNA (H, J, I, red), respectively. Cells expressing a high level of UCH-L1 (G, white arrows) had a relative low level of PCNA (H, white arrows), whereas cells expressing a low level of UCH-L1 (H, white arrowheads) had high PCNA levels (H, white arrowheads). Magnification: (A–C) ×100; (D–J) ×400. Scale bar: **Upper panels** (see **panel** C), 200 μm; **middle panels** (see **panel** F), 50 μm; **lower panels** (see **panel** J), 50 μm.

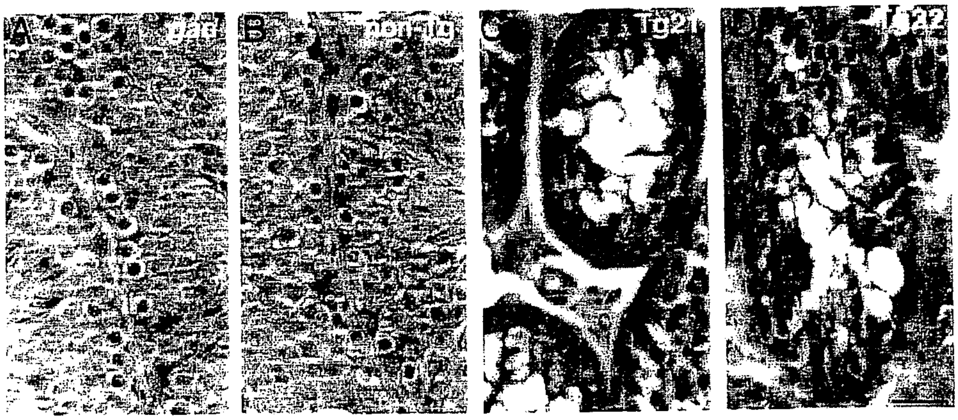

Fig. 5. Vimentin immunostaining in the testes of a *gad* mouse (A), a non-Tg mouse (B), and Tg mice (C, Tg21; D, Tg22). No difference was observed in the pattern and density of vimentin staining in Sertoli cells between *gad* (A) and non-Tg testes (B). In contrast, Sertoli cell staining was more intense in the Tg mice (C, D). Magnification: ×400. Scale bar, 200 μm.

suggesting the specificity of UCH-L1 effect on PCNA levels.

Sertoli Cells Exhibit High-Level Vimentin Expression in Tg Mice

We examined the immunoreactivity to vimentin, which is a marker of Sertoli cells (Oke and Suarez-Quian, 1993; Mori et al., 1997). Vimentin immunostaining was observed in Sertoli cells, and there is no difference between *gad* and non-Tg mice (Fig. 5A,B). In contrast, very strong expression of vimentin was observed in almost all Sertoli cells throughout the cytoplasm in Tg mice (Fig. 5C,D).

Bcl-2 Downregulation and Caspase-3 Upregulation in Tg Mice

The two key proteins, Bcl-2 and caspases-3 that involved in testicular germ cell apoptosis are especially altered during spermatogenesis or stress-induced germ cell apoptosis in *gad*mice (Harada et al., 2004; Kwon et al., 2004b, 2005). We thus examined the expression of these proteins in Tg and non-Tg testes to determine whether they are actually involved in countering increased apoptosis. Bcl-2 expression was downregulated in the testes of Tg mice compared with non-Tg mice (Fig. 6). In contrast to non-Tg mice, Tg mice had an elevated level of the activated caspase-3 subunit, p17 (Fig. 6), controversial to that observed in the retina of *gad* mice after ischemic injury (Harada et al., 2004). These results are consistent with the profound difference in UCH-L1 expression in these two mouse lines.

Upregulations of both Mono- and Poly-Ubiquitin in Tg Mice

Our recent studies suggested novel functions for UCH-L1, namely that it effectively upregulates ubiquitin levels at the post-transcriptional level (Osaka et al., 2003) and that ubiquitin induction plays a critical role in regulating cell death during cryptorchid injury–mediated germ cell apoptosis (Kwon et al., 2004b). Moreover, the testes of mice expressing K48R mutant ubiquitin are protected from cryptorchid injury (Rasoulpour et al., 2003). Given this information, we examined ubiquitin levels in *Uchl1* Tg mice. As expected, ubiquitin expression was strong in testicular cells of Tg mice (Fig. 7C,D), particularly in the arrested spermatocytes, but its expression was low in *gad* mice (Fig. 7B) compared with non-Tg mice (Fig. 7A). These data provide additional evidence that ubiquitin expression is induced upon UCH-L1 overexpression. To determine whether the increased ubiquitin staining represented monoubiquitin or polyubiquitin, we next examined the levels of both ubiquitin forms via immunoblotting (Fig. 7E). As expected, mono- and poly-ubiquitin levels in Tg mice were substantially higher than in non-Tg mice. A *gad* mouse control had relatively low levels

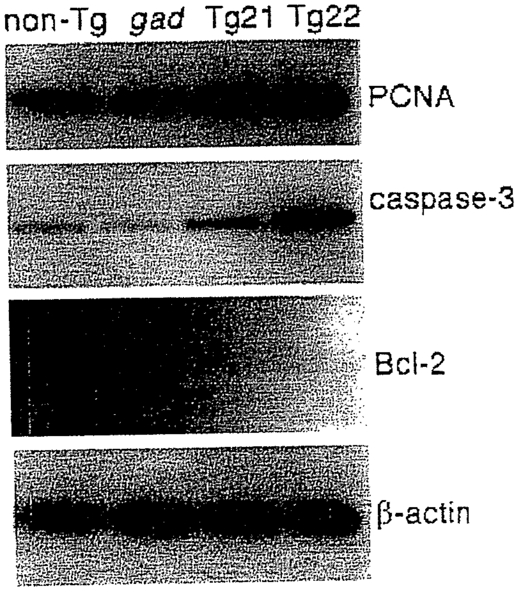

Fig. 6. Western blot analysis of Tg mouse testicular lysates. Consistent with the immunohistochemistry results, PCNA and caspase-3 substantially accumulated in Tg mice. However, the expression of antiapoptotic Bcl-2 decreased compared with non-Tg or *gad* mice.

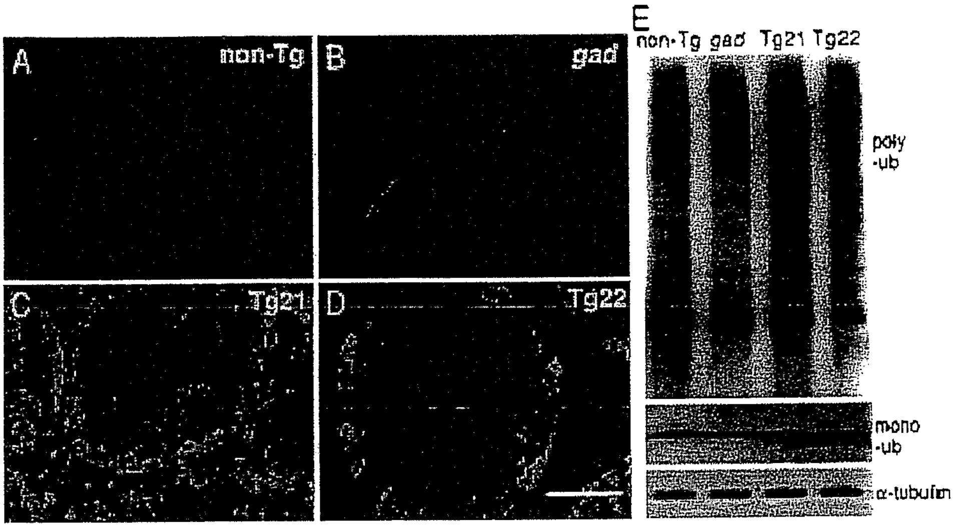

Fig. 7. The levels of mono- and poly-ubiquitin in the testes of non-Tg and Tg males. Double immunostaining for UCH-L1 and ubiquitin in the testis (A, non-Tg; B, *gad*; C, Tg21; D, Tg22). All strongly UCH-L1-positive cells (green) were also strongly positive for ubiquitin (red) in the two male Tg mice. Scale bar, 50 μm. E. An immunoblot showing that both mono- and poly-ubiquitin expression were significantly increased in the two Tg mice compared with non-Tg and *gad* mice (ub, ubiquitin).

of both mono- and poly-ubiquitin (Fig. 7E). These findings are consistent with previous studies and support the hypothesis that UCH-L1-mediated spermatocyte apoptosis involves the induction of ubiquitin expression.

DISCUSSION

Apoptosis in testicular germ cells is regulated by a complicated signal transduction pathway; however, the molecular mechanisms regulating this process are uncertain. We recently showed that *gad* mice, lacking UCH-L1 function, are resistant to apoptotic stress (Harada et al., 2004; Kwon et al., 2004b). These observations conclusively indicate that UCH-L1 plays a role in germ cell death during experimental stress-induced apoptosis. We thus hypothesized that germ cell apoptosis is directly induced by excess UCH-L1. To test this hypothesis, we utilized three mouse lines, wild-type (non-Tg), *gad* and *Uchl1* Tgs, which differ with respect to UCH-L1 expression. In Tg mice, germ cell apoptosis was barely detectable in spermatogonia or Sertoli cells, both of which strongly expressed UCH-L1. Apoptosis was observed mainly in primary spermatocytes, which had weak or negative UCH-L1 expression although they are derived from spermatogonia. These data suggest that excess UCH-L1 in fact does not directly induce apoptosis in spermatogonia or somatic Sertoli cells. These data further provoke the question of why apoptosis occurs during spermatocyte meiosis.

In our *Uchl1* Tg mice, there was no evidence of spermatogonia or Sertoli cell apoptosis despite the fact that these cells had stronger UCH-L1 expression compared with non-Tg mice. Accordingly, it could be concluded that overexpression of UCH-L1 in spermatogonia does not directly induce apoptosis in these cells (nor in Sertoli cells). Because spermatocytes are genetically distinct from the original mother cell (spermatogonia), we speculate that the Tg mice are highly susceptible to spermatocyte apoptosis in vivo, with the inference that spermatocytes seem to be particularly sensitive to UCH-L1 overexpression in spermatogonia even though spermatocytes themselves express a much lower level of UCH-L1. In contrast, *gad* mice are resistant to cryptorchid-induced germ cell apoptosis, and many germ cells undergo apoptosis in older animals although their testes develop nearly normally and produce mature sperm (Kwon et al., 2004b). These data suggest that the lack of UCH-L1 causes mice to have lower sensitivity to stress compared with wild-type males, although UCH-L1 is probably not essential for spermatogenesis under normal conditions. On one hand, UCH-L1 seems to be necessary for the stabilization of germ cells to protect against aging-associated apoptosis; however, the stabilization of germ cells appears to be limited by the concentration of UCH-L1, and consequently they may be damaged during spermatocyte meiosis when UCH-L1 is overexpressed. Despite the fact that excess UCH-L1 does not induce spermatogonial apoptosis, abnormalities in intracellular regulatory factors may potentially influence mitosis directly (i.e., as the cell divides into two daughter cells—spermatocytes). Some of these factors may accumulate or be reduced in the presence of excess UCH-L1, thereby causing disruptions such as arrested meiosis or the onset of apoptosis in spermatocytes rather than spermatogonia (Fig. 8).

Many of the factors involved in cellular apoptosis, including the Bcl-2 family and caspases, are targets for ubiquitynation. Previously, we have shown that Bcl-2 is upregulated (Kwon et al., 2004b) and caspases-3 is downregulated (Kwon et al., 2005) in *gad* mice. The decreased level of Bcl-2 and increased level of caspases-3

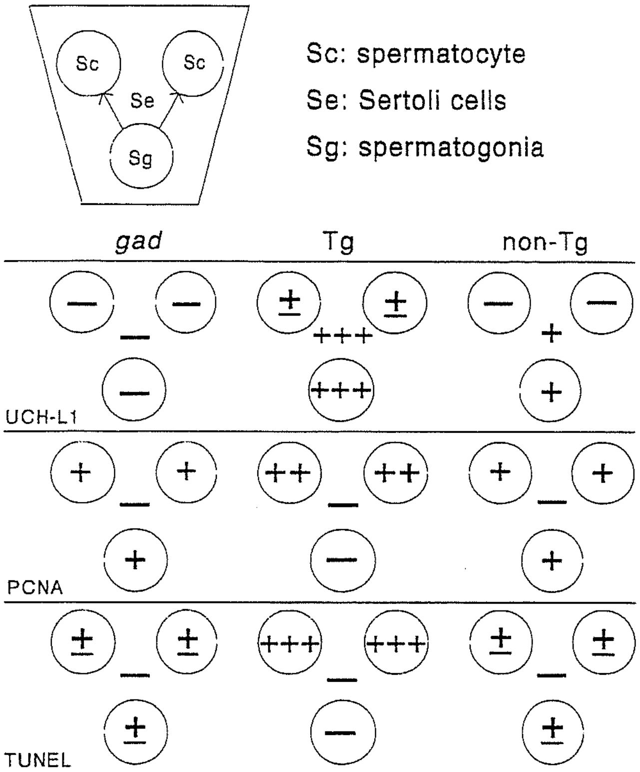

Fig. 8. TUNEL activity, and UCH-L1 and PCNA immunoreactivities in seminiferous tubules of non-Tg, *gad* and Tg mice. TUNEL activity or immunoreactivity: +++, strong; ++, moderate; + to ±, low to weak; −, not detectable.

observed in Tg mice in this study suggest that UCH-L1 can regulates the apoptosis during spermatogenesis by influencing the balance between apoptotic and anti-apoptotic proteins.

PCNA is ubiquitylated at lysine 48 (K48) and degraded by the ubiquitin-proteasome system (Yamamoto et al., 2004). In addition, PCNA is also monoubiquitylated at K164, thereby priming K63-linked polyubiquitin chains, which unlike K48-linked chains, do not promote proteasomal degradation (Hoege et al., 2002). In our present study, excess UCH-L1 relocalized PCNA from spermatogonia to spermatocytes and Sertoli cells in vivo and reduced PCNA expression to a low level in vitro. Based on these data, we hypothesize that UCH-L1, at least in part, may influence germ cell meiosis by affecting PCNA ubiquitynation, thereby disrupting its localization. In fact, PCNA significantly accumulated in primary spermatocytes of Tg mice (Fig. 4F). Since we did not obtain data regarding PCNA ubiquitylation in Tg mice, it is not clear whether the accumulated PCNA we observed was monoubiquitylated or polyubiquitylated. In any case, the accumulation of PCNA in primary spermatocytes may alter, damage or interrupt physical functions during meiosis (Fig. 8).

Germ cells and Sertoli cells are the only cell types expressed inside seminiferous tubules (McLaren, 1998). Germ cells constitute the male meiotic contribution to the reproductive cycle, whereas Sertoli cells support the growth and differentiation of germ cells. Direct interaction between germ cells and Sertoli cells may constitute an important part of the regulation of spermatogenesis (Russell et al., 1993). Indeed, mice exposed to Sertoli cell toxicants exhibit increased germ cell apoptosis (Lee et al., 1999). Therefore, Sertoli cells play a special role in nurturing and controlling spermatogenesis. Until postnatal day 16, UCH-L1 localizes only to spermatogonia, whereas after day 30 it also appears in Sertoli cells (Kon et al., 1999). Therefore, although UCH-L1 is highly expressed in both spermatogonia and somatic Sertoli cells, its function may be cell type-dependent. Under normal conditions UCH-L1 is a marker for activated Sertoli cells, in which it plays an important role in the degradation of abnormal proteins via the ubiquitin-proteasome system (Kon et al., 1999). Thus, we suspect that germ cell apoptosis in Tg mice might be related to the abnormal physical conditions in these cells. Our present work demonstrates that Tg mouse Sertoli cells are intensely immunoreactivity for UCH-L1, as expected. Furthermore, with vimentin, which is a marker present only in Sertoli cells (Oke and Suarez-Quian, 1993; Mori et al., 1997), we showed in this study that Tg mice had more vimentin immunoreactivity than non-Tg or *gad* mice (Fig. 5). Thus, forced expression of UCH-L1 in Sertoli cells perhaps may lead to gain of UCH function, thereby interrupting Sertoli cell-germ cell interactions that in turn promote germ cell apoptosis (Fig. 8).

In conclusion, we have demonstrated that UCH-L1 is an important spermatogenic factor related to PCNA and ubiquitin function. We used Tg mice overexpressing UCH-L1 to identify a new role for this protein. Overexpression of the *Uchl1* transgene inhibited spermatogenesis and induced germ cell death via an apoptotic mechanism, leading to male sterility. To our knowledge, the present data constitute the first description of a proapoptotic role for UCH-L1 in *Uchl1* Tg mice, as clearly revealed by the morphological and TUNEL results. Although UCH-L1 is constitutively expressed during spermatogenesis, and spermatogenic cell apoptosis is a normal aspect of mammalian spermatogenesis (Allan et al., 1992; Furuchi et al., 1996), the frequent cell death found in our *Uchl1* Tg mice could reflect an exaggeration of naturally occurring apoptosis. However, at present we do not understand whether the *Uchl1* transgene acts solely by inducing apoptosis or by interfering with differentiation so as to cause germ cell loss. This issue must be addressed to more fully define the role of UCH-L1 in the regulation and fate of spermatogonia during spermatogenesis.

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Effect of β-lactotensin on acute stress and fear memory

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ABSTRACT

β-Lactotensin (β-LT) is a bioactive peptide derived from bovine milk β-lactoglobulin and is a natural ligand for neurotensin receptors. We examined the effect of β-LT on restraint stress and fear memory in mice. Mice subjected to acute restraint stress exhibited a decreased number of head-dips and increased head-dip latency compared to non-stressed controls in the hole-board test, reflecting increased stress-induced behaviors. However, prior administration of β-LT improved the behaviors caused by stress. The anti-stress effect of β-LT was blocked by levocabastine, a neurotensin receptor subtype 2 (NTR2) antagonist. In the fear-conditioning test, the duration of freezing responses by cued fear conditioning was significantly reduced in mice administered β-LT compared with control mice. These results suggest that β-LT has an anti-stress effect and promotes the extinction of fear memory, which may be mediated by NTR2.

1. Introduction

Many bioactive peptides are derived from food proteins (e.g., β-casomorphin, ovokinin and gluten exorphin) [7,8,11]. These peptides elicit various biological effects, such as antinociception, hypotension and enhancement of learning and memory [4,19,21,27]. We previously isolated a 4-residue bioactive peptide β-lactotensin (β-LT; His-Ile-Arg-Leu) from a chymotrypsin digest of β-lactoglobulin [33]. We showed that β-LT is a natural ligand for neurotensin receptors (NTRs) [33]. There are three subtypes of NTRs. NTR subtype 1 (NTR1) [29] and subtype 2 (NTR2) [14] have high- and low-affinity neurotensin binding sites, respectively, and are G-protein-coupled receptors with seven-transmembrane domains. NTR subtype 3 (NTR3), however, is a receptor with single-transmembrane domain [15]. β-LT binds to both NTR1 and NTR2, and the binding affinity of β-LT to NTR2 was about 50-fold higher than to NTR1 [33]. While our in vivo studies of β-LT in mice showed that NTR2 peripherally mediates a hypocholesterolemic and antinociceptive effects [34,35], the effects of β-LT on higher brain function such as learning, memory, fear and anxiety have not been investigated. To date, there are some studies in rodents that have investigated the effect of neurotensin on behavior (e.g., food intake, locomotor activity and emotional behavior) [13,22,23]. Centrally administered neurotensin has been shown to stimulate the hypothalamic-pituitary-adrenal (HPA) axis in rat [18], suggesting that neurotensin can modulate stress response or other emotional status. In the central nervous system (CNS), NTR1

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mRNA expression has been observed in the thalamus, hypothalamus and the midbrain [2], whereas NTR2 mRNA is diffusely expressed throughout the brain [20]. NTR2 mRNA is expressed in the cortex and limbic region such as hippocampus, hypothalamus and amygdala [20]. These regions are important in the modulation of emotion and fear memory [5,10]. To examine the effect of β-LT on emotional behavior and fear memory, we performed the behavioral tests using β-LT. Among various kinds of emotional behavioral tests, we performed the hole-board test, because the hole-board test is one of methods commonly used for determining the anti-stress behavior. In addition, we performed the fear-conditioning test to examine the effect of β-LT on learning and memory, since the neuronal circuit for fear memory is well investigated. We also examined the effect of an NTR2 antagonist on mice pretreated with β-LT.

2. Materials and methods

2.1. *Animals*

Male C57BL/6J mice (8–9 weeks old) were used for all behavioral experiments. Mice were kept in a temperature and humidity-controlled room with a 12-h light–dark cycle (lights on at 08:00). Food and water were available ad libitum. All behavioral experiments were performed between 11:00 and 16:00 during the light cycle. All animal experiments were performed in strict accordance with the guidelines of the National Institutes of Neuroscience, National Center of Neurology and Psychiatry (Japan) and were approved by the Animal Investigation Committee of the Institute.

2.2. *Reagents*

β-LT (His-Ile-Arg-Leu; MW 537.7) was synthesized by American Peptide Company (Sunnyvale, CA) according to our order. β-LT was dissolved in saline and adjusted to pH 7.0 before administration to animals. Levocabastine hydrochloride was obtained from BIOMOL Research Laboratories Inc. (Plymouth Meeting, PA) and dissolved in saline with 5% dimethyl sulfoxide.

2.3. *Hole-board test*

The hole-board experiments were performed using a hole-board system (O'Hara & Co., Ltd., Japan) consisting of vinyl chloride board (50 cm × 50 cm) with equally placed four holes (3 cm diameter). The analysis of images was performed on a Macintosh computer using Image OFC 2.03x and Image OF 2.15x (O'Hara & Co., Ltd., Japan), a modified program based on NIH Image program. The program is a freeware developed by the U.S. National Institutes of Health and available on the internet at http://rsb.info.nih.gov/nih-image/. The experimental chamber was illuminated at 170 lx. The condition of restraint and the timing of drug injection were performed as described by Tsuji et al. [30]. Mice were either restrained in a 50 mL corning tube for 60 min (stressed group) or left in their home cage (non-stressed group). After release from restraint, β-LT (10 or 30 mg/kg) or saline (10 μL/g, control) was administered intraperitoneally. After 30 min, the hole-board test was performed and four parameters were measured for 5 min. The four parameters measured were: the number of head-dips, manually counted each time when mouse dipped its nose into the hole; the head-dipping latency which was the time elapsed before the first head-dip; total locomotor activity which was measured as the total moving distance of mouse measured in cm; the rate of visitation to the center area (referred to here as "% center") of the board, calculated as: [% center = staying duration in center area (s)/total experimental duration (300 s) × 100]. These parameters are indicators of the emotional status of mice [30]. Levocabastine (0.05 mg/kg) was given 10 min after the administration of β-LT in order to observe the effect of an antagonist on the anti-stress effect of β-LT. The doses of β-LT and levocabastine were as described previously [34].

2.4. *Fear-conditioning test*

Fear-conditioning experiments were performed using a computerized fear-conditioning system (O'Hara & Co., Ltd., Japan). On the conditioning day, each mouse was placed in the conditioning chamber (10 cm × 10 cm × 12 cm, clear plastic) equipped with an electrified 10 cm × 10 cm floor grid for 2 min before the onset of a tone (70 dB, 10 kHz) that lasted for 30 s. A foot shock (0.5 mA) was delivered through the floor grid during the last 2 s of the tone. The mice received the foot shock two times with a 1 min interval. β-LT was administered intraperitoneally after the conditioning. The doses of β-LT was followed the previous report [34]. On the second day, the freezing behavior was examined for 3 min in the same chamber without the tone or footshock (contextual fear conditioning). On the third day, mice were placed in a new chamber (10 cm × 10 cm × 12 cm, white plastic) under red light (cued fear conditioning). After habituation period of 2 min, the same tone (70 dB, 10 kHz) that has been used during conditioning was given for 3 min. The contextual and the cued test were performed 24 h and 48 h after the conditioning, respectively. The two tests were also performed with the same mice 1 week and 3 weeks after the conditioning. The freezing score (%) was presented as the ratio of time spent in a freezing state during the experiment. The freezing images were analyzed on a Macintosh computer using Image FZC 2.22 (O'Hara & Co., Ltd., Japan), a modified program based on NIH Image program. The program is a freeware developed by the U.S. National Institutes of Health and available on the internet at http://rsb.info.nih.gov/nih-image/.

2.5. *Statistical analysis*

The values are presented as the mean ± S.E.M. Statistical analyses were performed using the unpaired Student's t-test or ANOVA (followed by Bonferroni's multiple comparison test). p values < 0.05 were considered statistically significant in all statistical tests.

3. Results

3.1. *Hole-board test*

3.1.1. *Effect of β-LT on head-dipping behavior*

At first, we performed the hole-board test under non-stress condition to examine the effect of β-LT on mouse behavior.

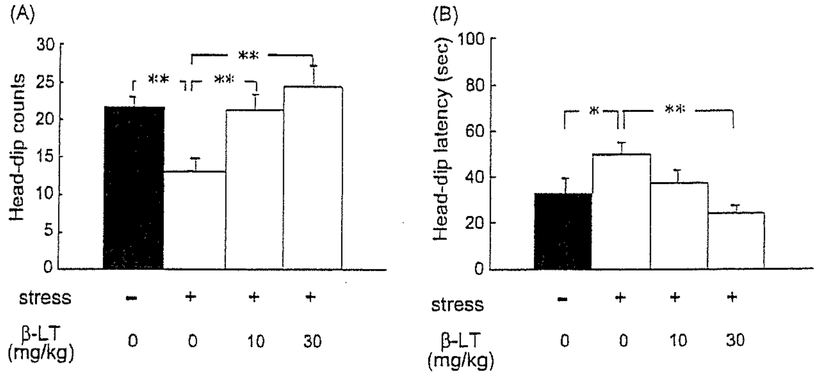

Fig. 1 – Effect of β-LT on the number of head-dips (A) and head-dipping latency (B) after stress/non-stress during the hole-board test. The hole-board test was performed 30 min after i.p. administration of β-LT. The values shown are mean ± S.E.M. ($n = 12$). $^{*}p < 0.05$ and $^{**}p < 0.01$ vs. control using the unpaired Student's t-test.

However, significant difference was not observed in any parameters between β-LT-treated mice and control mice (data not shown). Since there was no difference in the hole-board test without stress, we performed the hole-board test under restraint stress to examine the effect of β-LT on stressed mouse behavior. Sixty-minute restraint-induced stress decreased the number of head-dips compared with non-stressed control mice [non-stress: 21.67 ± 1.3; stress: 13.0 ± 1.78, $p < 0.01$] (Fig. 1A), in agreement with previous results [30]. Administration of β-LT significantly increased the number of head-dips after restraint stress compared with group treated with saline in a dose-dependent manner [β-LT 0 mg/kg: 13.0 ± 1.78; 10 mg/kg: 21.27 ± 2.09, $p < 0.01$; 30 mg/kg: 24.50 ± 2.57, $p < 0.01$]. The latency to the first head-dip was significantly extended in mice given restraint stress [non-stress: 32.63 ± 6.38 s; stress: 49.49 ± 5.15 s, $p < 0.05$] (Fig. 1B). Pretreatment with β-LT also improved the latency to the non-stressed control level in a dose-dependent manner [β-LT 0 mg/kg: 49.49 ± 5.15 s; 10 mg/kg: 37.33 ± 4.70 s; 30 mg/kg: 24.47 ± 2.76 s, $p < 0.01$].

3.2. *Effect of β-LT on spontaneous activity in the hole-board test*

To determine the spontaneous activity of mice that were pretreated with β-LT, total movement was examined using the hole-board test. In addition, the amount of time the mice spent in the defined center area (% center) was measured. Total locomotor activity and % center did not differ between the non-stressed and stressed control groups, and pretreatment with β-LT also did not affect these two behaviors (Fig. 2A and B). These results suggest that β-LT or restraint-induced stress does not affect spontaneous activity as measured by the hole-board test.

3.3. *Effect of an NTR2 antagonist on head-dipping behavior*

In our previous studies, we demonstrated that β-LT is a natural ligand for NTR2 and that some of the physiological effects of β-LT are mediated by NTR2 [34,35]. Thus, we investigated the effect of the NTR2 antagonist, levocabastine,

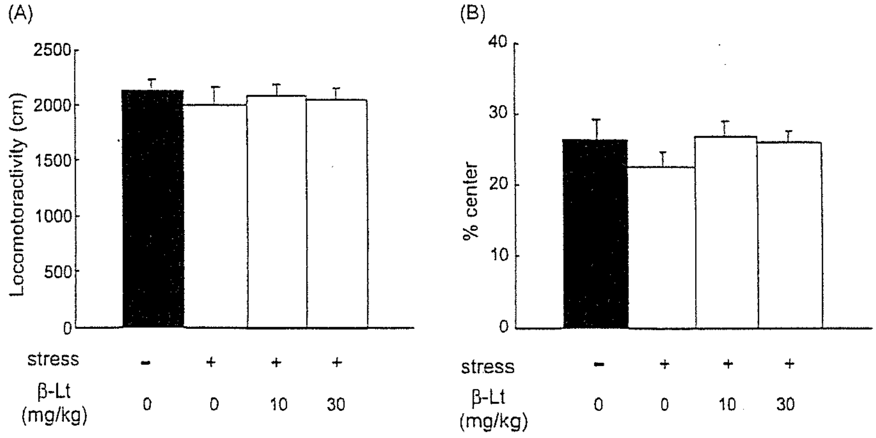

Fig. 2 – Effect of β-LT on total locomotor activity (A) and the rate of visitation to the center area (% center) (B) after stress/non-stress during the hole-board test. The hole-board test was performed 30 min after i.p. administration of β-LT. The values shown are mean ± S.E.M. ($n = 12$).

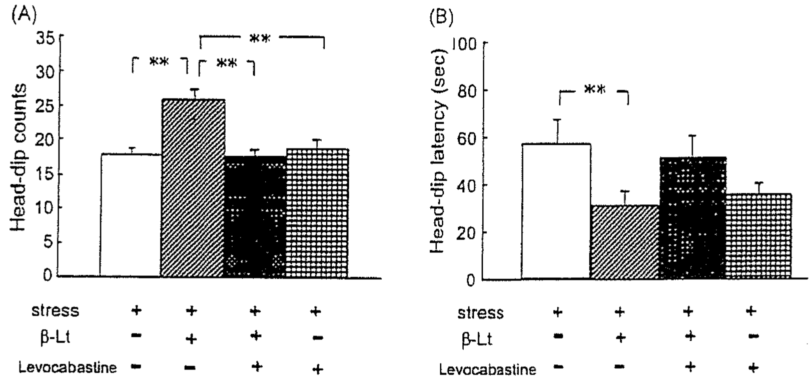

Fig. 3 – Effect of the NTR2 antagonist levocabastine on the number of head-dips (A) and head-dipping latency (B) after stress following the administration of β-LT during the hole-board test. β-LT was administered i.p. at a dose of 30 mg/kg. Levocabastine was given intraperitoneally at a dose of 0.05 mg/kg 10 min after β-LT administration. The values shown are mean ± S.E.M. ($n = 8$). $^{**}p < 0.01$ vs. control using ANOVA, followed by Bonferroni's multiple comparison test.

on mice pretreated with β-LT. In mice that received β-LT, levocabastine blocked the anxiolytic effect of β-LT and the number of head-dips decreased [levocabastine (−): 25.78 ± 1.59; levocabastine (+): 17.67 ± 1.01, $p < 0.01$] (Fig. 3A). Levocabastine tended to block the effect of β-LT in the head-dipping latency [levocabastine (−): 30.55 ± 6.04 s; levocabastine (+): 51.03 ± 9.24 s, $p = 0.06$] (Fig. 3B). Levocabastine itself did not affect these head-dipping behaviors. These results suggest that the anti-stress effect of β-LT on mouse behavior can be blocked by an NTR2 antagonist.

3.4. *Effect of β-LT on fear-conditioning test*

Prior to the experiments with β-LT administered mice, we tested with naive C57BL/6J mice to ascertain the validity of the fear-conditioning system. In the conditioning, mice habituated in the grid chamber (freezing: <1%). After two electrical shocks with tone, mice showed freezing response (27.9 ± 8.7%). In the contextual test at 24 h after conditioning, mice froze in the conditioned chamber (30.8 ± 10.9%). In the cued test, mice were freely moving in the novel chamber before the tone (<1%). After the tone stimulus, they froze in the chamber (26.3 ± 7.5%).

Thus, the validity of the fear-conditioning test was confirmed, and we performed next the fear-conditioning test to investigate the effect of β-LT on fear memory. There was no difference in freezing behavior among the three groups during the conditioning (data not shown). Immediately after the conditioning, β-LT was administered intraperitoneally. In order to give the same conditioning circumstance, β-LT was administered at this point. Contextual tests conducted at 24 h, 1 week and 3 weeks after the conditioning showed that contextual fear memory was not affected by β-LT treatment (Fig. 4A). On the other hand, cued test conducted 1 week after

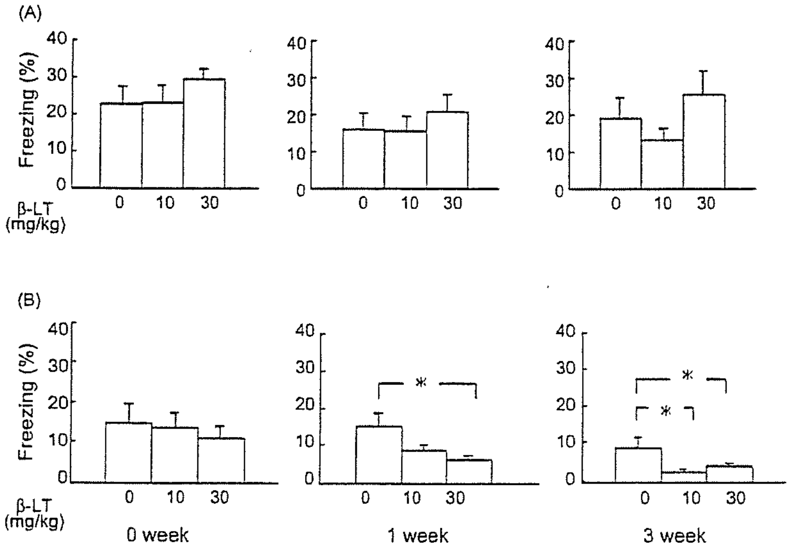

Fig. 4 – Effect of β-LT in the fear-conditioning test. (A) Effect of β-LT in the contextual test; (B) effect of β-LT in the cued test. Immediately after the conditioning, β-LT was administered intraperitoneally. The rate of freezing (%) was calculated to indicate fear memory. The values shown are mean ± S.E.M. ($n = 10$). $^{*}p < 0.05$ vs. control using the unpaired Student's t-test.

the conditioning showed that β-LT significantly decreased cued-fear memory in a dose-dependent manner [control: 14.27 ± 2.91%; β-LT 30 mg/kg: 6.03 ± 0.41%, $p < 0.05$] (Fig. 4B). In addition, the difference in freezing behavior between control mice and β-LT-treated mice was still evident at 3 weeks after the conditioning.

4. Discussion

In our present study, pretreatment of restraint-stressed mice with β-LT increased the number of head-dips and shortened the latency to the first head-dip compared to the control levels in the hole-board test. As we observed, Tsuji et al. [30] showed a significant decrease in the number of head-dips and a significant increase in head-dipping latency in mice 1hr after acute restraint-induced stress. Since there was no difference in the hole-board test without stress, our results suggest that β-LT has anti-stress effect on stressed mouse. Physical or psychological stress is known to activate the HPA axis [12], suggesting that peripheral administration of β-LT may modulate the activation of the HPA axis. The anti-stress effect by β-LT was blocked by levocabastine, an NTR2 antagonist. The *Ki* values of levocabastine for NTR1 and NTR2 are >10,000 nM and 17 ± 2 nM, respectively [17]. Although, levocabastine is an antagonist not only for NTR2 but also for histamine H1 receptor [14,32], it was shown that histamine H1 receptor was not involved in the head-dipping behavior in the hole-board test [3]. These results suggest that the blockade of the effect of β-LT is due to the inhibition of NTR2.

Though the intracellular signaling of NTR2 is very important, the mechanisms of signaling properties are still controversial. For example, when the receptors are expressed in mammalian cells or in *Xenopus oocytes*, the receptor shows different characters that may be species-dependent [31]. In addition, neurotensin acts as an antagonist in human NTR2 expressing in CHO cells though it acts as an agonist endogenously. Since the NTR2 is Gq-coupled type receptor, the signaling pathway may be mediated by Gq-related IP3 as a second messenger. β-LT may be a useful tool to investigate the signaling pathways downstream of NTR2.

In the cued fear-conditioning test, freezing response was significantly reduced in β-LT-treated mice 1 week after conditioning. In order to examine whether the effect of β-LT is mediated by NTR2, we tested the effect of levocabastine on the fear extinction effect of β-LT in the fear-conditioning test. Levocabastine reversed the reduction of freezing induced by β-LT (data not shown). However, levocabastine itself also reduced the freezing response in our study. We could not confirm the NTR2 blockade by levocabastine in the fear-conditioning test, while levocabastine could block the effect of β-LT in the hole-board test, suggesting the involvement of NTR2. One of the reasons for this discrepancy is that the timing of drug adminstration is different between the hole-board test and the fear-conditioning test. In addition, though levocabastine or histamine H1 receptor has not been reported to affect the fear memory, our results suggest that H1 receptor may be involved in fear conditioning.

In this study, during the conditioning session conducted prior to the fear-conditioning test, all mice froze (data not shown). This indicates the fear memory was normally acquired. And the results obtained from the subsequent contextual as well as cued tests, conducted after 24 h and 48 h, show that the fear memory was consolidated. However, generally this consolidation is not stable, and fear memory become labile when the animal is exposed to the same circumstance again, or the conditioned stimulus such as sound is given [1]. It has been reported that once the fear memory becomes labile, it will either consolidate or extinct [1,26]. In our study, the freezing response began to decrease 1 week after the conditioning. Consequently, two possible causes are considered; namely, consolidation of the fear memory may not be completed, and/or extinction of the fear memory may be promoted. Since consolidation and extinction are known to occur simultaneously, β-LT tends to destabilize memory consolidation and promote fear memory extinction.

There are several possibilities on how β-LT can promote the fear extinction. It is known that the fear extinction requires time-dependent novel protein synthesis. Stiedl et al. [25] showed that a protein synthesis inhibitor cycloheximide injection at posttraining in the fear-conditioning test promoted memory extinction 24 h after the first test. Thus, posttraining injection of β-LT may modulate the protein synthesis, and affect on the memory extinction process. Furthermore, Sotres et al. have reported that the inhibitory signal from ventral medial prefrontal cortex is transmitted to the lateral amygdala and induces the reduction of freezing response in the fear memory extinction process [24]. Our findings suggest another possibility that β-LT may promote the extinction of cued-fear memory by modulating the signal from the medial prefrontal cortex to the lateral amygdala.

Peripheral administration of peptides derived from milk protein can modulate anxiety-related behavior and distress [16,27]. Miclo et al. reported that i.p. administration of α-casozepine, a tryptic peptide from bovine milk casein, improved anxiety in the elevated plus maze and defensive burying test [16]. They showed that the antianxiety effect of α-casozepine may be mediated by the $GABA_A$ receptor. In pigs, orally infused colostrums, from which lactoferrin, a milk-derived peptide, is produced by enzymatic digestion, can be transported via circulating blood into the cerebrospinal fluid where it binds to the Lf receptor in the choloid plexus (CP) [9,28]. Flood et al. reported that i.p. administration of mammalian bombesin-like peptide, gastrin-releasing peptide (GRP), enhanced memory [6]. Vagotomy inhibits the memory-enhancing effects of GRP, suggesting that this peptide affects by activating ascending vagal pathways [6]. To date, the distribution of functional NTR2 in the CP and peripheral vagal ganglion has not been reported. Further investigation is needed to learn more about the mechanism of how β-LT affects the CNS.

Our present study shows that β-LT, which is derived from β-lactoglobulin, has an anti-stress effect and promotes the extinction of fear memory in the CNS. Given that anti-anxiety or anti-stress drugs sometimes induce adverse side effects such as drowsiness, thirst, and addiction, the fact that β-LT is a natural product from milk protein suggests that β-LT may be a safe and useful substance to modulate emotional disorders.

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